Light Coal:
Development of a torrefaction reactor and business system for Himalayan India

Culture in Business Structure and Reactor Modelling

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Abstract

Novel methods of the implementation of technology can be instrumental in aiding the growth of developing countries. Here, torrefaction has been investigated for its application to rural, Himalayan India, for the production of solid fuel briquettes from pine needles for sale to the food industry. Here, both technical and social aspects are combined to simultaneously develop the entire business system. In the technical research, the design, modelling, construction, and testing of a torrefaction reactor have been carried out. After the design of a locally adapted reactor, a model was developed for the heat transfer, solid decomposition, and gas production in the reactor. Moderate results were achieved, with reasonable mass yields and estimates of the fuel value of the produced gas. In the social research, the design of the business system with emphasis on cultural considerations has been carried out, including the business model, value propositions, stakeholder analysis, logistics system, business management structure, operations and maintenance systems, financial analysis, and environmental analysis. Various measures have been proposed to incorporate a professional work culture with local values into the management structure. In addition, the financial and environmental analyses show strong advantages over local competitors in cooking fuels. Although further research is needed to develop the technology before realization of the project, this novel method of simultaneous development of the technology and business system with contextual consideration has produced a promising foundation of a business with much potential. This project has been carried out in tandem between Vidyut Mohan and Ryan Helmer, and thus methods and findings are divided between the reports of each of the authors.

1.0   Introduction

This project is focused on the development of bio energy for rural, developing areas, particularly aimed at the context of the region of Kumaon, in the state of Uttarakhand, in northern India. Here, pine needles will be assessed as a source of energy for the region. Furthermore, this project aims at addressing various social and environmental issues through the implementation of this biomass resource in this developing region.

1.1   Socio economic context

India has grown substantially in recent years in being a powerful country economically and politically. The growth of industry in industry has put among the world's largest producers of good, and it has become a global leader in information technology, with 8% of their exports coming from high-tech products (World Bank 2015). However, despite recent surges in growth of this country, India still faces numerous social issues in their journey of development that must be addressed in the coming years.

India's population, currently at 1.3 billion, has been maintaining a fairly constant growth rate in population over the past 20 years, at 1.3% annually according to World Bank statistics. Furthermore, their economy has been likewise growing steadily over the same time frame at a rate of above 5% annually in terms of Gross Domestic Product (GDP), and currently sitting at 1.9 trillion USD. However, despite tremendous growth overall, parts of the country are still struggling, as 21.9% of the population lives below the poverty line, determined by a variety of indicators (World Bank 2015).Furthermore, rural regions lag far behind the industrial and commercial centers of the country in many ways, including economic growth, infrastructure, and the availability of basic facilities (educational and medical).

1.1.A   Lack of Facilities/Infrastructure/Education

In particular the mountainous region of Kumaon in the state of Uttarakhand suffers from these issues as well. This region is comprised of numerous series of mountains, from the foothills coming out of the plains, until the high Himalayas on the border with China. In this region, infrastructure is still in need of development, as the primary means of transportation of goods and people is via automobile on narrow, inadequately maintained roads that maneuver the steep mountain ranges. On average, vehicles are able to travel only 25-30 kph on these roads, resulting in long delays in delivery of goods. Beyond the city of Haldwani, which rests on the edge of the foothills, many basic materials, including simple sheets of mild steel, must be procured directly from outlets in Haldwani, and delivered by truck to locations in the mountains. Furthermore, electricity, although it has reached the majority of communities in Kumaon, is far from reliable. Power outages are almost a daily occurrence, with outages lasting several hours at a time, particularly when inclement weather arrives.

It is important to clarify that the mountainous regions of Uttarakhand, including Kumaon, have both regions that sit in the plains, as well as regions that sit in the Himalayan Mountains, although the mountainous regions are much larger than those in the plains, comprising 10 of the 13 districts of the state of Uttarakhand (Chandrasekhar 2014). However, there is great disparity between the mountainous region and the plains region, for obvious reasons, infrastructure above all else. Due to these difficulties with infrastructure in the mountainous region, this area is very slow to develop. Procurement of simple construction materials or equipment involves substantial delays, and specialized equipment is far more complicated. The steep terrain makes construction immensely difficult, and investors and new industries are scarce in developing. Hospitals are few and far between, as government support for medical facilities is lacking, and private doctors have difficulty finding financial return for the added investment of beginning a practice in such remote locations. Education is slow to grow, as teachers are also reluctant to come from other regions to such remote locations. Furthermore, few people in the region are able to pay high prices for education or medical services, thus reducing the incentive for professionals in these fields to come to this area.

Therefore, due to the lack of facilities, predominantly educational and medical facilities, and the lack of jobs, many families who are able to transition to the plains, to large cities such as Haldwani or Delhi, in order to establish a better life. Higher quality education in these areas allows for following generations to improve their way of life, in addition to the practical peace of mind from being close to quality clinics and hospitals. Above all, it is much easier for industries to operate in the plains than in the mountains, providing far more jobs in the plains.

1.1.B   Decline in Agriculture

In addition, agriculture has been for centuries, the predominant form of livelihood in the Kumaon region of Uttarakhand, which has been maintained by the passing down of traditional ways of life to successive generations. However, in recent years, this region has suffered significant deterioration in agriculture as a way of life. India as a whole has lost 23.3 million jobs in agriculture over the period of 2004-2010, which causes a tremendous impact when over 50% of the nation's employment is in agriculture(Chandrasekhar and Sharma 2014). Specifically in the hill region of Kumaon, 72% of the workforce is employed in agriculture. However, only a small portion of the land (14%) is usable for agriculture, due to the mountainous terrain and ecological decay in recent years (Mamgain 2011). Furthermore, land holdings of residents are insufficient to support families, as, over the years, land holdings have been divided among various children, and distributed disjointedly, so many farmers possess small, disconnected plots of land, making agriculture very difficult(Mamgain 2011).

Therefore, many local residents resort to temporary labor, occasional jobs for local construction projects or other jobs. However, sustained employment in the form of a salaried job is rare in Uttarakhand, forcing the local population to scavenge for marginal, or casual, jobs, to support themselves. Thus, although unemployment is not an issue in this region, as one simply cannot survive unemployed, underemployment is much more a common problem in developing areas. Thus, due to a lack of productive employment, among other reasons, many in the labor force, particularly men, are idle much of the time, up to 63% of their days, whereas women are much less idle (34% of their days), as they are the principal caretakers of the house and farm (Mamgain 2011). Furthermore, many of the youth, particularly young men, receive basic education, but have little useful, technical skills, and very few grow up with any interest in carrying on the tradition of agriculture, with up to 70% of young men not being involved in agriculture (Mamgain 2011).

1.1.C   Urban Migration

In the rural, mountainous areas, it is clear that sources of productive employment are lacking. Due to the higher concentration of industries in urban centers, such as the area around Delhi, many people migrate to these areas from more rural areas for the prospect of jobs. Migration within the country is a widespread phenomenon, as, according to the 2001 Census in India, 315 million persons of the 1.03 billion in India reported being migrants based on last place of residence, 31% of the total population, with 30% of these migrants being youth (Rajan 2013). As seen above, a lack of employment is a large motivation for this migration, being the second most common reason among migrants for moving, totaling 10% of migrants (Rajan 2013, Chandrasekhar 2014). (Marriage is the largest reason for migration in India, as this a strong traditional practice in this culture. Here, the focus will be on migration for employment, which almost always drives people from rural to urban locations). 81% of young internal migrants, in the age range of 15-29, migrate from rural areas, rather than urban areas, showing that it is rural areas that are suffering drastic reshaping due to the movement from rural areas (Rajan 13).

However, the migrants to the cities are often faced with a more difficult situation than in their homes. According to a study on urban migrants, many of them report enduring exploitative working conditions, having low education and few skills. Many end up working as waste pickers, rickshaw pullers,

construction workers, or domestic workers, unskilled jobs, with 91% of migrants receiving less than minimum wage. Furthermore, 41% of these migrants live in slum areas (Mander 2010). In the region of Kumaon, many people move to the cities of Haldwani or Delhi without much in terms of defined skills. Thus, many end up working in kitchens as coos or dish washers for basic wages and living in poor conditions. Furthermore, many youth that migrate to the cities go merely to leave behind the rural lifestyle in aspiration of an idealized city life, and then struggle to find work and survive. Many of these young migrants resultantly return to the rural areas later, but still struggle to find employment, and thus 92% of the unemployed population is youth from 15-29 years of age (Mamgain 2011). Thus, it is very clear that sources of productive, consistent employment in rural areas are in great need.

1.1.D   Cooking and Heating Fuels in Rural India

In addition to issues in the local economy of Kumaon, there is a growing need for a sustainable source of energy, primarily in the form of a cooking fuel. In India as a whole, the vast majority of Indians, almost 70%, rely on biomass, such as wood or cow dung, for their primary cooking fuel (Woodbridge and Sharma 2010). Furthermore, in urban and rural homes alike, fuel costs comprise 10% of the household expenditures, on average, being the second highest expense behind food. The average household budget amounts to a mere 2,719 INR (60.43 USD) (Woodbridge and Sharma 2010). In rural Uttarakhand, 77% of households use firewood, while 18% use liquefied petroleum gas (LPG) and another 2% use dung cakes for their primary cooking fuel. 44% of rural houses use kerosene for lighting, while 55% are able to use electricity for this purpose.

In Kumaon specifically, the electricity grid has grown substantially in the last decade to cover the vast majority of villages and houses in the region. However, due to the lack of reliability of the grid, among other reasons, electricity is not often uses for cooking in households. Above all, two trends are seen in the area: households in small towns or cities likely have reasonable access to government-subsidized LPG cylinders, while households in remote locations and villages likely rely on firewood for fuel. No other fuel is used widely.

The government run business Indane Oil has control of the distribution and sale of LPG cylinders. In order to procure an LPG cylinder for a subsidized price (for domestic use), one must have a legitimate permit (or connection) to purchase. Uttarakhand is reported to have the 4th highest number of LPG connections per capita, thus indicating fairly high access to LPG in this state. However, on average, 60% of LPG connection sit in urban areas, with only 40 sitting in rural areas (IISD 2014), while in Uttarakhand, 47% of the population live in urban areas (Mamgain 2011). Thus, in the rural areas, there is satisfactory access to LPG cylinders, particularly in towns, but remote villages still struggle to have availability.

However, the government subsidy for LPG comprises a massive expenditure for the government, exceeding the Indian government's total expenditures for education (Rs 63 billion in 2002-03) (World Bank 2003). Dependency on oil imports rose to an estimated 71% in 2012, from which transportation fuel and LPG are derived(Dunn 2014).The price paid by the consumer varies across the state, but in the area of Berinag, Uttarakhand, the price sits around 200 Rs/cylinder, periodically fluctuating, giving a cylinder price of 687 Rs to the consumer. Furthermore, in the past year, the cap on the accessibility of domestic cylinder was raised to allow 12 domestic cylinders to each connection holder per year, further

increasing the financial burden on the government by 500 million INR annually (Hindustan Times 2014). Naturally the consumption of LPG is increasing, having more than doubled in India in the last 10 years(IISD 2014). Furthermore, as this resource, being derived from non-renewable energy sources of crude oil and natural gas (IISD 2014), continues to be gradually depleted, the prices will continue to rise in the long term, and the availability of the resource will decline (World Bank 2003). Thus, although availability of LPG in Kumaon is currently satisfactory, with a very competitive price, over the long term a sustainable solution needs to be found.

Alternatively, the use of firewood as a source of energy carries its own difficulties, predominantly being drudgery of work, especially in terms of time and physical fatigues, and the strained natural resource of the forests. In rural Uttarakhand, 88% of households report gathering cooking fuel from free collection or from home grown stock, not purchasing. Only 10% of firewood users actually pay for it (Woodbridge and Sharma 2010). Thus, obviously, the lack of monetary cost is a large driver for the use of free wood for fuel. Thus, many villagers in Kumaon, predominantly women, spend significant amounts of time collecting wood, up to 10 hours per week, and carrying 10-15 kg of wood at a time (Author Interviews). On these trips, it is not uncommon to walk several kilometers from the village to collect, due to constrained resources. The Regional Forest Department restricts the cutting down of trees for wood, as this organization typically sells the pine trees in the forest to industrial clients willing to pay for the resin and lumber. Village lands are occasionally properly maintained to provide for the fuel needs of the village, but often villagers are still forced to search on Forest Department lands for wood. Overall, villagers seem content despite the high time and labor cost of firewood collection. Furthermore, currently wood resources appear to be just ample to supply local needs, but increasing pressures on the future may make the collection of wood very difficult.

1.1.E   Ecological Considerations

In addition, the Kumaon region of Uttarakhand harbors a unique biomass resource in pine needles, released in large quantities from the plentiful pine forests in the region. The pine forest region of Uttarakhand totals 343,000 hectares of land, producing about 2.1 million tons of dry pine needles annually (about 6 tons per hectare on average) (Bisht, Singh, and Kumar 2014). These pine needles have little application, being only nominally utilized for bedding for livestock, but otherwise lie unused on the forest floor. As these needles are highly flammable, and lie in such large quantities, there is a high tendency for forest fires to start from these pine needles, which are known to mark the Kumaon landscape during the dry months of the year(Khan 2012).

While these fires in general do not grow to pose any large threat to human life in the area, they are severely damaging to the local ecology. Above all, these fires damage the topsoil of the forests, reduce cattle grazing lands, degrade biodiversity in the forests, and encourage a fragile monoculture of pine trees in the region. Above all, the pine trees alone are able to survive these fires, while the native oak and cedar trees are constantly disappearing (Vishnoi 2009)(Author Interviews). This loss of biodiversity makes the ecosystem of the forests much weaker, reducing the quality of drinking water, erosion protection, in addition to the overall thinning of the forests, which reduces the availability of wood for fuel. The Regional Forest Department encourages this monoculture, as it can benefit economically from the sale of large quantities of pine trees, due to their fast growth rates and resin contents (Regional

Forest Department 2015). Furthermore, the weakening of the forest is connected to the degradation of the soil, which in mountainous regions, can lead to deadly landslides, such as those seen during the 2013 monsoon season, killing thousands and wiping away entire villages (Chopra 2013). Thus, although not the cure for all of these ecological problems, a tangible application for these pine needles could aid in the ecological health of this region.

1.2   Torrefaction Overview

1.2.A   Process Conditions

The biomass processing technology of torrefaction shows promise in providing a solution for providing a sustainable biomass fuel for the region of Kumaon. This process has been developed for the application of upgrading second generation biomass sources, such as sawdust and wood chips. This process consists of a light-roasting process, creating a charcoal like fuel product, typically called bio-coal. Above all torrefaction requires several essential components: the slow heating of the biomass to temperatures between 200 and 300°C, using ramping rates of less than 50 °C per minute in the heating phase (J. S. Tumuluru et al. 2011)(Bergman and Kiel 2005). Furthermore, after the desired reaction temperature has been reached, then the biomass is held at that temperature for a moderate residence time of around 30 minutes (J. Tumuluru, Sokhansanj, and Wright 2011). A graphical depiction of the process is shown below.
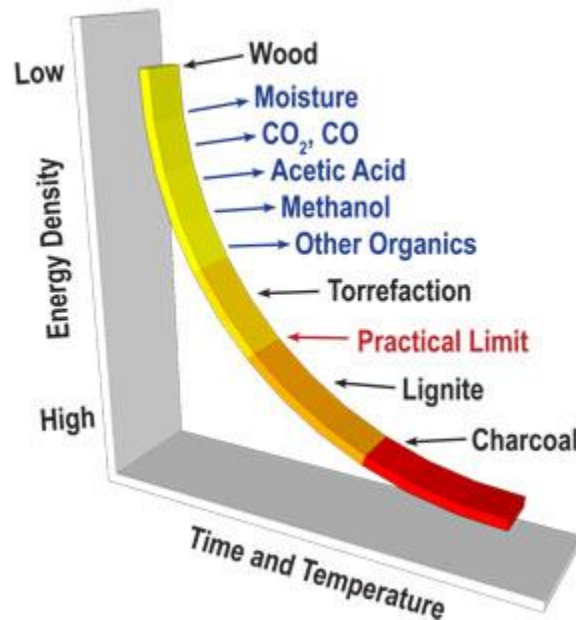
Figure 2 - Diagram of the degradation during torrefaction (ecoTech Energy Group 2010)

During this process, the biomass begins to decompose and release various volatile compounds. Second generation biomass, consisting primarily of the three components of cellulose, hemicellulose, and lignin, primarily undergoes the release of hemicellulose compounds in the form of volatiles and permanent gases during torrefaction, although the fibrous cellulose fraction decomposes somewhat at the higher temperatures of torrefaction as well. These volatiles primarily consist of organic acids, such acetic and

formic acid, and methanol, in addition to a large portion of water released in the initial heating phases, while the permanent gases include carbon dioxide and carbon monoxide primarily(J. S. Tumuluru et al. 2011). Thus, the gas released during torrefaction is slightly combustible, having a calorific value on the order of 5.3-16.2 MJ/ Nm^3, on same order of producer gas from biomass gasification, at 4-7 MJ/ Nm^3 (J. Tumuluru, Sokhansanj, and Wright 2011).

In addition, it is imperative that the environment in which the biomass is heated be highly inert, usually containing no oxidative elements (air - free) and typically heated in a nitrogen environment (J. Tumuluru, Sokhansanj, and Wright 2011). Thus, torrefaction does comprise a form of pyrolysis, which is the heating and decomposition of biomass at elevated temperatures in an oxygen free environment. However, torrefaction must be distinguished from other fast forms of pyrolysis in that the biomass is not heated to higher temperatures (400 to 800 °C) which causes severe degradation of the cellulose and lignin components of the biomass, but primarily the hemicellulose compounds (Uslu, Faaij, and Bergman 2008). Furthermore, the biomass is not heated quickly or maintained for short residence times, as the residence times of fast pyrolysis on the order of seconds, which produces a large portion of liquid product (Bridgwater 2012). Rather, torrefaction, above all, produces a solid char product, consisting of 80% of the initial mass and 90% of the initial energy content, with the gaseous components released containing the remainder (Bergman and Kiel 2005). Therefore, importantly, the vast majority of the energy content and mass content of the initial fuel is retained in the torrefied biomass.

1.2.B   Applications

This process has been shown to be applicable to a broad range of feedstocks, not only wood wastes, if the processing conditions are adjusted to the feedstock (Kleinschmidt 2011). Furthermore, the Energy Center of the Netherlands (ECN) has developed a process combining the torrefaction process with densification (pelletization) with improved efficiency which produced a dense, durable fuel of consistent size and density (Bergman and Kiel 2005). These bio-coal pellets can be combusted in appliances and process that currently use charcoal or coal, as their properties, particularly in regard to energy density, calorific value, and grindability, are very similar to that of coal, with a heating value on the order of 21 MJ/kg (Koppejan et al. 2012)(Bergman and Veringa 2005; Kleinschmidt 2011).

The option of torrefaction for biomass upgrading is attractive over pelletization alone for several reasons. Grindability of torrefied biomass is often discussed in literature (Arias et al. 2008), however this is primarily beneficial in co-firing applications with pulverized coal in power plants. For rural applications, the benefit comes in the logistics chain, as torrefied biomass is easier to pelletize than raw biomass, which is partly due to its grindability, which reduces the energy required to pelletize, but also due to the partially degraded lignin content which acts as a natural binding agent (Koppejan et al. 2012). Furthermore, torrefied biomass has been removed of its moisture content, usually having 1-3% after processing, which improves the combustion properties, but also eliminates the transport of water mass. This, combined with the improved calorific value of torrefied pellets, results in much more efficient transport of the energy containing biomass than transporting raw biomass(Bergman and Veringa 2005). Furthermore, the low moisture content inhibits the biological degradation of the biomass during long term storage (Batidzirai et al. 2013). In the case of the mountainous region of Kumaon, this advantage becomes crucial due to slow and expensive transportation.

Furthermore, in order to improve the energy efficiency of the torrefaction process, various options have been researched, such as recirculation of flue gases used to heat the biomass, or recirculation of the torrefaction gases produced, to reduce the loss of heat in the cycle(Kleinschmidt 2011). In addition, the combustion of the torrefaction gas also been researched, to provide heat for the drying process, and to reuse the energy lost in the volatiles in the process itself (Bergman and Kiel 2005). If proper process integration is achieved net efficiencies of 70-98% have been reported for the torrefaction process (Koppejan et al. 2012). Thus, this project will investigate if the torrefaction gas can be utilized in a rural plant based on pine needles in order to improve the process efficiency.

Thus, torrefaction poses a promising option for the utilization of unused biomass resources in rural areas and the application of it in energy applications, such a cooking, heating, and possibly electricity generation. This project will in particular investigate applying torrefaction to pine needles for use in the region of Kumaon.

1.3   Social Entrepreneurship among Models for Development

1.3.A   Development Measures

Within the realm of global development, a broad range of methods exist to instigate the growth of nations and communities, in general falling into one of two categories: Top-Down development or Bottom-Up development. Top-Down development embodies more formal, commonly used methods of development, typically channeling money in the form of aid between governments of various nations. For instance, the World Bank is a prime example of aid extended in the form of financial support towards developing nations in the pursuit of eradicating poverty. Many of these aid efforts began after the closure of the Second World War, in hopes of restoring the economic stability of nations after the devastation of the war.

However, in recent years, this model of development, primarily in the form of aid money from economically strong countries to developing countries, has come under intense criticism. Some of the critics include former leaders within the World Bank itself, such as William Easterly. In his book The White Man's Burden, he demonstrates the innate problems with the aid model of development (Easterly 2006). Proponents of aid espouse unreachable utopian goals, often for the sake of promoting political appeal, and these goals are often too diverse and broad for single organizations to address with any effectiveness. Aid efforts often channel funds through governments in hopes of it reaching the poor, although the governments of developing countries are often unstable and rife with corruption, resulting in little good for the poor. The aid model also rewards observable efforts that do not produce substantial growth, whereas many small advancements without glamorous appeal go unnoticed, and are thus not often adopted by non-governmental organizations (NGO's). Importantly, aid-driven organizations are in essence responsible to the donors, who provide their means of sustenance, as opposed to the targets of aid reforms: the poor. Their motivations are divided, trying to please both donors and the poor, and those providing the finances often hold more sway (Fowler 2000). Thus, those receiving the "help" often have little influence in the measures taken, and have little voice to hold aid agencies accountable. Lastly, the aid model presupposes that an adequate, well-constructed plan can

achieve these high goals, ignoring much of the complexity and uncertainty within modern, global society (Easterly 2006). Still other experts discuss how aid fostered patronage, dependency, and financial malpractice in developing countries (Fowler 2000).

1.3.B   Market Driven Solutions

Thus, Easterly, in addition with other development experts have begun advocating market driven solutions to achieve development. These solutions are accountable to the target audience of the poor, and must properly meet their needs if their aim is to survive. Where aid is successful for short term solutions, such as in the instance of natural catastrophes, long term growth cannot take this top down approach (Isaac 2012). Furthermore, enterprises that able to focus on specific solutions and issues, without the pressures to meet idealistic, top-down goals are thus more effective. These solutions can bypass governments, where money is often siphoned into undesired purposes (Isaac 2012). Such social enterprises have become well known worldwide, integrating profitable activities with social benefit achieved by them (Fowler 2000).

Aids measures are often contrived by bureaucrats and workers in developed countries, disconnected from the context of implementation in a developing nation. A lack of information and understanding thus results in the failure of many attempted projects, resulting in wasted funds, largely from tax payers. Development solutions must be submerged and rooted in the local context, with a firm understanding of the social norms and cultural environment, in order to make sustainable impact. Thus, it is imperative that a social enterprise be steeped in the local context, in terms of economic, environmental, political, but also socio-cultural aspects from its very inception. All of these facets are vital to the success of the venture, and must all be given ample consideration.

Social enterprises led by local entrepreneurs, in a bottom-up approach, are much more conscious of these contextual issues, and these are much more able to adapt to circumstances than rigid plans for government aid contrived by large overseas aid organizations (Easterly 2006). In this project, a synergistic blend of knowledge from external sources, in this case academic institutions, with insider understanding held by local entrepreneurs, is sought in order to develop the most effective business approach. Thus, an understanding of cultural idiosyncrasies of the local context is paramount for external experts to constructively contribute to the business design process.

Furthermore, the current study is based on the idea that the most sustainable solution for the economic and social issues of a developing community must involve an in depth understanding and detailed information of the local context from before the inception of the venture. Thus, the design of not only the product or service must be designed with contextual insight, but also the design of the business system itself, including the logistics chain, the managerial structure, and the manufacturing process technology itself. A holistic approach, taking everything from culture to technology to finances into consideration from the onset, is thus needed.

1.4 Scientific Relevance

1.4.A Social Research

On the social side, large amounts of research regarding different aspects of business development have been explored in research. Substantial research exists in the Industrial Design field on exploring how to incorporate social-cultural norms and preferences into the design of products and services, even for environments of developing countries, such as in the case of Generative Design research, which will be discussed later (Sanders and Stappers 2014; van Boeijen 2015). Also, the integration of service systems and manufacturing systems for optimum sustainability with social, environmental, and economic considerations has been developed as well (Manzini and Vezzoli 2003; Aurich, Fuchs, and Wagenknecht 2006). In the field of Business Management, issues arising from cross-cultural differences and methods to address them have been discussed extensively in recent decades, being led by research such as Hofstede and Trompenaars, in addition to numerous other researchers (Hofstede, Hofstede, and Minkov 2010; Trompenaars and Hampden-Turner 1997; Zeynep Aycan et al. 2000; Ajiferuke and Boddewyn 2014), although these are typically applied to large corporate structures for international companies, as opposed to the design of a new business or the application to a small business.

Likewise, in the field of Process Engineering, methods of Conceptual Design have been thoroughly refined, involving the development and implementation of a process technology within the economic and environmental constraints of a larger supply chain (Wood and Agogino 1996) (Wang et al. 2002). However, very little literature exists exploring methods of holistically structuring the company, as opposed to innovation within an existing company structure. The innovative design with the above mentioned considerations (socio-cultural, economic, environmental, financial, and political) is often restricted to specific aspects of the business, such as the product or service, or is limited in scope, only considering economic and environmental aspects. Thus, the current study has undertaken the design of the entire business system, including the business model and service system, logistics chain, and internal managerial structure, simultaneously, in addition to the design of the manufacturing technology itself, with all contextual considerations.]

1.4.B Significance of the Present Study

To be specific, the design presented in this study is focused on the model of a small, locally based enterprise, ideally led by local entrepreneurs. The concept of Socially Inclusive Business has risen in popularity in recent years, as a means for large, mostly international corporations, to incorporate Corporate Social Responsibility into their business structure. These methods explore how to use local resources and understanding and connect with local entrepreneurs, in developing countries, to expand and adapt their current value chains for the mutual benefit of both the corporation and the developing communities (van der Klein, Chevrollier, and Collee 2012)(Gradl and Knobloch 2010). However, this wave of research is focused on the adaptation of current corporate structures, not the establishment of new enterprises, for which there currently exists very little concrete research, particularly for social enterprises in developing countries. This current study documents this design process, and sheds new light on methods suitable for social enterprise to stimulate further discussion and cooperation among entrepreneurs.

Furthermore, one of the central goals of this project, and also the largest aspect of its scientific relevance, was the holistic nature of design of a social enterprise. There do exist various social enterprises in India working on various issues, but there is a lack of discussion of ideas on methods of developing social ventures, although likely many of these enterprise do this, such as SELCO (Mukherji 2011). This study was focused on the simultaneous development of both the technological systems, namely the torrefaction reactor design, and the business systems, all rooted in the local context of Kumaon. The technological design started from the materials and labor available in the area, instead of beginning with the most cutting edge technology available. Likewise, the business system was laid on a foundation of understand of local socio cultural institutions and practices, in addition to environmental, political, and economic factors. Simultaneously, the business system and technological system developed in repeated iterations, constantly considering the context. Thus, this study gives an example method of such an integrate method of design of such a social venture.

Furthermore, this basis in the local context goes a step further than many social ventures, in designing the technology itself to be manufactured, operated, and maintained from local natural and human resources, while many social enterprises adapt technology imported from foreign manufacturers to developing contexts. The goal was to encourage economic growth that is not dependent on outside sources as much as possible, and is thus more self-sustaining; therefore, in the present project, the technology was designed with local resources and capabilities as much possible. This was constantly balanced with the understanding that outside resources and knowledge have the great potential to strengthen the technology and/or business. Thus, ultimately, the strongest synergy between local resources and external resources was sought in order to create the most robust enterprise possible...

Lastly, this study has substantial practical significance, in that it aims at created a business plan with realistic possibilities of implementation. This research seeks to go beyond the purely theoretical and apply the theory to generate tangible solutions, that is, the development of an actual plant in the Kumaon region. This application of theory is central in the current project.

1.4.C   Technical Research

On the technical side, this study contributes to a growing body of knowledge on biomass energy, and specifically to research done in the field of torrefaction. To date the application of torrefaction to pine needles has not been explored, although other sources, such as forestry residues, such as wood chips, wheat straw, and bagasse have been studied in detail (Peng et al. 2012; Shang et al. 2013). Thus the experimental results of this study shed new light on this biomass type as a source of energy, particularly in terms of mass and energy yields, thermogravimetric behavior, and gas production during torrefaction of pine needles.

Furthermore, this study explores the operation of a novel type of reactor, being heated convectively by hot combustion gases indirectly, while using conductive heat transfer within the biomass bed itself. Various other reactors have been researched and tested, including rotary drum reactors, screw-type reactors, direct convective reactors, and other novel designs such as the Torr-Bed design (Dhungana, Basu, and Dutta 2012; Kleinschmidt 2011)(Sun et al. 2011)(J. Tumuluru, Sokhansanj, and Wright 2011). This study, on the contrary examines a more simplified reactor design for application in a rural,

developing country environment. Furthermore, although various reactors have been tested on a pilot scale, little data has been published for prototype testing, as this is primarily intellectual property of various Western companies. This study also aims to provide data on the testing of a prototype reactor, and explore torrefaction's application to developing countries.

Lastly, this project has implemented a basic model of the reactor design and tested, considering aspects such as heat transfer and temperature distribution as well as solid decomposition rates and gas production rates (including permanent gases and condensable volatiles). Although various models exist for the performance of torrefaction in terms of mass yield, energy yield, and mass loss rates (Prins, Ptasinski, and Janssen 2006a; Prins, Ptasinski, and Janssen 2006b; Bates and Ghoniem 2012; Di Blasi 2008), few incorporate the derivation and modeling of the chemical kinetics of gas evolution. Bates has proposed a model for this gas production (Bates and Ghoniem 2012), however this study proposes to derive a simplistic model based on experimental estimation of reaction kinetics and the prediction of the resultant gas evolution in the reactor, as opposed to retroactive fitting of model results to experimental data. These results are then used to predict the calorific value of the torrefaction gas produced for assessment of system integration and efficiency.

1.5 Research Goals

Therefore, this project has undertaken to address the following question as the principal research goal:

How can the torrefaction process be adapted to rural Uttarakhand, India and implemented as a local business?

The project has two major focus areas: technical and social. The technical focus lies on the manufacturing process itself for the fuel, while the social portion explores the larger context of the business system. Furthermore, this project has been divided between two students, both the present author and Vidyut Mohan, both of whom executed this project for their graduation project for the Master's of Science in Sustainable Energy Technology. The research is thus divided into common research goals and individual goals, and the division of tasks is given in Appendix A.

1.5.A Technical Research Questions

- *How can the torrefaction process be adapted to socio-cultural, economic, and environmental constraints in the form of a thermochemical reactor, for use in a local business?*

Sub Questions - Common

- o What are the essential characteristics of the torrefaction process?
- o What is the optimal process design for torrefaction in the context, taking into account local constraints?
- o What are current reactor designs in torrefaction, and what is the optimal design for the chosen application?

Sub Questions - Individual

- How can the designed reactor be modeled with computerized software, including heat transfer, temperature distribution, solid decomposition, and gas evolution?
- How do the gases, both permanent gases and condensables, develop during the torrefaction process, and how can their reaction kinetics be estimated experimentally?
- Which design parameters have the most impact on the torrefaction process? Which have the least impact?

1.5.B   Social Research Questions

- *How can the torrefaction process be implemented in a service system that benefits all stakeholders in the local context participating in the venture?*

Sub Questions - Common

- What is the current biomass/fuel use paradigm practiced in the local areas, including fuel sources, transportation, fuel availability, biomass sources, and methods of fuel utilization?
- What are relevant dimension of the local culture and social institutions, and how would they play a role in the local business?
- What is the optimal service system and business model design for implementation of the torrrefaction in the local context?

Sub Questions - Individual

- What is the optimal internal structure for the venture in this context, including management structure, operations and maintenance, and financial balances?
- What relevant policies exist related to the internal structure and operation of the business? Including relevant subsidies, but also labor laws, etc.
- What would the environmental impact of the business be, in terms of broad ecological considerations and in terms of a Life Cycle Inventory Analysis?
- What would the long term outlook of the business consist of, in terms of future roadmap and the associated risks with the venture?

In order to investigate these questions, the authors travelled to Kumaon, India for three months for field research, including designing, constructing, and testing several torrefaction reactors on site, and performing numerous interviews about the business system. This was done with the support and cooperation of Avani, an NGO located in Berinag, Uttarakhand, India, working in various projects for community development.

In this report, the social/business aspects will be addressed in Chapter 2, such as Business Culture, Operations and Maintenance, and Environmental Analysis. The technical elements are addressed in Chapter 3, including Reactor Construction and Reactor Modeling. Chapter 4 concludes the report with a summary of results and future outlook.

2.0 Business System Design with Cultural Considerations

The design of the business system is of utmost consideration in gauging the feasibility of such a project involving the implementation of a biofuel. Ultimately, it is the economic success of the business that determines how the biofuel will become a reality in addressing social needs. Many technically feasible projects fail due to the lack of adequate financial planning. Thus, this chapter is focused on discussing several essential aspects of the business system. In this project, the overall plan for the business included the development of the Business Model/Service System, Stakeholder Analysis, Logistics System, the Culture in Business Structure, Operations and Maintenance considerations, Financial estimates, Roadmap, Risk Assessment, and Environmental Assessment. The first three of these are addressed in the companion report by Vidyut Mohan, and thus will not be discussed here. Thus, this chapter will detail the Business Structure, Operations and Maintenance, Plant Overview and Capital Costs, Financial Overview and Business Roadmap, Risk Assessment, and Environmental Assessment, in that order.

2.1 Business Structure

2.1.A Cultural Implications in Business Design

As discussed in the Introduction, the design of the business system for a torrefaction enterprise included assessment of various facets, namely economic, political, social, environmental, and cultural. Although all aspects are considered at some level, this project took a particular emphasis on the consideration of cultural aspects, as appropriate, in the design of the business system, which are particularly applied to the Business, or Managerial, Structure. This was done as cultural aspects are often overlooked in business planning and technical research.

Culture theory as a field has been developed extensively by various researchers and authors, predominantly Geert Hofstede and Fons Trompenaars. Hofstede, at the beginning of his book Culture and Organizations, explains, "Questions of economic, technological, medical, or biological cooperation have too often been considered as merely technical. One of the reasons why so many solutions don not work or cannot be implemented is that difference in thinking among the partners have been ignored" (Hofstede, Hofstede, and Minkov 2010).Similarly, Trompenaars states that "if something works in one culture, there is little chance that it will work in another" (Trompenaars and Hampden-Turner 1997). It is for this very reason that this project integrates culture into the business design, as the interactions among various stakeholders is crucial to the business, and this cannot be optimized without considering the ways in which people think and interact. Also, as this project was based in the context of a European university, it was essential to give special attention to cultural considerations to ensure a higher chance of successful implementation of the business.

Hofstede goes on to explain that everyone carries patterns of thinking, feeling, and acting that were learned mostly in childhood, what he refers to as mental programming. To be clear, this "software of the mind" only indicates what responses are likely and understandable, given a person's past and social surroundings, and as individual experiences vary from person to person, so do these values and patterns. However, patterns of thought can often be similar within a group of people located in

particular geographical locations around the globe, thus resulting in what is called "culture;" as Hofstede defines it, the "collective programming of the mind that distinguished the members of one group or category of people from others"(Hofstede, Hofstede, and Minkov 2010). Furthermore, although culture consists of various layers, the outer most layers of culture are practices which depend on the core of culture, which are values, held consciously or unconsciously, by the individual and the group.

Trompenaars connects culture with methods of problem solving that are shared by a group of people. These ways of thinking and addressing issues have been developing over long periods of time, and have become second-nature, unconscious perspectives and patterns of thought. These patterns of thought drive individuals to ascribe meaning to different things in their environment, and these meanings, or values, shape to a large extent how they react to their circumstances. . He goes on to categorize cultural categories into three broad types: values affecting relationships with people, attitudes towards time, and attitudes towards the environment(Trompenaars and Hampden-Turner 1997). Thus, different groups of people have developed certain values for different phenomena in each of these contexts, in order to appropriately deal with problems arising in these three broad areas. Thus, to understand how a person will likely think or react in a given situation, these underlying values must be understood.

Therefore, both of these authors have dissected the various aspects of culture to give their own lists of cultural dimensions. Similarly, other authors have proposed their own lists of cultural dimensions (Zeynep Aycan et al. 2000)(Harrison and Huntington 2000), many of which overlap in many ways, thus the authors of this present project have deemed it the most logical to consider the various dimensions proposed by different authors, but ultimately focus the business design only on the relevant and useful dimensions. Thus, only these dimensions will be discussed here, forgoing an exhaustive discussion of all lists of cultural dimensions.

2.1.A.1   Collectivism vs. Individualism

Each of the cultural dimensions exists as a gradient, a tension between two extremes, in terms of patterns of thought, and every culture lies somewhere between the extremes of this line, while having its unique emphasis and values concerning it. This is shown below in Figure 3. Likely the most commonly understood aspect of culture is the tension between the collective mentality and the individual mentality, and almost all cultural anthropologists include this in their discussion of cultural values (Trompenaars and Hampden-Turner 1997; Zeynep Aycan et al. 2000; van Boeijen 2015; Hofstede, Hofstede, and Minkov 2010). The essential concern here is over the relative importance of the concerns of the individual versus the concerns of the group, which may be the family, the company, or the society. Which of these should be given more importance, and in which situations? Furthermore, the way of reaching decisions is influenced by this factor: are decisions made by one person, or should decisions be the result of consensus of the group. Also, in individualistic culture, highest productivity is achieved when individual tasks are given, whereas people from collectivist cultures operate much more effectively in teams. Similarly, is it acceptable for an individual to express his or her personal feelings on an issue, or should confrontation be avoided?

Figure 3 - Culture Dimensions Gradients (van Boeijen 2015)

2.1.A.2   Power Distance and Ascribed Status

Hofstede puts particular emphasis on his dimension of Power Distance, which can be seen in a variety of situations (Hofstede, Hofstede, and Minkov 2010). This dimensions centers on whether differences and inequalities among people are acceptable and/or desirable. In a business structure, this manifests itself in a largely hierarchical structure, where power of decision making is held by superiors, and obedience to instruction is valued, in a culture with high Power Distance. In a culture with lower Power Distance, structures are more "flat," with more autonomy and independence given to lower employees, in addition to more input into the decisions of the company. Thus, with higher Power Distance, there is also a need for more supervisory personnel, and lower employees are more dependent on leaders to give direction.

Similarly, Trompenaars constructs his dimension of achieved vs. ascribed status. In cultures where status is granted via ascription, respect is given for qualities of seniority, experience, title, gender, etc., whereas cultures based on achieved status grant respect out of the performance of the individual or organization. Ascribed status can be linked somewhat to Power Distance, where the title of a superior automatically grants him or her a certain amount of respect and reverence, which is not questioned, and trust and allegiance are automatically given without the prerequisite of demonstrated performance. In contexts where respect must be earned, there is a much more openly critical atmosphere, and the act of questioning a superior is more accepted. In addition, the motivation and pressure is to perform, as performance is the source of respect, and no one's status is solid as performance can constantly vary(Trompenaars and Hampden-Turner 1997).

2.1.A.3   Uncertainty Avoidance

Cultures also differ in the level of acceptance of the unknown in various circumstances. Is it necessary for all of the expectations and details to be clear, or is it acceptable if the direction is not completely clear and the structure is somewhat vague? This is strongly linked to a desire to control future events, or merely let the events occur as they may. Therefore, in seeking to avoid ambiguity, these cultures often

desire more rules and standards to make expectations and boundaries very clear, as opposed to a system of unstructured freedom. In addition, these cultures are not as tolerant to change and risk, as change is unfamiliar and untested compared to the status quo, and although change can be challenging for someone from any culture, it is typically more stressful for high uncertainty avoidance cultures.

2.1.A.4 Specific vs. Diffuse

Furthermore, Trompenaars discusses Specific vs. Diffuse cultures, where individuals in specific culture like to keep a separation between their work lives and personal lives, whereas diffuse individuals embrace the integration and overlap of the two spheres. In addition, in specific cultures, professional relationships often are restricted to the work context, whereas relationships among coworkers in diffuse cultures often extend beyond the workplace even into family life. As seen in Figure 4, for diffuse cultures, it may be difficult to penetrate past the sphere of being acquaintances, but if a person is admitted into the deeper sphere of the personal, then the relationship carries much more meaning, even being a work relationship. For specific cultures, it may be easy to treat an acquaintance or a work colleague with friendliness, but the relationship does not often carry a very personal significance to it. Thus, for diffuse cultures, the relationships formed in a work environment highly affect the level of identification and commitment, and these drive the motivation of the person. In specific cultures, performance is motivated by more tangible means, such as monetary compensation. In addition, specific people do business in a very direct, to the point manner, whereas diffuse individuals prefer to establish a trusting relationship before engaging in business matters (Trompenaars and Hampden-Turner 1997).
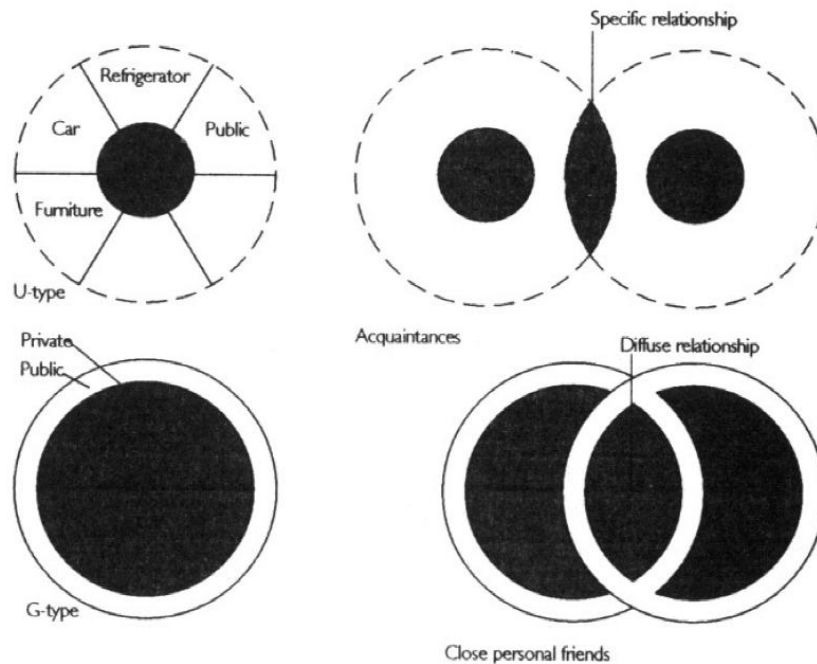
Figure 4 - Specific vs. Diffuse Cultures(Trompenaars and Hampden-Turner 1997)

2.1.A.5   Time Perspective

Time perspectives also have tremendous impact on decision making, particularly in a company setting. Trompenaars dissects time perspectives into two broad categories: Past-Present-Future, and Sequential vs. Synchronic. In Past-Present-Future, persons of different cultures place different emphases on each of these sections of time. What is more important: the potential future that one will arrive to, or preserving long-held traditions? Or, is conserving the status quo the most desirable? This often has much bearing on whether people are open to change to not. Furthermore, it often dictates the extent to which people take risks. Is the potential future valuable enough to risk what one currently has? In addition, people can think more Synchronically or Sequentially. A synchronic thinker is much more able to engage in various activities at the same time, and handle various commitments simultaneously, whereas a sequential thinker focuses on executing one task at a time. This has impact on how scheduling and planning happens, and to what extent these plans are adhered to or not. Are plans flexible, or are they adhered to with utmost strictness? To what extent can a person be expected to handle various tasks, or is it more effective to give tasks one at a time? Thus time perspectives can be highly influential (Trompenaars and Hampden-Turner 1997).

2.1.A.6   Gender Roles

In addition, the differences in expectations between the roles and tasks of men and women are important. Although Hofstede extends his discussion of Masculinity and Femininity to broader social implications, here it will be limited to strict sense of gender roles, particularly in the workplace. Annemiek van Boeijen, rather, focuses on the differences between the tasks and roles of the men and women (van Boeijen 2015). Are they interchangeable to a large extent, or do men and women engage in distinctly different activities? Similarly, how are positions of leadership regarded? Is it accepted for a woman to be in a place of leadership, or is this reserved for men typically? In cultures with high differences in gender roles, men and women may also have difficulty working with each other, even if they are on the same level. Furthermore, women may feel very uncomfortable in a professional setting, as this may typically be seen as a man's role. Conversely, a man may be very reluctant to take on certain jobs, such as collecting pine needles, if this is seen as a woman's task.

2.1.A.7   Affective vs. Neutral

Lastly, communication styles, particularly in terms of the level of emotion expressed in communicating, can differ greatly between cultures, and a business should understand what is normal and acceptable in the workplace in terms of how emotional or rational communication, and decision making, should be handled (Trompenaars and Hampden-Turner 1997; van Boeijen 2015).

Thus, the above cultural aspects above were considered in the design of the business system as being of highest relevance.

2.1.B   Culture in Business Structure

2.1.B.1   Theory

In order to design the business system, it was deemed essential to understand the local trends and preferences of how businesses operate in the sense of how superiors, subordinates, and peers interact with each other, and how this structure of interaction and exchange can be optimized per the local context to achieve a healthy, productive business. Thus, as the authors were largely unfamiliar with the culture of Kumaon, India, it was essential to first understand the cultural norms of interaction, primarily within a professional setting but also in daily life, in order to approach the design of the business structure.

Trompenaars himself points out numerous examples of how many management styles and solutions cannot be applied universally, and can result in disaster if improperly applied to the inappropriate situation, such as applying task-oriented management structures in cultures that are much more relational (Trompenaars and Hampden-Turner 1997). His emphasis is not only the specific aspects of how a business is structured (task division, hierarchy, etc.) but also to understand what these things *mean* to the people in the business in order to know how to make them work well on a daily basis. However, conversely, Hofstede shows examples of how organizational, or corporate, culture of certain companies can develop in such a way that they starkly contrast the culture typified by the surrounding region (Hofstede, Hofstede, and Minkov 2010). Thus, this tension, of understanding how people in a region perceive relationships and interactions within the corporate setting with the possibility of creating a distinct culture within the business designed here is subtly incorporated into the business structure conclusions discussed below.

In addition, other researchers have explored how the culture of a given region affects the managerial and human-resource management practices of companies in that region, and the connection between organization culture with regional culture(Zeynep Aycan et al. 2000; Z. Aycan, Kanungo, and Sinha 1999; Ajiferuke and Boddewyn 2014). Furthermore, researchers such as Aycan and Graham have taken this a step further by seeking to understand the limits of applicability Western management theory to other cultures, and how to usefully adapt it to other contexts (Zeynep Aycan 2005; Graham 2010). Thomas and Mueller likewise apply this perspective to entrepreneurship, discussing how changes in culture affect the nature of entrepreneurs and start-up businesses in other countries (Thomas 2014). Many of these methods employed are very quantitative and statistical in nature, which was deemed to be beyond the scope of this project. However, a qualitative approach to assessing the local culture and adapting company culture and managerial values to it will be taken here, as demonstrated by the Ubuntu company in South Africa(Kroesen and Rozendaal 2010).

2.1.B.2   Methods of Studying Values

However, given the various dimensions of culture to be considered, the challenge thus arises of how to gather information about the values and preferences of people from a certain area. This sort of information is most thoroughly understood through first-hand experience over the course of a long period, i.e. living in the culture for a number of years. However, for this project, this was not feasible, and thus, as discusses previously, the values and preferences of people in the area were studies via first-

hand experience for the time allowed (3 months), personal discussions and interviews, and Generative Design sessions, which is explained below. Firsthand experience allowed for the observation of habits and behaviors, while dialogue and direct questioning gave information on explicit information and easily expressible ideas and feelings. However, it was also deemed useful to attempt to understand deeper values, and gain information on tacit and latent ideas and assumptions that were shared by people in that area. Often, this information is subconscious, as mentioned above, and thus can be very difficult for a given person to express in words.

Therefore, methods developed in the field of Industrial Design were employed in this project to gather this sort of information, using techniques in the field of Generative Design. Above all, based on recommendations given by researcher Jairo de Costa Junior from TU Delft, the methods used in this project were heavily based in the book Convivial Toolbox (Sanders and Stappers 2014; van Boeijen 2015). Generative design is focused predominantly in the field of consumer product design, or service system design, but can be adapted for other areas. The basic premise of this method of design is that potential users of a given product are the experts in knowing their own needs and preferences. Furthermore, these users have the capacity to be a part of the creative process of design. Thus, the role of the "designer" is to facilitate the co-creation process, aiding the participants (potential users) to express these values and preferences which they are likely not accustomed to thinking about or expressing.

Thus, the methods used in Generative Design are highly focused on deeper levels of knowledge. Whereas Explicit and Observable knowledge can be understood superficially, by simple discussion or observation, Tacit and Latent knowledge that individuals carry is more difficult to make explicit. Thus, the methods are focused on drawing these ideas and values out. The book emphasizes the need for allowing stages of the creative process, for ideas to take root, develop, grow, and come to fruition. A strong emphasis lies on giving time to the participants to allow the ideas to "incubate," allowing several days from the initial activities of the design process until the final activities, allowing more profound creativity to develop. Furthermore, the sequence of activities should lie on what is termed the "Path of Expression." In simple terms, the most effective sequence for enabling participants to express and design for their needs is to begin first with the Present situation. What do you presently do on a regular basis, for a given activity? For example, the first activity could ask a participant to document his/her routine for preparing food on a daily basis. After thinking on the present situation, the participant is then directed to recollect Past experience. For instance, they could be asked to discuss or act out fond memories from childhood pertaining to cooking, such as with family or at holidays. After rousing these value-laden memories from the past, the participant is finally directed to take these values and preferences, which are fresh in the mind, and creatively imagine future scenarios and solutions. For example, they could be given a design challenge of creating a kitchen space that is more inviting or welcoming.

Various different types of activities can be implemented in Generative Design sessions, and the facilitators are encouraged to be creative and try different activities to engage all sorts of personalities and communication styles. As much as possible, activities from each of three main categories should be studied: *Do Activities* (where the research can observe the habits and tendencies of the participants

actually doing a normal activity, such as watching how someone cooks), *Say Activities* (discussions or interviews related to the target topic), or *Make Activities* (where the participant is invited to create something related to the target topic). In general, sets of materials, called Toolkits, are used in the sessions, which are often built of basic school materials - paper, pencils, crayons, stickers, images, glue, etc. Images (photos, clip art, etc.) are often part of the activities, as these can often be very useful in jogging the memory of the participants as they try to remember previous events or even their current routines. The activities are documented to whatever extent possible, ideally using video/audio recording, photos, and the created artifacts themselves (whatever collages or created designs the participants generated). These artifacts are used after the sessions to analyze the information and draw conclusions and inferences regarding the deeper values and preferences of the user.

These methods are highly developed for users of consumer products in developed countries, but can be difficult for users in developing countries. First, the needs of these people are very different, in addition to having possible difficulty doing activities that are geared for participants with some type of formal education. Thus, it is then logical to adapt these methods, as researched by Annemiek van Boeijen (van Boeijen 2015). She specifically applies the methods of Generative Design to developing countries, with a special emphasis on discovering cultural values and norms in the target context. The methods discussed there are thus an extension of Generative Design, incorporating and demonstrating how specifically cultural values are important to consider in the design process, particularly in an increasingly globalized economy. Thus, a set of cultural dimensions, built on the work of Hofstede and other author's, is incorporated, as well as different methods and considerations for employing Generative Design in developing countries.

2.1.C   Methodology of this research

In order to gain first-hand knowledge of the local context, interviews were conducted with a number of various professionals in the area, including entrepreneurs, mid-level managers, and lower-level employees in businesses such as biscuit factories, hotels, resorts, dairy cooperatives, and NGO's, predominantly Avani. These interviews were typically semi-structured, with various questions prepared relating to different aspects of hierarchy, approachability of managers, communication styles, etc. (See Appendix B for examples of the question lists). As wide a variety of interviews as possible was obtained, including professionals from different levels, from low level to upper managers, both male and female, as well as persons with backgrounds from across India, both rural and urban. From the responses of the interviewees, explicit information directly related to the topics of interest was gathered and evaluated. A summary of the interviews conducted can be seen in Appendix W.

 In addition to interviews, various Generative Design sessions on Business Structure were held with different target groups, including a group of female employees, a group of male employees, Avani employees from villages, among others. These sessions were all structured with similar activities focusing on interactions in a professional setting. For detailed instructions and results of the Design sessions, see Appendix C and Appendix S.

Three activities were designed to assess the Present Situation, Past Experiences, and a desired Future Setting. For the Present, the participants were asked to create collage/diagram, using photos and

written descriptions, of the various people encountered in a typical (work) day, how the participant interacts with them, and what qualities are appreciated and what qualities are undesired. For the Past experiences, a simple discussion was had with the participants over memorable experiences in the workplace, positive or negative, and the details of those experiences. This included being given recognition for good work, moments of high stress, or memories of reprimand by a supervisor. For the Future, potential scenarios of occupational situations were constructed, in which the participants were to imagine themselves, and give their reactions for each of the situations. For example, in a given scenario, the participant was to play the role of an employee in a local restaurant, faced with a supervisor that was treating customers unfairly, giving preference to the friends of the supervisor. The participants were then to give their hypothetical reactions towards the supervisor, in addition to their motivations behind those reactions. All of the sessions were documented with audio and video recording, with transcripts of the English translation of the Hindi dialogue, in addition to the products generated by the participants (collage/diagram). Examples of these artifacts and transcripts are presented in Appendix Q.

Several weeks after the conduction of the sessions, the various artifacts (video, transcripts, etc.) were analyzed in order to understand the implicit information therein, generating much deeper information than merely the explicit answers of the participants. Aspects such as body language, tone, habits, and styles of communication were discussed in order to understand the preferences and values of the participants regarding professional situations. For instance, a confident tone or a quick response could imply a feeling of certainty or strong conviction in a given response, whereas hesitation or a tentative tone could imply uncertainty or weak conviction, thus giving additional information otherwise lost, but nonetheless essential in understanding the values and preferences of the participants. Thus, notes were gathered from the analysis sessions, and these can be found in Appendix D.

2.1.D   Important Conclusions

After gathering tremendous amounts of information on the perspectives of numerous types of people in the area and their preferences on professional interactions, a number of important and, in certain instances, surprising results were discovered. The concrete measures to be taken by the company to incorporate local culture into the company are summarized at the end of the section, inconsiderations:

Table 1.

On a superficial level, it would be possible to rely on local human capital for the bulk of the business operations. Skilled labor in certain tasks, predominantly with equipment construction and maintenance, may need to be brought in from other regions of India, such as the plains, where industrial development is higher. Avani similarly recruited a technician from Bangalore to oversee the operation of their drying equipment. However, assuming the business can keep the operation of the reactors a mildly skilled task, then the business can heavily rely on locals for the majority of tasks. However, training would be essential for all levels of the business, and this will be discussed below. In addition, the authors observed that locals are able to adapt to jobs with broad responsibilities, as would be typified by a small startup initially, or with specific tasks, as would be more common as the company were to grow in division of labor more necessary. In interviews by the authors, various employers commented on the

dedication of workers to their tasks; they are very good at following orders and working diligently to accomplish their expected assignments.

2.1.D.1   Hierarchy in the Workplace

Initially, before beginning the field research phase of the project, it was expected by the author that a vertical structure would be both typical in that area and also desirable, embodied by much hierarchy, a strong chain of command for following orders, and a strong dependence on the upper management. According to Hofstede's research, India scores relatively high in Power Distance Index, 10th out of 53 countries around the world, indicating a tendency for managers to fill very respected and unapproachable roles, operating the business in a very top-down manner. As this appears to be something typifying the culture, it may also be something desirable in that area, and workers may operate most comfortably when having a very authoritarian supervisor. However, after numerous discussions with people from the Kumaon area, it became clear that although authoritarian styles of management and high levels of power distance are not uncommon in that area, it is not something desired or deemed helpful. Far from it, there is a strong consensus that the more approachable and open the supervisor is, the easier it is for employees to feel free in their workplace. Many voiced the desire to express their thoughts, opinions, and critiques to the upper managers, however, in that area, the hierarchical tendency results in much hesitation by lower employees, often out of fear of repercussion or loss of their job.

It is apparently clear that hierarchy is essential and unavoidable, particularly as the company grows and expands its operations, with the need for more diversity in operation and specific tasks for individual employees. This naturally makes the company operate more efficiently. Furthermore, locals may unconsciously feel more comfortable in a more hierarchical environment, to some extent, without explicitly expressing it. In one interview in particular, the owners of a local resort called Misty Mountain emphasized the importance of developing the middle manager and affirming his authority by always directing the chain of command through him; otherwise his authority would be usurped and lower workers would not respond to his direction. Thus, there will also be a need for developing levels of middle managers to ensure proper organization and execution of tasks, as seen in various organizations in the area, such as Avani, Aanchal Dairy Cooperatives, large regional banks, and other large organizations However, the style of management largely determines the environment in the workplace and the openness of communication. In some organizations in the area, communication from managers to lower employees takes a very patronizing tone, giving orders essentially, while other supervisors have a much more open stance, acknowledging the concerns and perspectives of those working under them. In personal discussions, this was always expressed as being the desirable situation, a more flat, open structure of the business.

Therefore, in a company, extra focus and measures need to be taken on the part of the various levels of management to maintain this level of openness and approachability, all the while maintaining respect for the chain of command. One important method of achieving this is through fostering an appropriate management style in the company through the process of selecting, to some extent, and especially training, the management of the company to lead with a balanced attitude: they must be personal and relational in how they interact with the workers, expressing interest and concern for them, while at the

same time using their authority for making difficult, strong decisions. This relationship could be likened to a caring father or older brother figure. More on this training program is described in the section below on training.

Also, this can be achieved by regular meetings to allow employees to voice their concerns and opinions about certain practices or decisions by the management. This could be done in several ways. First, the managers should have regular, private meetings with each employee, possibly every quarter, in order to give the employee a personal instance to express their concerns, doubts, and opinions. However, given the collectivistic culture of India, group meetings to voice these concerns may be much more effective, in addition to creating company unity. Similarly, these regular meetings to gather input for large company decisions, which affect the entire organization, or at the very least to clearly communicate the motivations and goals behind company decisions, and receive feedback from lower employees, would greatly assist in an open business culture. Thus, one concrete solution would be holding weekly meetings, with the whole company or within sections, depending on the size of the company, and discussing any points or concerns any of the workers want to raise. Also, the managers can also communicate important decisions or events in the company. Lastly, one simple practical measure of allowing employees to be heard is an anonymous suggestion box, allowing employees to individually express their opinions and thus be heard. Employees in general would feel much more valued by the company and more integrated into the direction of the company, which would foster personal identification with the company and a feeling of personal responsibility. As employees identify with the company more, and see demonstrations of openness by the management, they will be more intentional in voicing their opinions, in addition to being more dedicated to the company overall.

2.1.D.2   Communication in the Workplace

Clarity

Communication is always difficult to achieve in a professional setting, but it can be much more of an obstacle when there is a lack of formal training in the required skills, from formal presentations to reporting to personally approaching a supervisor about a given issue. Above all, the management must be the leaders in quality of communication. In various discussions and interviews, many individuals expressed or demonstrated a need to have very clear instructions for various tasks. In Design Sessions, repetition and clarification of the instructions were constantly requested by the participants, indicating a general need to understand the expectations, to have the structure of the task clear. Various interviewees expressed frustration to the authors, arising from unclear or insufficient communication, and they wanted to have supervisors give clear explanations and instructions. Otherwise, many people appeared very uncomfortable accomplishing tasks before the assignment was well understood. This is likely indicative of higher level of uncertainty avoidance, as discussed by Hofstede(Hofstede, Hofstede, and Minkov 2010), where the employees would feel rather nervous and uncertain in situations where the expectations and goals are ambiguous. Thus, managers would need to take special measures, both formally and informally to ensure that the direction is clearly understood by all, and ensuring that the product meets the expectations of the supervisor. Thus instructions for specific tasks, general expectations for meeting deadlines, and standards of conduct in the workplace would need to be clearly communicated, in initial training sessions and a written manual, so that all members of the organization

have the same understanding of how the business is to operate and how he/she should operate within it.

Company Values

Also, the leaders should communicate the importance of the team, the goals and direction of the organization, and how each member is an essential part of reaching those goals. From the various interviews conducted by the authors, there seemed to be a tendency in the area to not view the personal importance of a job, but rather to take a job as merely a rote task, a necessary obligation, without any personal identification with the job. In terms of diffuse culture, this could be seen as the thin exterior layer of personal meaning, as maybe they have not been invited into a place of value in the company and allowed to take on a level of "ownership" of it. Thus, workers lose interest and dedication in an organization, and the overall morale and energy of the organization decreases. However, as the staff is brought into the vision of the company, challenged, and made aware of their value, they will be more dedicated to the company. Several interviewees expressed the desire to have a job with meaning and purpose, in addition to a challenging environment. However, if employees feel unimportant within an organization, they will not identify with it and operate without energy or motivation. It could also be beneficial to use written documents and posters, of company mission, vision, policy, guidelines, etc. to reinforce the communication and understanding of the structure and expectations of the company. This would likely create a much more relaxed environment for all employees, allowing them to operate well in a well-defined environment. Similarly, as discussed previously, it would highly beneficial for the leadership to communicate important decisions to the entire organization. At the very least, this should entail communicating their reasons and motivations behind these decisions. Additionally, they should be open to critical feedback from the staff, or possibly include members of the staff in the decisions making process, voicing their concerns in the process. Thus, as mentioned above, employees would feel more valued and identify with the organization more, invoking more personal responsibility and dedication to the organization, and a greater sense of unity in the workplace.

In this area, as mentioned, relationships tend to be more diffuse than specific. Similarly, as seen in responses from the Design Sessions, the importance of one's work to an individual can be very high, particularly the relationships established there, common for diffuse cultures, as opposed to carrying a superficial meaning. Thus, it is important to make the workplace a meaningful environment for the employees, and not an experience with superficial meaning. Thus, if the relationships between supervisors and lower level employees are established, and lower level employees feel as though they can identify personally with the organization, due to the diffuse culture, this will improve motivation tremendously and prove more effective than monetary incentives, although these should not be neglected either.

Standards of Communication (Gender/Caste)

Communication in the opposite direction, from lower level employees to managers, should also be fostered. As mentioned above, critical feedback should be encourage in meetings, and managers must demonstrate a receptive stance toward this feedback, actively taking note and taking it into

consideration. This could be implemented via formally noting complaints or critique expressed in meetings or otherwise, taking this into consideration, and following up by communicating how the management will address those concerns in concrete ways. Above all, communication of these concerns, in the proper manner, should be encouraged and appreciated.

Lastly, as mentioned above, the management would need to communicate their expectations for interpersonal communication between employees, predominantly the need for respect and professionalism between members of different castes and gender. Furthermore, it should be encouraged that distinctions of caste will not be publicly shown or expressed in the workplace, rather encouraging the respectful interaction of all staff regardless of background. Likewise, men should treat women professionally. These expectations must be clear, and fostered in professional training programs, as discussed below.

2.1.D.3   Adaptation to a Professional Environment

Through the discussions, interviews, and observations, it became clear that many people in that region do not have substantial experience in a professional setting, and thus lack basic skills to function in that environment. Education is lacking in that region, so the ability to communicate effectively in a professional environment, such as via reporting or presenting, are not strong in general, or in approaching a superior, as discussed above. Furthermore, skills with computers or working independently are less strong as well. Thus, it would be crucial, if local human capital were to be used in the business, to establish training programs, and have continual training and workshops to encourage these skills at all levels of the organization. These training programs would need to be implemented with an understanding that change would not happen immediately, and supervisors would need to be patient and flexible, particularly during the first few months of a new employee, and allow for an adjustment period for them.

Initially, basic expectations of operating in a professional environment would need to be formally taught, demonstrated, and practiced. These would include: punctuality, communication skills, clarity and precision in tasks, attention to detail, and expectations in interactions in a professional environment. The importance of punctuality and the value of time in a business setting would need to be explained, and then expected of the employees in terms of arriving to work and finishing tasks. Regarding professional relationships, it would be expected that employees of different caste and gender respect each other equally and treat each other thus. An environment would need to be created where no disrespectful speech would be tolerated, but rather encouraging to gather together regardless of gender or caste, in formal company tasks or informal gatherings, such as for meals.

For positions involving a technical task, such as maintaining the reactors, operating the various pieces of equipment (reactors, briquetting machines, etc.) or other tasks, precision in execution would need to be fomented in the workers. Due to a lack of formal education where these habits of precision, in things like measurements, or fabrication, are encouraged, this would need to be compensated for in the business by providing training and supervision by competent managers, particularly initially, in order to ensure proper execution. Furthermore, precision in planning and in communication is likewise uncommon, and thus in organizing, planning, and communicating within the company, clarity would

need to be demonstrated in these training sessions and required in the various regular assignments, such as progress reports.

Furthermore, although people in Kumaon are known for their ability for following orders, in interviews supervisors voiced a shortcoming in terms of ability to work independently, as well as taking initiative in making decisions or innovating to solve problems. These decisions are often left for supervisors to deal with, despite the ability of the subordinate to tackle the issue himself/herself. Thus, discussions of decision making in hypothetical situations and role playing could be a part of the training program. In addition, managers would need to very conscious of gradually easing new employees into having more and more independence and responsibility within the organization, not giving too much initially, but gradually guiding and motivating them to operate more independently. This is particularly true when bringing a new manager into the company with little previous leadership experience; higher managers would need to personally coach and mentor the new manager during the on-the-job training to ensure the manager becomes equipped to operate effectively.

Being able to have discussions and carrying out design sessions with people from local villages, both those who stay predominantly in the village and those who work in formal jobs in nearby towns, it became very clear to the author how, although many people from the villages may initially lack the professional skills to work in a formal job, training and experience can remedy this. Those who had worked for numerous years exhibited much higher levels of confidence, ability to communicate their ideas, and independence than those without such experience, even though they similarly came from small rural villages. The people in the region are very capable of adapting to a professional environment, given adequate training. Thus, different training regimens would need to be detailed for various levels and positions in the organization to equip the personnel there, such as for technical operators, administrative staff, managerial staff, etc. These programs would be adapted as the business grows, with other programs possibly being included at later points.

2.1.D.4   Incentives, Motivation, and Benefits

Above all, the incentive for performance in the company, as will most companies, should be monetary, and bonuses and raises would naturally be a part of company loyalty and performance. There is a need for employment in that region especially, and this could possibly result in managers or owners taking advantage of the situation. It is certainly common that employees endure somewhat unfair treatment, such as low wages, as there are few opportunities in that region. Thus, the ethics of salaries and payment would need to be regularly assessed, such as the payment for those collecting pine needles. A difficult balance would need to be found for each situation regarding the appropriate amount to pay an employee, seeking to provide a legitimate employment opportunity, one of the primary goals of the company, without decreasing profitability of the company beyond acceptable limits. Likewise, in the payment schemes outlined in this report, a balance was sought, attempting to pay a reasonable amount for labor, such as pine needle collection, yet being limited by the need to produce a reasonable profit.

In addition to monetary incentive, there would need to be more intrinsic motivation by the employees. As the culture of the business develops to bring the staff into the vision and goals of the organization, and thus they begin to identify and personally support the company, they will more naturally motivated

to give their energies to the company. Similarly, the company should consider other additional benefits for their employees. As stipulated by the government, the company must take contribute to social security benefit/retirement account.

However, beyond this the company should value their employees and seek to provide support in other ways. For instance, a cooperation with a local school could be arranged, such that all employees, especially those living in villages, be required to send their children to school, with the company paying a portion of the costs associated with the study. In addition, although uncommon for that area, medical insurance for employees could be given through local financial institutions, such as State Bank of India, which provides such services.

From interviewing various employers, it is clear that punishments in the form of pay cuts are common in that area as a means of discipline for poor performance, in addition to terminating an employee. Although this would be an option for negative reinforcement of performance, positive forms of incentives, such as pay increases and personal recognition, should be more common in the company. Again, many employees would endure poor conditions, enabling their exploitation by the employers, due to the unavailability of jobs in the area. It would be important to consider carefully whether to implement these positive incentives on a group or individual basis, as both motivations are present in Indian culture. It would likely be wise to institute group-based monetary incentives, like bonuses for performance, while giving personal recognition for work in the form of an Employee of the Month board.

As mentioned before, one of the primary goals is to provide meaningful employment, and the company thus cannot view the staff as mere machines, seeking to extract as much labor as possible from them, but to respect them as humans, and encourage their interaction with family. There is a strong tendency in that region to demand long hours for little pay, ignoring a person's obligations to his/her family. However, the company designed here would need to establish internal policies to avoid this exploitation. Furthermore, managers should constantly strive to maintain the focus on the employees, not the profits, and encourage a family-like environment, at least to some extent, and this would in turn keep employees motivated to work hard.

In conclusion, the following concrete measures should be taken by the torrefaction company to incorporate cultural considerations:

Table 1- Conclusions for Business Structure

Company Measure	Specific Objectives of the Measure	Cultural Aspects Addressed
- Training - Employees	- Company Values and Goals and the importance of all members of the company - Technical skills required for the job (operation of the equipment,	- Gender Roles - Collectivism/Individualism - Power Distance - Specific vs.

	maintenance, need for precision in operation etc.) - Professional skills as necessary (computer skills, report writing, presentations, conduct during meetings) - Company Policies with a written manual for clarity (equal treatment of men and women, persons of different castes, punctuality and deadlines, etc.) - Teamwork (training and activities sessions - working cooperatively and working independently within a team) - Communication (encourage to approach supervisors, clarity in communication - Note: this program would be include an initial training period and periodical reinforcement workshops	Diffuse (voluntarism, communication - Professional Adaptation - Affective vs. Neutral (communication)
- Training - Management/Engineers	- Values and Goals of the company (Social enterprise with focus on providing meaningful employment, etc.) - Managerial style (fostering respecting, caring relationships with employees while maintaining authority in decisions and actions, allowing employees to voice their perspective in company direction) - Communication style (clearly expressing expectations and company direction/values to employees, listening to complaints) - Note: this program would be include an initial training period and periodical reinforcement workshops	- Power Distance - hierarchy and approachability - Affective vs. Neutral Communication - Uncertainty Avoidance - Time Perspective - Specific vs. Diffuse (identifying with the company)
- Personal Meetings	- Personal meetings between supervisor and employee (quarterly)	- Power Distance
- Company Vision	- Convey the goals and	- Uncertainty

Posters	expectations of the company	Avoidance - Specific vs. Diffuse (voluntarism)
- Suggestions Box	- Posters with the mission of the company throughout the workplace -	- Power Distance
- Pay Scale Review	- Meeting among management to critically review how appropriate the wages/salaries in the company are	- Motivation and Incentives
- Group Bonuses	- Reward positive performance of a section collectively with monetary incentives	- Collectivism/Individualism - Motivation and incentives
- Secondary Benefits - Health Education	- Improve the general well-being of employees and their families (plan for employee children to attend school, health insurance).	- Motivation and incentives - Specific vs. Diffuse (involvement of employer in family life)
- Employee of the Month Board	- Recognition of individual performance	- Motivation and incentives

2.2   Operations and Maintenance

The basic system of operations and maintenance within the plant is outlined below. The major aspects taken into consideration are the staff positions, the various expenses incurred running the plant, and maintenance considerations. Similarly, differences in the system for various logistics system, corresponding to the analysis of Mohan in the accompanying report, are discussed below. The final operational costs are presented as well for each of the cases.

2.2.A   Operations Overview

Essentially, three basic situations were considered in terms of operational structure: centralized production with cable car (or trolley system, for transporting the raw pine needles after collection), centralized production without cable car, and decentralized production, and the differences in these will be discussed below. (Centralized production here refers to a system where all the pine needles are gathered and processed in one large facility. Decentralized refers to a system having various small plants at different locations, each with their own biomass collection and processing.) Also, a transition from mechanical to electrical cable car after 6 years will be assessed for this system with the cable car. It is important to note that the costs in this section are often given in terms of per reactor, to be consistent

with the other financial calculations. The number of reactors (or similarly the cumulative volume of all of the reactors) is a measure of the size of the plant, and thus all other aspects (produced fuel quantity, required biomass demand, etc.) can be placed in terms of plant size, or number of reactors. More detailed values can be seen in Appendix E.

2.2.B   Labor Structure and Costs

The structure of the staff at the plant was the largest consideration, and the major expense of the operations. The labor force was divided into two groups: seasonal labor to work during the harvest, or "high," season, and employees to work year round. For the high season workers, there are only two types of workers considered: reactor operators and cable car operators (for the appropriate system). It is assumed that computer controllers will be arranged for the torrefaction reactors, and thus will a programmed controller, there will not be a need for much human supervision - therefore, it was assumed that one operator could oversee 10 reactors simultaneously (each reactor being roughly 0.5 m in diameter and 3 m high). This assumption was held for all of the three cases. Cable car operators were only included in the centralized case with a cable car to assist in the transport of the pine needles. For this, according to the logistics system described by Mohan, 7 cable cars will be installed, with 2 operators per cable car (1 at each end of the cable-way). Thus, an additional 14 laborers are needed for this case. These operators, for the reactors and the cable cars, are only needed during the collection season, and thus will not be employed during the remainder of the year. It is assumed that the reactor controllers will be designed to be user friendly, and easy to understand. Even so, a short training program will be implemented to acclimate inexperienced operators. Thus, largely unskilled labor can be employed in the reactor operation.

During the high season, the plant will be operating for longer hours. It is of utmost importance to harvest the pine needles quickly, as the monsoon season, which follows the harvest season, will soak the pine needles and foster biological degradation of the biomass. Furthermore, the longer the pine needles are on the forest floor, the longer they are a hazard of forest fire. The harvest season is often marked by numerous forest fires, and this must be prevented. Thus, the plant will be operated for 14 hours a day, 6 days a week during the 12 week harvest season. This will be comprised of two shifts of 7 hours each, beginning early in the morning and finishing at night (possibly 6 AM to 8 PM). (To note: in India the working week is at least 6 days long, occasionally 7 days, depending on the profession.) These workers will be paid 35 Rs/hr, which results in a reasonable salary of around 6000 Rs/month for a wage laborer.

Around the year, other services will be required. The regular employees are shown in Table 2 below:

Table 2- Year Round Employees

Position	Number
Driver	1
Briquetting/Packing Workers	3
Security Guard	1
Janitors	2

Administrative Assistant	1
Technical Manager	1 (paid double)

A driver is needed to transport the briquettes to the clients in the company vehicle (Bolero). Workers are needed to pack the briquettes and operate the briquetting machine. It was estimated that an average output of 201 kg/hr is needed to meet the estimated market demand (see Mohan's report for the market demand estimate). Since the chosen briquetting machine is rated at 450 kg/hr (Zhengzhou Allance Trading Co. 2015), it will only need to be operated for less than half of the workday, and the remaining time the workers will pack the sacks with briquettes. Due to incidents of vandalism in the Kumaon area, it was also deemed necessary to employ a security guard. 2 janitors are also employed. The administrative assistant would assist primarily in managing the office tasks. One technical manager would be staffed to oversee the operation of the plant, and this manager would receive a higher (double) salary. To normalize this total, this results in 0.024 employees per reactor.

The regular employees will work for 48 weeks per year, with 50 working hours a week (spread over 6 days). These employees will be paid 40 Rs/hr, slightly higher than the seasonal workers, resulting in a monthly pay of a little more than 8000 Rs/month, a healthy income for the area.

Decentralized System

In the case of the decentralized plant, however, there would be a need to employ more staff, as the organization naturally becomes more complex with a decentralized system. The number of employees, and the complexity of the structure, increases with the number of villages in the system. (It is assumed that with more villages, a smaller plant would be installed in each village, to maintain the same total production). As discussed in Mohan's report, 5, 10, 15, and 20 villages were considered, with 5 being the most profitable. 2 regular workers will be employed year round. This was deemed to be sufficient, as these workers would be primarily responsible for overseeing the briquetting, packing, and general oversight of the plant (the reactor operation would be carried out by others, and other drivers would be employed for the transportation. Briquetting would be carried out by smaller machines, rated at 200 kg/hr, and each village would be supplied with one of these.(Zhengzhou Allance Trading Co. 2015). For businesses with 10 or 15 villages, the plant size in each village would be much smaller, and thus only 1 person per village would be needed. In addition, a technical manager and an administrative assistant for the company (not per village) will be employed.

For transportation, it was assumed that about 1 driver/bolero could serve 3 villages. Thus, for 5 villages, 2 drivers are employed, for 10 villages, 3 drivers, and for 15 villages 5 drivers are employed, on top of the other employees.

As an important side note, it will be essential to establish a system of training for new employees, particularly those operating the various pieces of equipment. Currently, it is assumed that seasonal labor can be found with skills able to operate the torrefaction reactors. The computerized controllers of the reactors will be designed in such a way that user friendliness will be high, and thus the operator will be able to adapt quickly to the job. However, it will be necessary to have a training workshop (or series

of training days) before harvesting season to help the new reactor operators acclimate and learn how to operate the reactors.

2.2.C   Energy Costs

Heating Costs

In addition, the energy demand for the various operations at the plant was considered. First, the energy required to torrefy the pine needles was calculated. For the business system, an electrically heated reactor was considered, with the same dimensions as the second convective reactor designed for this project (with a simple cylindrical canister of biomass, heated from outside). However, the business would employ a reactor that uses electrical heating tracer, wrapped around the outside of the reactor, to heat the pine needles. Fiberglass insulation would also be placed around the tracer to contain the heat. Essentially, the decision to use electric heating over convective heating was made to reduce the input energy required for the process, and increase the process efficiency.(Note: this decision was made following extensive analysis of the convective reactor, presented in Chapter3, and the reasoning discussed below, due to unsatisfactory performance. Therefore, the business system is based on the use of electricity for heating in the torrefaction process.)

The convective reactor is compared with the electrically heated reactor. The energy input for the convective reactor is taken directly from experimental data, based on the pine wood fuel for combustion. The assumptions for this energy input calculation are shown in Appendix X. A total of 112 MJ in pine wood (7.7 kg) or torrefaction pellets would be required for each batch, which only produces 84 MJ of energy in torrefied pine needles. As deforestation for the process is not a sustainable option in such a region, torrefied pellets would need to be used as fuel. Clearly, as the input to the process in terms of fuel is higher than the output, the process cannot be sustained (all of the torrefied pine needles from one batch, plus extra fuel, would be needed for the next batch, leaving none for sale). The overall energy efficiency, calculated by including the initial energy value of the pine needles, the fuel input, and the final energy value of the torrefied pine needles comes to 36%. The values for this calculation are shown in Appendix X.

For the electrically heated process, the amount of energy required is based on various measured and assumed parameters, including the reactor size, the packing density, the moisture content of the pine needles, and the temperature of the torrefaction process. The specific heat of increasing the bed to 250°C (based on considerations discussed in Mohan's report) and the latent heat of vaporization for the moisture in the biomass. Furthermore, a heat loss of 20% during the process was assumed. The other assumptions are given in Appendix X.

The energy input is calculated according to the equation below.

$$Q = V\rho c_{p-bed}\Delta T + V\rho_{packing}Y_{moisture}h_{fusion}$$

The required energy input was calculated to be 7.2 MJ, much more efficient than the convective reactor. The overall process efficiency, calculated with the initial and final energy values of the pine needles, and

the electrical input was calculated, shown below to be 64%. This is a drastic improvement over the convective reactor, which apparently is highly inefficient.

Thus, calculating the heat required to torrefy the biomass for each batch, assuming 20% loss of heat, 1.80 kWh of electricity is required, resulting in 2300 Rs/year/reactor in electricity costs, assuming a standard rate of 4 Rs/kWh, according to interviews.

Other Electricity Costs

In addition, the an electric cable car was considered, but in order to distribute the capital costs of the system, it was decided that the optimum scenario would build a mechanical operated (human powered) cable car initially, and after 6 years this car would be retrofitted with an electric motor and necessary components (such as a gearbox). Specifications for a cable car constructed by Avani were used, using a motor of 7.5 kW running 4 hours per day; for the business scenario here, 7 of these would be needed for the 7 cable cars. Thus, in the first years, no electricity costs would be present from the cable car, but in the 5th and subsequent years, electricity costs would total 142.5 Rs/year.

The computer controllers would also consume electricity. Desktop computers can consume from 60W to 300W of electricity on average (Calculator 2015). Assuming that software such as LabView does not consume much computing power, and the computer will be used strictly for this purpose, 100W was assumed. Thus, given the assumptions of 1 computer for ten reactors and peak season operating hours, the electricity consumption was estimated to be 40.32 Rs/yr per reactor.

Lastly, the briquetting machine would likewise incur electricity costs. The chosen briquettor is rated at 30 kW and 450 kg/hr at rated power. Assuming it only runs at capacity, and it produces enough to meet demand, the briquetting machine brings a cost of 389 Rs/yr. Including costs for a binder for the briquettes, such as starch, the total costs of briquetting amount to 390 Rs/year, per reactor. For the decentralized case, the briquetting costs will be slightly higher, as 5 small machines will be needed, as opposed to 1 large machine, thus slightly increasing briquetting costs to 439.12 Rs/yr per reactor. These calculations are given in more detail in Appendix E.

2.2.D   Maintenance

Maintenance would necessarily be a part of the operation of the plant. The major equipment that would need servicing would be the cable car (motor, bearings, moving parts), the torrefaction reactor (replacement of worn/stressed parts), the Bolero vehicles, and the briquetting machine (motor, bearings, etc.). Working in Kumaon, certain basic maintenance tasks could be accomplished by local technicians, but more complex repairs or complicated replacement parts would need to be procured from outside. It is difficult at this point to estimate what precisely will need maintenance most, or how much this will cost. However, according to standard accounting practice, a percentage of the capital costs (here assumed to be 7.5%) are assumed to be required for annual maintenance. The maintenance costs will thus vary for each of the cases, as the capital costs and relevant components change depending on the system. For the maintenance of the reactors, due to the simple design, this can be carried out by a local technician, familiar in welding and machining techniques. The company could partner with this local technician and hire him on a contract basis for maintenance repairs. This same

technician could be trained to deal with maintenance issues with cookstoves, and would similarly be hired to address these issues with the clients of the torrefaction business. The maintenance costs per reactor are shown in more detail in Appendix E. A summary of these costs is shown below.

Table 3 - Maintenance Costs (per reactor)

Scenario	Centralized, mechanical cable car	Centralized, electric cable car	Centralized, no cable car	Decentralized
Maint. Costs (Rs/yr)	1236.38	1241.55	759.25	987.33

2.2.E   Overview of Operational Cost

In the final, selected design, the plant would be centralized with cable car operation, using a company vehicle to transport the fuel to the market. (The justification of this decision is discussed by Mohan in the logistics section). The over view of the costs for this system is given below. As seen from the table, the labor costs comprise the largest portion of the costs, predominantly in the high season. Next, the electricity costs for heating are a large expense, and then maintenance costs.

Table 4 - Operational Costs Overview

Category	Costs (Rs/reactor yr)
High Season Labor Costs	4692.24
Year Round Labor Costs	2264.15
Heating Energy Cost	2297.89
Briquetting Cost	390.39
Cable Car Electricity Cost	0 (142.50 after year 6)
Computer Electricity Cost	40.32
Maintenance Costs	1236.38
Total Operational Costs	**10921.36**

2.3   Plant Overview and Capital Costs

A rough layout of the facilities at the plant was also planned, as this determines general sizes of land area needed, estimates of capital costs of the plant, and sets the basis of maintenance cost estimates (discussed in the Operations and Maintenance section).

2.3.A   Reactor Costs

First, all of the various costs were estimated on the basis of per reactor, or per m3 of total reactor volume (assuming a uniform reactor design). As discussed before, this per reactor basis allows for estimating costs with different scales of plant, as the number of reactor is related to the overall size of the plant. Thus, first, the land costs per reactor were estimated, assuming 3 square meters were needed per reactor, to include space for the reactors as well as the storage space and other facilities. The costs for this land were estimated by current real estate listings (OLX.in 2015). Next, materials costs (for sheet metal, reinforcing bar, etc.) and labor costs (for cutting, gas welding, etc.) were taken as the same costs incurred by the authors in India for the reactor construction. The electrical heating tracer needed to heat the biomass was estimated from a supplier in India of heating tracer (Isotherm International 2015). Computers were also required for operation and control of the reactors. One simple desktop computer, for 250 USD, per 10 reactors, was assumed (Guangszhou Hengyue Electronic Technology Co. Ltd 2015). Insulation costs were likewise estimated from a supplier in India (U.P. Fiberglass Limited 2015).

Following these costs, the costs of the buildings were estimated. It was assumed that two warehouses (industrial sheds) would be needed to house both the reactors and the biomass (torrefied and briquetted). Using rough estimates found in literature, the amount of total storage space was calculated, using the limiting case of the end of harvesting season. At this point in time, the warehouse would be filled with torrefied biomass (no raw biomass), and this will gradually be briquetted throughout the year. In addition, the space required to house the reactor was simply taken at 2 square meters per reactor, to allow enough space for the operators to work. To meet the estimated market demand of 363 ton/year, a total storage space of 164 m^2 was estimated, and a reactor shed space of 660 m^2 was needed. With this, estimates from industrial contractors specializing in such structures were used to come to the final cost, normalized to a per reactor basis (Weifan Tailai Engineering Co. 2015). The normalized reactor costs are shown below in Table 5. More details calculations are shown in Appendix F.

Table 5 - Reactor Capital Costs

Component	Cost(Rs/Cu.m)
Land Cost	286.28
Materials (sheet metal, etc)	4180.00
Labor	5220.00
Heating Tracer	45902.64
Insulation	135.50
Computer	392.98
Storage Shed	19028.43
Reactor Shed	46458.40
Reactor Capital Cost	*121604.23*

These costs are applicable to the case of a centralized plant, but the costs will be slightly higher for a decentralized plant. Since each village would require its own facility, with storage and reactor sheds,

then spaced is not used as efficiently and higher costs would be incurred. Thus, reactor and storage shed costs, per reactor, increase. These costs, with the adjust reactor capital cost, are shown below.

Table 6 - Decentralized System Reactor Costs

Component	Cost(Rs/Cu.m)
Storage Shed	28542.64
Reactor Shed	59732.23
Decentralized Reactor Capital Cost	**144392.27**

2.3.B   Other Capital Costs

Other capital expenses were not estimated on a per reactor basis, as these were not easily scaled up or down with the plant (for example the logistics system could be very different dependent on the plant size, and thus these costs, for vehicles or cable cars, would not scale simply with the number of reactors). Also, these would vary depending on if a centralized or decentralized plant was constructed.

In a centralized plant, one Mahindra Bolero truck would be used (this is the most widely available transport in the area), estimated to cost 5 lakh (500,000) Rs (CarDekho 2015). Also, an industrial briquetting machine was selected for the plant, with a cost of 288,000 Rs (Zhengzhou Allance Trading Co. 2015). This briquettor was selected as it gave adequate output (450 kg/hr at capacity vs. the 200 kg/hr required to meet market demand). Lastly, for systems using cable cars, these costs were estimated from interviews with Avani bio energy. Costs for a mechanically operated (human powered) cable car were estimated at 3 lakh (300,000) Rs, while a motor driven cable car would cost 6 lakh Rs (with electricity costs additional). Thus, it was decided that the best scenario would be to install a mechanical cable initially, and operate it manually, for the first 6 years, until the value of the investment had depreciated (the assumption of 6 years will be discussed below). At this point, the cable car system would be retrofitted with an electric motor and necessary components. Thus, the total investment of 6 lakh Rs would be divided over two installments, essentially, 6 years apart, thus lowering the burden of the capital investment. In addition, tarpaulins would be purchased to cover the pine needles during inclement weather, and these costs, estimate from a local supplier (Tarpaulin House 2015), were also included.

For the decentralized system, these capital costs would also increase. More briquetters would be needed, with each village plant needing one, although these would be smaller in size. Thus, a smaller briquetting machine was chosen from the same supplier, at 96,000 Rs per unit, although a total of 5 would be needed for the plants (Zhengzhou Allance Trading Co. 2015) . In addition, more vehicles would be needed to ensure the transportation of the fuel from the various locations, maintaining the assumption of about 1 vehicle (Mahindra Bolero) per 3 villages, thus at least doubling these costs compared to the centralized system. No cable cars would be used in the decentralized system.

2.3.C   Financial Considerations

In order to annuitize the capital costs for financial purposes, mainly assessing profits and payback periods, a project lifetime was assumed. Although many project in renewable energy have payback

periods of at least 10-20 years, such as in the case of a wind farm or solar farm, this is not applicable for a project with a more dynamic and uncertain market, and a biomass source that can fluctuate (much more so than wind or solar patterns). According to an example for charcoal production, a project lifetime on the scale of 5 years is appropriate, i.e. investors would want their principal recovered in this time frame (FAO Forestry Department 1985). Ideally, the reactors and equipment should last for 10 years, but investors would likely not be willing to distribute the investment over such a long time. After reviewing the various costs for production and the revenues received, it was decided that, with a selling price of 15 Rs/kg for the fuel, the capital costs could be paid back in 6 years. (For reference on the decision for the selling price of the fuel, see the report by Mohan). Thus, a project lifetime of 6 years was chosen for the majority of components in the plant.

However, this depreciation rate of investment is not admissible according to India Tax law for buildings. According to the Income Tax Department of India, in accordance with the Income Tax Act and the Companies Act, a depreciation rate of 10% for most non-residential buildings is permitted. For equipment and machinery used in a bioenergy generation facility, an 80% depreciation rate is permissible(Income Tax Department 2013). Thus, a project lifetime of 6 years is maintained for the majority of capital expenditures, but the reactor and storage sheds were given a lifetime of 10 years.

In addition a real interest rate of 10% was assumed for the project. To annuitize the capital costs, the annuity factor was calculated according to the formula below:

$$Annuity\ Factor = \frac{1 - (1 + r)^{-n}}{r}$$

With r as the interest rate and n as the number of periods (years). The capital costs are then merely divided by the annuity factor to put them in terms of Present Value (Annuitized). Thus, for the chosen system, using a cable car and own vehicle transportation, and the target market demand of 363 ton/year (equating to a reactor volume of 21 cubic meters), the capital costs are summarized below:

Table 7 - Capital Costs Summary

Cumulative Reactor Volume (m³)	Total Capital Costs (Rs)	Annuitized Capital Costs (Rs/yr)
21	43,083,990.33	1,170,024.52

More complete calculations are given in Appendix F.

2.4   Financial Overview and Roadmap

The following section gives an overview of the finances and outlook of the business. Again, details on certain sections not contained in this report can be found in Mohan's report. A depiction of the business system, in a Business Model Canvas and a System Map, can be found in Appendix U.

2.4.A   Finances for Phase 1 – Years 1-6

The numbers given thus far for financial aspects have pertained to the initial phase of the business, being the first 6 years. The various costs were compiled and then compared with revenues to verify that profits are reasonable. The revenues are derived solely from the sale of torrefied fuel briquettes. The

pricing and value proposition for the target market is discussed in detail in the report by Mohan. In these calculations, it is important to note that the cost induced by from the cookstoves, being completely absorbed by the company and not the restaurant owners, is taken as a reduction in revenue, as opposed to being an operational cost. (More information on the cookstove plan for dhaba owners is discussed by Mohan). The revenues for the business, for a cumulative reactor size of 21 m^3 and a selling price of 15 Rs/kg of the fuel, are summarized below:

Table 8 - Overview of Revenue

Cumulative Reactor Size (m3)	Selling Price Charcoal (Rs per kg)	Cumulative Output (kg fuel/year)	Revenue (Rs/yr)
21	15.00	375,352	5,484,831.63

Following this, the costs were totaled, including Logistics costs (Collection/Distribution), Operations and Maintenance Costs, and Capital Costs. These were then divided by the fuel output of the plant to calculate the total production costs in Rs/kg. Lastly, the difference between the revenue and the costs gave the profits. These results are shown in the table below. The specific costs for the fuel, being 14.3 Rs/kg, are covered by the fuel sale price of 15 Rs/k, but only slightly. This yields a meager profit of 1.1 lakh Rupees per year for the business (1,500 EU approximately). However, this was deemed acceptable for the first 6 years, in order to be able to recover the capital costs, with the expectancy that later years would yield higher profits. More detailed calculations of revenues and profits can be seen in Appendix V.

Table 9 - Overview of Costs and Profits

Cumulative Reactor Size (m3)	Revenue (Rs/yr)	Total Costs (Rs/yr)	Specific costs (Rs/kg)	Profit (Rs/yr)
21	5,484,832	5,377,4196	14.326	107,412

2.4.B   Finances for Phase 2 – Years 7-10

To give a more complete picture of the plan of the growth of the business, the business will grow into production in two phases. Assuming the beginning of the first fiscal year in January, the company will spend the first four months focusing on demonstrations to acquire the first lead users, and constructing a pilot plant. In this phase, two lead users (dhaba owners) will be sought for a contract (including 1 free cookstove each and fuel for 15 Rs/kg). Simultaneously, the pilot plant will be constructed to meet the fuel demand required by these two lead users, requiring an output of 66 tons of fuel/year and a total of 60 torrefaction reactors, approximately. This pilot plant will be completed by May of the same year, in order to begin fuel production when the harvesting season arrives in that month. Sale of the fuel will begin to the two lead users in that or the following month.

Over the course of the following year, the industry will grow to full capacity, reaching 5% of the market in the Almora area (estimated at around 7 clients = 11 cookstoves = 363 ton fuel/year). This market

estimation is discussed more fully in Mohan's report. Thus, the clientele will be expanded through marketing activities, demonstrations, etc. Construction will continue to expand the plant to a total of 330 reactors (21 cubic meters of cumulative reactor capacity). The construction will finish by May of the second year to begin production and sale at that time.

As discussed above, most of the capital expenditures will be written off by the end of year 6. At this point, the cable cars will be upgraded to have electric motors. Thus, an additional capital cost will be incurred at this time, and will be paid off by the end of year 10 (thus a 4 year payback). The capital costs for the buildings will continue until the end of year 10, when the total project life will be ended, and serious renovations, especially of the reactors, briquettors, and vehicles, will be needed. In this period from year 7-10, the profits will increase dramatically, almost by a factor of 15, to 16 lakh Rupees (approximately 23 thousand EUR). Specific costs will likewise reduce to 10.38 Rs/kg. A comparison of the costs and profits in the two phases (year 1-6 and 7-10) are shown below. Detailed numbers are given in Appendix V.

Table 10 - Costs and Profits in Initial Two Phases

Year 1-6		Year 7-10	
Specific costs (Rs/kg)	Profit (Rs/yr)	Specific costs (Rs/kg)	Profit (Rs/yr)
14.33	107,412	10.38	1,587,914

2.4.C   Further Growth

Following the completion of the full plant by May of the second year (1.5 years after the inception of the business), the business may likely grow more slowly. Here conservative estimates are taken, although it is possible that more clients will request fuel. However, here it is estimated that over the course of the next four years, a second full facility will be constructed, as the clientele expands to 10% of the market in the Almora area. Thus, by May of the sixth year (5.5 years after inception), a total of 640 reactors in two plants will be operating, producing 726 ton fuel annually, serving around 14 establishments in the Almora area. The profits of the second plant will follow the pattern of the first plant, with meager returns in the first 6 years, but substantial returns after year 6. This growth plan is summarized in the table below.

Table 11 - Plan for Expansion in the Market

Time after inception (yrs)	Number of Clients/ Contracts	Fuel Produced (ton/yr)	Number of Reactors Built
0.5	2	66	60
1.5	7	363	330
5.5	14	726	660

In addition, after the inception of the second plant, other markets will be explored, particularly local, rural industries, such as dairy plants and dying facilities. This business case would be explored and

refined further during that time, and is therefore not discussed here. In addition, the potential of domestic customers could be further explored in this time as well.

Most importantly, after the inception of the second plant, the company will begin to look into larger scale growth, particularly with the vision of larger impact in the region. Again, the goal is to impact the local economy positively, to boost rural industries, provide gainful employment, and to bolster the ecological stability of the Kumaoni forests. Thus, large scale growth could bring these about. This company would aim to do that by equipping and enabling other local entrepreneurs to begin their own venture in the same business. Thus, part of the revenues in the later phases would be reinvested into the company explicitly for the purpose of developing a traineeship program for local entrepreneurs. Local talent would be sought out, with passion and ability for establishing a new venture with the goal of positive social and environmental impact. These entrepreneurs would be trained in the company for a period of 1-2 years, given an understanding of the vision and system of the business, and equipped with the skills necessary to establish their own. At the end of the program, the trainee will be supported in establishing his or her own venture in another area of Kumaon. The exact structure and program of this traineeship would need to be more clearly outlined before commencement. However, this program would aim to perpetuate this sort of social venture, build on local human capital, and increase the positive impact to more areas of Kumaon.

2.5   Risk Assessment - SWOT Analysis

Before beginning a venture, it is imperative to evaluate the risks associated with such a venture. Thus, here the widely employed SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) will be employed.

2.5.A   Strengths

- Integration of Local and External Knowledge
    - One of the most apparent strengths of the business detailed in this report is the integration of both local knowledge and external knowledge. As discussed in previous sections, the successful implementation of the business is highly influenced by how easily the business integrates in the local context, including the local economy, culture, and society. Thus, the perspectives of local knowledge, represented by the local entrepreneurs and managers who would be heavily involved in the direction of the business, and eventually preside over the company essentially. This integration of local insight is essential, and would greatly aid the business.
    - Furthermore, the benefit of external expertise, specialized in energy engineering, and having experience from various parts of the world, would bring additional insight to the company that many other local rival businesses would likely not have. Understanding of business systems in greater India, Europe and the United States would bring alternative perspectives and approaches to solve various problems and generate innovate ideas to adapt to a dynamic economy.
- Established Local Contacts

- o The team designing this business also has already established contacts and rapport in Kumaon, and to some extent in the Almora area. They already have a mild grasp on the local context in order to have a somewhat clear image of what would be required to being the venture. Thus, having experience and contacts in the region, the team already has a basis to begin development.
- o Importantly, the team has already established contact with the local governing authorities, including the District Magistrate and officials in the Regional Forest Department. Thus, issues arising from policies, particularly with the forest and pine needle collection, could be avoiding by strengthening these relationships with these parties.

- Logistical Advantage
  - o Compared to producing raw biomass pellets, torrefied pellets/briquettes have distinct advantages, particularly in the logistics chain. Torrefied pellets are much more energy dense (having a higher calorific value and higher energy density) than raw biomass, as the moisture and other low-energy components have already been extracted during torrefaction. Thus, the transport and storage of this fuel is much more efficient, being already in a compressed, high energy form, than as bulky pine needles or raw briquettes which contain significant moisture. This reduces logistics costs substantially. Torrefied pellets, also, are far less susceptible to biological degradation in the storage phase, which currently occurs in Avani's operations. This reduces loss in the costly biomass resource which could otherwise significantly hurt the economic sustainability of the company. Furthermore, the briquetting process requires far less energy than that for raw pine needles, as the torrefied needles are much more brittle, further reducing costs compared to raw biomass pellets.

- Key Partnerships
  - o Several key partnerships that would sustain the business are readily available. As mentioned, relationships with the local Forest Department have already been established, helping to secure the biomass. In addition, cookstove suppliers in India are looking for markets for their product and are readily offering training and support to new clients. Thus, the torrefaction business would be able to collaborate with the cookstove suppliers to provide customer support and maintenance for the cookstoves sold, helping the transition of users to a new cooking technology/fuel.

2.5.B Weaknesses

- Immature Technology
  - o The largest weakness currently is the technology, simply put. The actual technology of the torrefaction reactor needs development, and is currently far from being on production level. The concept of torrefaction has been proven, and the possibility certainly exists to apply it to pine needles. However, the design of the reactor must be refined in order to gain both the control needed to produce a consistent output but also to limit the energy input required to produce the fuel. With this research, the first steps have been taken in designing an effective reactor, but more research is needed still.

- Current Lack of Business Development
  - Currently, the business has not been tangibly developed to a significant extent, other than small test set-ups and contacts with local stakeholders being made. However, even these are largely not located in the immediate surroundings of Almora, and thus would only be mildly useful in developing the business. Thus, the business, in many ways, would be starting from scratch, and thus large investments and resources would be necessary, in addition to time on the scale of years, in order to reach operation. In addition, the resources of the team are quite limited, as the team currently has no backing of larger investors or organizations. Thus, resources would need to be found quickly.
- Dependency on Other Energy Sources
  - The distribution system uses automobile transportation for distribute the torr coal, which is dependent on the local costs of diesel, or other fuel. Furthermore, various processes at the plant require electricity. Thus, the viability of the business is dependent on the prices of these sources of energy.

2.5.C   Opportunities

- No Competition for Feedstock
  - No business is currently using the pine needles in large quantities in the area, for fuel applications or otherwise. Avani is using them for electricity generation, but these activities do not reach the Almora area, where this project would be based. Thus, there is currently no competition for the pine needle resource. Therefore, the market is open a new venture taking advantage of this resource. Furthermore, there is no local production of fuel of any sort, for commercial sale, be it biomass based or otherwise. The vast majority of fuel is imported from industrial centers in the plains of India, or from other countries. Thus, at the onset, no competition would exist for the company, and much potential for accruing clientele.
- Unexplored Market
  - Furthermore, very few companies have ventured into commercial production of torrefied fuel, primarily being based in Europe and the USA, with India being an untested market for this product, with no current competitors in torrefaction. Thus, this venture has the opportunity of exploring new possibilities in the market and gaining valuable experience and knowledge, particularly with this technology in its development, before this advantage has been taken by other entrants.
- Large Potential Profits
  - The financial analysis shows the opportunity that lies in the local economy, that significant profits can be generated from this business. It does pose a realistic economic opportunity. To reiterate, profits are not the main goal of this company, but the potential profits demonstrate that this venture, with social aims, is financially sustainable, and can thus attract the support of investors.
- Replication of the Business

- o This business model, although somewhat particular to the region of Kumaon, can likely be adapted to other regions of the Himalayan mountains in India without need for significant change. Thus, the business would be possibly able to expand to other parts of Himalayan India, and certainly to other area within Kumaon.

2.5.D   Threats

- Government Control of Feedstock
  - o The pine needles are technically the legal property of the Regional Forest Department, and thus the rights to harvest and use them reside primarily with them. Thus, the business will need to cooperate with the Forest Department to acquire and maintain permission to use this natural resource. Avani currently performs their operation with the permission of the Forest Department, and thus our business would do likewise. However, if this relationship were to become difficult, such that the Forest Department either limits the harvest of pine needles or requires payment for the harvest, then the profit margins could be direly in danger.
- Possible Future Entrants and Current Competitors
  - o In addition, after a business would be established and proven profitable, certainly other entrepreneurs would enter the market to compete. This may not be in the form of torrefaction for pine needles specifically, but another enterprise may seek to utilize the pine needles for other applications, such as extracting oils or resins, or producing charcoal, as companies in other regions currently do to a small extent. Such a competitor could put a strain on the pine needle resources, and thus hurt profit margins.
  - o Currently, a threat for biomass briquette production does exist, from a business based in Haldwani (in the plains region of the state) which produces briquettes from raw pine needles. This business also uses this plentiful resource to generate an inexpensive fuel, and although based in a somewhat disconnect location from Almora, this business does supply to the Almora area, and does pose a threat to a company producing torrefied pine needle briquettes locally. However, this company does not employ torrefaction, and thus must deal higher logistics costs.
- Resistance to Change in Fuel Use
  - o Likely none of the potential fuel users are currently using biomass pellets for cooking currently. Thus, these users may exhibit strong resistance to transitioning to a new fuel, having no prior experience with the fuel or the cookstove technology. Particularly in the cooking context, the users will want to stick with what they know works, and thus finding faithful customers may prove difficult.

The results of the SWOT analysis are summarized in the table below.

Table 12 - SWOT Results

Strengths	- Integration of Local and External Knowledge

	-Established Local Contacts
	-Logistical Advantage
	-Key Partnerships
Weaknesses	- Immature Technology
	-Current Lack of Real Business Development
	- Dependency on Other Fuel Sources
Opportunities	- No Competition for Feedstock
	- Unexplored Market
	-Large Potential Profits
	-Replication of the Business
Threats	- Government Control of Feedstock
	-Possible Future Entrants and Current Competition
	- Resistance to Change in Fuel Use

2.6 Environmental Analysis

As one of the primary goals of the venture was to produce a more environmentally sustainable fuel than the status quo, the environmental costs of the entire value chain of the torrefied fuel were assessed and compared to the use of LPG as a cooking fuel. For this, an in-depth Life Cycle Assessment was not performed, as that was not necessary, as many of the processes and materials used have already been assessed. Thus, a less in depth approach to LCA was taken to obtain an adequate estimate of the environmental burden of the torrefied compared to LPG. The methods used here, called the Fast Track LCA, build on data of many well-known processes to give an estimate of environmental burden of a product/process, and thus the accuracy of the method is not compromised. These methods are outlined by Vogtlander (Vogtlander 2012).

2.6.A Methods

According to Vogtlander, there are several essential steps to executing this analysis. First, the scope and goal of the LCA must be defined, essentially whether the analysis is to compare two alternatives or to evaluate improvements on an existing system. Second, the system, the functional unit, and the system boundaries were to be established. The system entails all the processes and materials involved in the production of the torrefied fuel, within reason, and the chosen boundary of the extent of the analysis was also chosen. (Not all steps of transportation or production of products remotely connected to torrefaction would be assessed - just the essential ones). The functional unit defines the basis of the

analysis. This could be chosen to represent the vague function achieved by the product, such as cooked food, or alternatively the Declared Unit can be used, usually being the primary means of measuring the product, in terms of kilogram of fuel. These processes of identifying the system, boundaries, and unit are often iterative to some extent.

Third, the quantities of materials, energy, and other inputs into the system were to be gathered, primarily from information from the design of the system or estimates from industrial sources. After these quantities are known, databases are employed to find the environmental burden of each of these inputs. The databases from EcoInvent (Creative Commons, Vogtlander, and Delft University of Technology 2015) are based on standards outlined by the International Reference Life Cycle Data System (ILCD), developed by the European Commission Joint Research Centre. These databases have the calculated "eco cost" of numerous products and processes, including the impacts in terms of human health, eco-toxicity, resource depletion, carbon footprint, and other aspects. The methods of calculation employed in generating the databases will not be discussed here, as this is beyond the scope of this report. More detailed information on this approach can be gathered from the database source directly. These eco-costs are given in terms of quantity of a product, or some other appropriate measure, and thus, combined with the quantity required for a given system, the eco-costs of that system can be calculated. After these total costs are totaled, finally, the results can be evaluated.

2.6.B   Results

For this assessment, the logical goal was to compare LPG with torrefied pellets as a cooking fuel, as this is currently the main competitor. (Alternatively, the comparison of wood against torrefied pellets would also have been valid for village level cooking, but this is not the main competitor currently, and torrefied fuel would clearly have higher Environmental costs than wood collection, which would be practically zero). Furthermore, the entire value chain of the torrefied fuel was considered in the analysis, including the major sub-processes of Collection, Torrefaction, Briquetting, Storage, Use, and End of Life. The majority of the construction processes were included in the torrefaction sub process, as the reactors and the reactor shed fall into the actual torrefaction process. Furthermore, each sub process includes materials, transportation, and end of life for the various components therein. An overview of the LCA system is shown in Figure 5.The diagrams of the systems considered, in addition to final selection of the system boundaries, is shown in Appendix H.
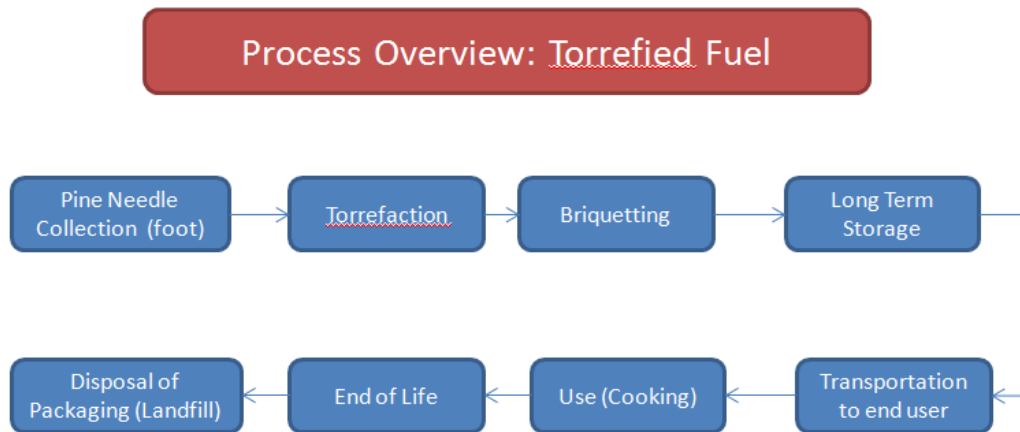
Figure 5 - LCA System Schematic

The functional unit was decided to be kilogram of torrefied fuel, for simplicity, and then this was converted into kilogram of LPG equivalent for cooking applications. (The process for conversion of kg torrefied pellets into kg LPG is given in detail in Appendix G. As this conversion is depending on many varying factors, such as cooking apparatus and user control, this conversion gives a range of possible values, with high and low estimates, of the equivalent mass of torrefied pellets per 1 kg of LPG).

The quantities of materials and processes employed were taken from the construction process for the reactors and the collection process. Other needed assumptions were acquired from various industrial suppliers of products, from sheet metal to warehouse construction companies. These assumptions can be found in detail in Appendix H. Furthermore, the precise calculations of the eco costs for the subsystems can be found there as well.

An overview of the results of the eco-costs assessment for the torrefaction process are given below in Table 13, showing that torrefied pellets have an associate eco cost, for the production and consumption of the fuel, of 0.015 EU per kg. The largest portion of the eco costs comes from the briquetting machine.

Table 13 - Total Eco Costs - Torrefied Pine Needle Fuel

Component	Life Span (yr)	Total eco-costs (€/p.u.)	Specific eco-costs (€/kg fuel)
Reactor	10	50	0.0044
Briquetting Machine	10	34000	0.0070
Reactor Shed	40	24000	0.0013
Storage Shed	40	11000	0.0006
Total		69000	0.0132
Distribution	-	-	0.0019
Total			0.0151

The results of this analysis in themselves have little significant meaning unless compared to a known alternative, here chosen to be LPG fuel. Again, the assumption for this calculation of eco costs can be found in Appendix H. As seen in Table 14 below, LPG consumption in Almora has an associated eco cost of 2.67 EU per kg. On the other hand, when the eco costs per kg torrefied pellets are converted in fuel equivalent of 1 kg LPG (here calculated to be from 1.3 to 15.4 kg torrefied pellets required to equal 1 kg LPG), the reduced environmental burden of torrefied pellets is clear. Even for the high estimate, torrefied pellets have an eco-cost of 0.23 EU per kg LPG equivalent, while the low estimates give a cost of 0.02 EU per kg. Thus, the torrefied pellets are 10 to 100 times more environmentally sustainable than the use of LPG as cooking fuel in Almora.

Table 14 - Eco Costs - LPG Equivalents

Estimate	kg Torr Coal/kg LPG	Specific eco-costs (€/kg LPG equivalent)
Low Estimate	1.3	0.0198
High Estimate	15.4	0.2331
Actual LPG	1	2.6741

2.7 Conclusions of the Business Design Aspects

In this chapter, various aspects of the business system based on torrefied fuel have been developed, including the Business Structure, Operations and Maintenance Costs, Plant Overview and Capital Costs, Overall Finances and Business Roadmap, Risk Assessment, and Environmental Assessment. The business structure described in this chapter is thoroughly based in cultural theory applied to the local context of Kumaon, and has outlined a managerial strategy to create a productive working environment that builds on the aspects of the local culture. This approach to business structure will likely play a very important role in sustaining the productivity and positive environment of the company. In regards to the various costs for the business, including Operations, Maintenance, and Capital costs, all of these have been rigorously researched, considering local demands and resources, and accurate estimates have been given. When these costs are then compared to the expected revenues, the business has shown to be

profitable, a very promising result for a social enterprise, balancing its social aims with the need for financial profits, and based in a region where industry is generally difficult to establish.

Furthermore, plans for growth and expansion have been laid out, as the success of this model could be extended to other areas in order to amplify the positive benefit to the local economy and local ecology. There are various risks associated with business, including concerns with the feedstock supply and the government control of it, in addition to new entrants. However, with diligence in maintaining proper relationships with important stakeholders in the area, these threats can be minimized. Above all, the potential of an untapped biomass resource has large potential. Lastly, the environmental benefit of using this fuel over the status quo option of LPG is clear - local biomass energy in general should be more sustainable than imported fossil fuels. In all, the business system outlined has demonstrated promising results for future implementation.

3.0   Technical Verification of Reactor Design

As the previous chapter detailed several aspects of the business system for an enterprise in torrefaction, this chapter focuses on the technical design of the actual torrefaction reactor itself. This section of the project, comprising the technical aspects of the project, consisted of several major sub sections, being the design and construction of the reactor, testing of the reactor, experimentation on the raw biomass, and modelling of the reactor design. The core of the design is discussed by Vidyut Mohan in his report on the project, while aspects of the construction of the reactor, with several basic design calculations, are discussed here. Furthermore, the reactor testing and the biomass testing are discussed in the accompanying report by Mohan, while the reactor modelling is discussed here. It is important to make clear that this technical section is based on a convective reactor, heated by combustion gases from the burning of wood. The business case was based on an electrically heated reactor, of similar geometry, and with a similar mode of heat transfer, due to expected improved performance with electric heating. This decision was made after the conclusions of this technical analysis of the convective reactor were completed.

3.1   Reactor Construction

3.1.A   First Reactor (Annular Biomass Chamber)

Upon arrival in India, the first reactor was constructed within the first weeks, with subsequent revisions en route. Before arriving at the headquarters of Avani, the bulk of the manufacturing was completed at the regional hub-city of Haldwani, lying at the foothills of the mountains. Based on information received from one of the project supervisors from Avani, greater manufacturing capabilities were to be found in this city, and thus it was decided to contract local labor for the bulk of the construction work.

For the main reactor drum, a 200 L steel oil drum was procured, measuring 60 cm diameter by 90 cm height. After exploring various options for the chimney and combustor, it was decided to use a series of cylindrical oil canisters, size 28 cm diameter by 40 cm height, welded in series for the chimney. These were gas welded together, using an oxygen-LPG torch. The lids were removed from the canisters and the bottom walls were cut out. The combustor consisted merely of an extra canister, welded to the bottom of the chimney, which coincided with the bottom of the reactor drum. In the main reactor drum, doors were cut into the side walls for loading and unloading of the biomass. Four doors on walls of drum were cut, with two at the top of the reactor and two at the bottom, on opposing sides, having a geometry of approximately 25 cm by 50 cm. These were cut with a torch, and reattached with hinges and latches. This change in design, having side doors rather than top doors, was suggested by the manufacturer, as this option seemed to be easier to construct than a door at the top of the reactor. Furthermore, the drums allegedly do not com fitted with removable lids, but must be cut open, and a new lid made for resealing. This also allowed for direct welding of the reactor drum to the chimney, preventing air from leaking into the reactor drum at that point.

After this construction was accomplished, the reactor was shipped up to the Avani headquarters, where the construction was finished. At the workshop at Avani, the retort pipes were installed. The carbon steel pipes, 2 inch diameter, were recut to this size. It was decided to install them inside the reactor drum, to reduce the heat lost by the torrefaction gases in the travel to the combustor, as opposed to

pipes placed outside the reactor drum. Thus, first, holes were cut in the bottom of the reactor drum, 1 cm inside the outer wall, at opposite sides of the reactor. The pipes were inserted through the holes, extending 10 cm below the base of the reactor drum, and welded to the reactor based. These welds were made extra strong in order to solely support the weight of the pipes. It was suggested to provide extra rigidity to the pipes via clamps to the inner reactor wall, but this was deemed unnecessary by the manufacturer.

At the bottom of the pipes, a T-junction was attached and another short pipe segment was subsequently inserted into the T-junction on each side of the reactor, measuring approximately 12 cm, extending into the combustor. Holes were cut in the combustor to accommodate these pipes, which were not welded to the combustor, as this was not necessary. For a grate inside the combustor, holes were cut into the combustor wall to allow for three square profile steel rods (5 mm width, 40 cm length) to rest inside. These supported a circular section of steel wire mesh which supported the biomass fuel for the torrefaction process. Other holes were cut in the combustor as well. A hole for loading biomass, of 10 cm by 20 cm, was cut above the wire mesh, as was a hole of the same size, below the mesh, made for ash removal.

Following this, the insulation was assembled. Upon arriving at Avani, pieces of fiberglass insulation were procured; however, these were not of uniform size, and were not one piece. Furthermore, there was no backing supporting the fiberglass. Thus, in order to increase the usability of the fiberglass, and make it easily removable and reusable, the fiberglass was stitched together between two thin sheets of aluminum using a basic wool thread. This completely enclosed the fiberglass, reducing the exposure of the workers to fiberglass.

After these essential elements were finished, various modifications were made to the reactor at later stages in the testing process. A damper was integrated into the chimney, above the reactor, by merely welding a thin, circular sheet of steel onto an axle of reinforcing bar. Simple doors were attached to the combustor openings by merely fixing rounded sheets of steel with pins or wire to the door. A layer of bricks (5 cm thick approximately) were placed at the bottom of the reactor, to prevent the over-charring of the bottom layer of biomass. Lastly, fins, in the biomass chamber, extending radially from the chimney wall to the outer wall, were placed. These were made out of sheets of aluminum, and fixed to the chimney wall and drum bottom wall with screws. They were cut to fit, and thus were pressing against both the chimney wall and the outer wall, spanning a gap of about 15 cm. Four of these were placed in the biomass chamber, approximately equidistant from each other.

3.1.B   Second Reactor (Cylindrical Biomass Chamber)

For the second reactor constructed, more raw materials were used, instead of prefabricated drums, in order to simulate a more realistic situation for construction a large number of reactors, and to save costs. This, reactor, as discussed by Mohan, included a central cylindrical chamber (30 cm diameter and 90 cm height) for the biomass consisting of a cylindrical canister with a removable lid. The lid was merely set on the cylinder and sealed with wheat dough. A small hole(2.5 cm diameter) was cut in the lid, with another small piece of metal (5 cm square) placed on top of the hole, to allow the pressure to release from gas build up inside.

This was placed inside another cylindrical chamber (40 cm diameter, 100 cm height) where the hot combustion gases would flow around the outside, convectively transferring heat to the biomass. Reinforcing bars were placed through the convection chamber to support the biomass canister. The combustion chamber (30 cm diameter, 40 cm height) was below the convection chamber, welded together with a funnel section in between. These walls were all made out of galvanized iron (GI) sheets, rolled to the proper curvature/diameter, and gas welded together. The conical, funnel-like sections connecting the combustion chamber to the convection chamber, and for the chimney, were carefully calculated, measured and cut from flat sections of GI metal. Holes for loading the biomass and removing ash, as well as provisions for a mesh grate, identical to that of the first reactor, were made in the combustor. A door was cut in the large convection chamber in order to insert the thermocouples and allow for rapid cooling. During torrefaction, a layer of fiberglass insulation was wrapped around the convection chamber.

A separate chimney was made, to set on top of the convection chamber. It was made to be removed to allow for loading the biomass chamber inside the larger convection chamber, and for removal after the process was over. The dimensions of the various components are given in detail in the design section of Mohan's report.

3.1.C   Possible Improvements

The second reactor was a large improvement from the first reactor. Being able to load the biomass from above made the preparation process much more efficient, and reducing the amount of sealing need for the biomass chamber. In addition, designing the reactor to assemble and disassemble it each time (loading the biomass chamber and placing the chimney above) also improved the efficiency of the loading and unloading process, and allowed for faster cooling of the biomass.

Manufacturing of the various joints and connections must be executed with precision, as this will prevent the loss of combustion gases (in the case of the convection chamber) or will ensure proper sealing (for the biomass chamber). The lid for the second reactor was not cut properly, and thus the chamber was not sealed properly, resulting in charred biomass.

It was noted that the doors to the combustion chamber, the fins, and the retort pipe had little effect on the performance of the reactor, and thus were deemed unnecessary. The damper was able to adjust the flow somewhat, but this did not noticeably change the combustor temperature or affect heat transfer much. Thus, these components were deemed unnecessary.

In order to improve the consistency of the product in the biomass chamber, a rod or tube could be inserted axially into the center of the cylindrical chamber. This could draw heat, or allow for gases to pass through, to heat the central biomass more quickly, and allow for a more uniform product.

Clearly, a more efficient way of heating the biomass is needed, as the energy input is currently much too high, consuming far too much wood to be sustainable. A modified convection chamber (will narrower gaps, baffles, fins, etc.) could improve this, but it is doubtful whether this would be sufficient. Thus, an electrically heated reactor is proposed in the business design.

3.2 Preliminary Design Calculations

In order to verify the functionality of various aspects of the initial design, several aspects needed to be calculated, including the overpressure inside the reactor, the flue gas velocity, and the steady state temperature profile. A schematic of the reactor is shown in Figure 6 below.
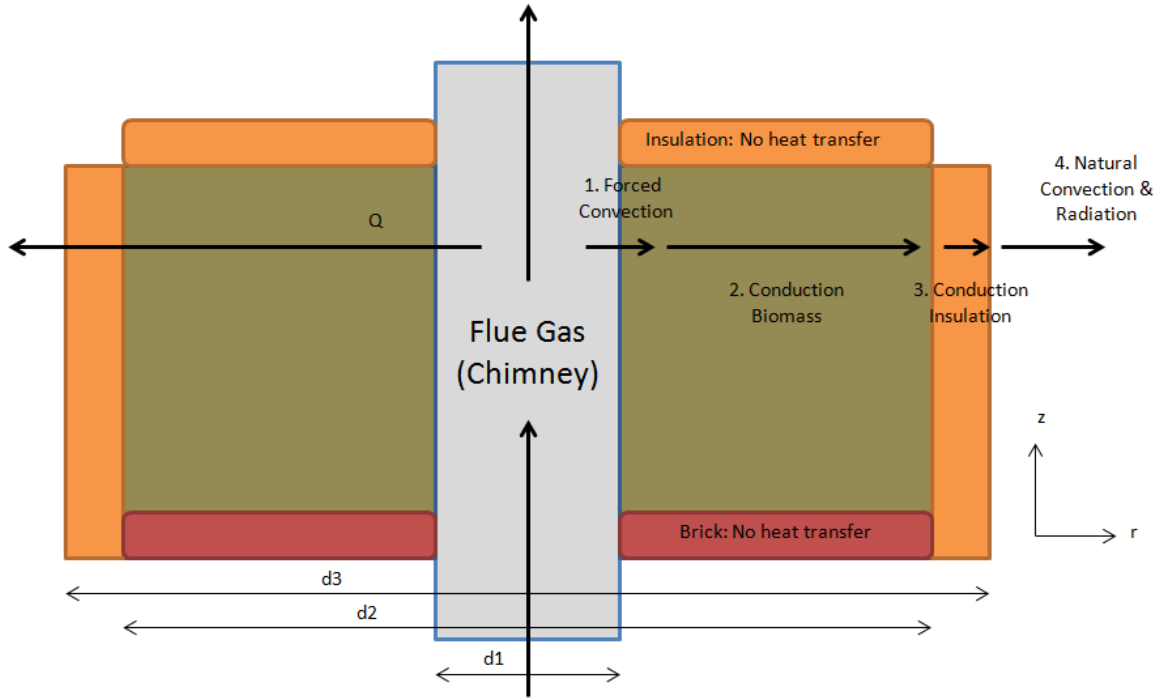
Figure 6 - Reactor Schematic

3.2.A Internal Pressure Limits

In order to ensure that torrefaction was achievable in the designed reactor, it was necessary to verify that an overpressure would exist in the reactor during the process. Thus, the production of torrefaction gases, predominantly water vapor, would create a pressure inside somewhat higher than atmospheric, which would ensure that no air would naturally flow in the reactor, thus disturbing the torrefaction process and allowing for oxidation/combustion of the biomass. In addition, it was useful to have an idea of the maximum pressure possible in the reactor, for safety considerations, to judge if a pressure release of some sort was necessary. Therefore, an initial estimate of what kind of pressures could theoretically exist inside the reactor was calculated, assuming a completely sealed container housing the biomass.

Thus, all gases that would be released by the biomass would, in this scenario, remain in the reactor, allowing pressure to build up to a maximum. After having the rough dimensions of the reactor, based on the reactor design, an estimate of the packing density was assumed from literature. Zhou reports a packing density (mass of biomass packed into a volume of reactor space) of 50 kg/m^3 for wheat straw, while Pandey reports a bulk density of 40 - 200 kg/m^3 for pine needles (Zhou et al. 2005; Pandey and Dhakal 2013). The latter values seemed somewhat high, so an intermediate value of 100 kg/m^3 was

assumed for a packed reactor of pine needles. From this, a mass yield of 0.75 was assumed (thus 75% of the initial mass remained at the end of the process), again giving an estimate on the higher end of possibility. Then, making some basic assumptions, first the pressure of gas was found if only carbon dioxide was produced, at 250°C, resulting in an overpressure (above atmospheric) of 2.47 MPa. Then, it was assumed that only steam would be produced, resulting in a much higher pressure, as water molecules are much lighter than carbon dioxide. The vapor density was calculated to be 25 kg/m^3. At 250°C, the maximum density possible is 20.0 kg/m^3, at a vapor pressure of 3.97 MPa, before it starts condensing, which thus appears to be possible. This clearly does not assume any leakages or any vents such as retort pipes, but it does give a maximum limit, useful for safety considerations. Thus, a perfectly sealed container was not suitable, and some sort of vent or pressure released would need to be installed. Moreover, due to the open pipes leading from the reactor bed to the combustor, the gases have an escape, and thus pressure will not build up in the reactor. Rather, this quick calculation verifies the flow of torrefaction gases to the combustor, and the presence of a (slight) overpressure to inhibit oxygen leakage. However, this calculation does indicate that the overpressure inside the reactor would help to limit oxidation of the biomass by air entering from outside. The calculations and assumptions for these can be seen in Appendix I.

3.2.B   Chimney Calculations

Next, the flow in the chimney was estimated. The chimney was important for the design, as this drives the flow of the combustion gases, which is directly connected to the heat transfer to the biomass. If insufficient draft is experienced, the heat transfer to the biomass will be limited. The main design constraints for the chimney were the materials that were locally available, modes of transportation of the reactor and reactor components after construction, and the operating temperatures. Above all, it was desired that the flow in the chimney be in the lower range of turbulent, to ensure proper mixing of the flow. However, it was also desired to maintain as low a velocity as possible to allow for a longer residence time in the chimney, and allow for more heat transfer from the flue gases. Thus, an initial estimate of a 2 m chimney, from combustor base to chimney outlet, was assumed. This was then checked to verify if the flow was appropriate according to these parameters. The other parameters, of temperature, were assumed initially to be 400°C for the flue gases, to ensure a proper temperature ramp of around 5-10 °C minute of the biomass, and an ambient temperature of 25°C.

The following calculation procedures were adapted from Nag and Hui (Nag 2008; Hui 2003), for natural draught produced by hot gases flowing through a stack. First, an estimate of the pressure drop over the chimney was calculated using the following formula:

$$\Delta p = \rho_0 * T_0 * g * H * \left(\frac{1}{T_a} - \frac{m+1}{m} \frac{1}{T_{fg}} \right)$$

where ρ_0 is the density of air at 0°C and 1 atm (1.293 kg/m^3), T_0 is 273 K, g is the acceleration due to gravity, H is the height of the chimney, T_a is the ambient air temperture in K, and T_{fg} is the flue gas temperature at the inlet in K. The flue gas temperature is here assumed to be fairly constant through the chimney, which will be verified in the model below. The variable m represents the amount of dry air supplied, in kg, per kg of fuel. For this case, it was assumed that pine wood is used as fuel, as this is a

readily available fuel in the Kumaon area, and was used for the testing of the reactor build in India. The stoichiometrically required air was found via applying the following reaction:

$$C_xH_yO_z + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + 3.76a\,N_2$$
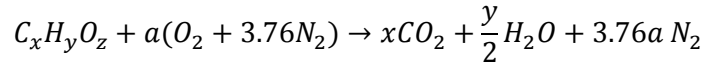
where $C_xH_yO_z$ represents the fuel. Here, only these three elements were considered, as nitrogen is assumed to form nitrogen gas, and the low quantity of sulfur (0.004 mol S per mol C in the fuel) was deemed negligible. Using values in literature from the ultimate analysis of pine wood (Hassan, Steele, and Ingram 2009; Lv et al. 2007), and normalizing per mol of C atoms in the fuel, the following chemical formula for the fuel was found: $CH_{1.68}O_{0.61}$. Thus, a was calculated to be 1.115, according to the stoichiometric balance. The value of m was found via the following formula:

$$m = a * MW_{air} * Y_C/MW_C$$

where m is the amount (in kg) of dry air per kg of dry fuel, a is the stoichiometric coefficient of the air group $(O_2 + 3.76N_2)$, MW_{air} is the molar weight of the same air group (137.3 g/mol), Y_C is the mass fraction of carbon in the dry fuel, MW_C is the molar weight of carbon (12 g/mol). The value of m was found to be 6.44. However, to ensure proper combustion, excess air is needed, which according to Nag, should be between 15 and 30% for a boiler. In the open combustor of the reactor for this project, it was decided to give 50% excess air, as the combustor is not as efficient as an industrial boiler. Thus, m was taken as 9.67.

Thus, the draught produced by the chimney was initially found to be 11.89 Pa, and after correcting for friction in the chimney, it was found to be 9.08 Pa. These calculations can be seen in more detail in Appendix J.

The velocity of the flue gases through the chimney were found according to the formula below (Hui 2003):

$$v_{fg} = K * \sqrt{2 * g * H * \frac{T_{fg} - T_a}{T_{fg}}}$$

where K is a dimensionless constant of 0.65. This gave a velocity of 1.03 m/s, and a volume flow of 0.0632 m³/s. This corresponds to a Reynold's number of 17000. (Note: this velocity and thus the Reynold's fluctuated somewhat at the temperature in the combustor fluctuated.) As the fully turbulent region begins at 10000, this value was deemed to be sufficient. Thus, the chimney properly achieves its purpose. By achieving turbulent flow in the chimney, the temperature is well mixed, ensuring heat reaches the biomass. Furthermore, the heat transfer for forced convection in the turbulent region is higher than for laminar flow. Therefore, the chimney achieves its purpose of providing forced, turbulent heat transfer.

3.2.C   Temperature Profile Estimate

Lastly, an estimate of the quasi - steady state temperature drop in the bed was calculated. This estimate laid the foundation for the heat transfer model, discussed later in this chapter. The temperature

gradient is essential for the torrefaction process, as proper torrefaction can only be achieved when the temperature of the biomass is well controlled, and uniform fuel will only be produced when the temperature is uniform. For this model, several basic assumptions were taken. First, clearly, the system was assumed to have reached steady state. The flue gas flow through the chimney was the same as taken above. A porous bed of biomass was assumed, approximating the porosity and using values from literature for the thermal properties of the pine needles. Natural convection on the external surface was also assumed. Lastly, no variation in the axial (z) direction was assumed, only radial. This was verified later by the full model. The method of estimating the various part of the heat transfer model will be discussed below in the section on the full model. The equations were integrated into a MatLab code, which can be found in Appendix K, and the temperature profile was calculated and plotted, which is shown below:
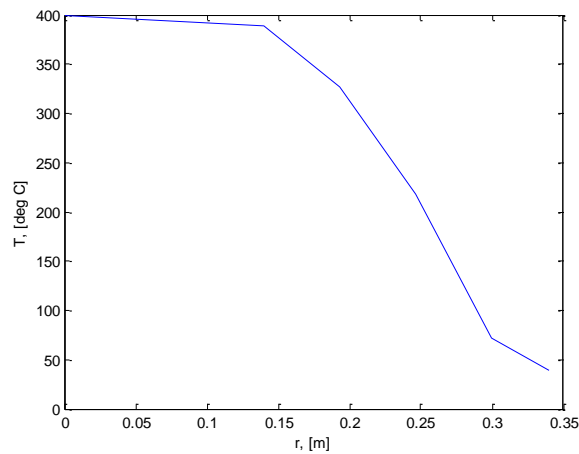
Figure 7 - Steady State Radial Temperature

The temperature at the wall has dropped only slightly to 389°C. Across the biomass, the temperature drops logarithmically to 72°C at the outer wall of the biomass section. Over the insulation, the temperature drops further to 39°C at the outer surface of the reactor. Thus, this shows the difficult heat transfer via conduction through the biomass. A large temperature drop of more than 300°C over 15 cm is seen, from the wall of the chimney to the outer wall of the reactor. This was verified through experimental measurements, as seen in Mohan's report. Thus, this was seen to be the largest barrier for achieving consistent product of torrefied material throughout the bed. However, due to the reasons discussed by Mohan on reactor design, the conductive reactor design was kept, with the hope that various modifications in the design could be made to drastically improve the heat transfer.

3.3   Reactor Modelling and Simulation

Building upon the basic fundamental calculations for basic verification of the reactor design, shown above, a model of the reactor was developed to demonstrate various aspects of the performance of the design. For this, MatLab software was chosen to implement the various equations simultaneously and depict the results. Above all, the following items were to be assessed from the model:

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- the effectiveness of the heat transfer, in terms of temperature gradients in two dimensions (axial and radial) in a transient state
- the variation in product throughout the reactor bed, and the expected mass yields
- the composition of the torrefaction gas produced
- the sensitivity of the above results on selected parameters

At the onset, the model was divided into three major sections: the heat transfer model, the solid decomposition model, and the gas production model, according to the first three goals mentioned above, as this seemed to be a logical division of tasks. The heat transfer model would essentially be the basis of the other two models, producing the temperatures throughout the biomass bed, and the rates of decomposition and gas production would thus be dependent on the temperature primarily, and the initial mass. These sections will thus be discussed in this order below. The full code is given in Appendix P. In the end, the goal of the model was primarily to improve and verify the business case in two ways: predict the mass yield of the industrial reactor (and thus output of fuel product) and predict the usefulness of using torrefaction gases for heating in the system (increasing efficiency and reducing costs).

3.4 Heat Transfer Model

3.4.A Methodology

The heat transfer model was focused on modelling the temperature throughout the packed bed of pine needles during the torrefaction process, from the initial heating until the end of the torrefaction process. In the reactor designed in this project, the heat was supplied by hot combustion gases being ducted through the chimney, which passes through the middle the annular space where the biomass was packed, as seen in Figure 6. Thus, the heat travels primarily radially from the flue gases in the chimney, conducting radially through the biomass, through to the layer of insulation surrounding the biomass bed, to the outside surface of the reactor. From there, natural convection removes the heat to the ambient air.

3.4.A.1 Assumptions

In this model, a constant temperature of the flue gases entering the chimney was assumed. Although this was highly difficult to achieve in the actual testing, as seen in the accompanying report by Mohan, the goal of the model was more focused on the biomass product than on the operation of the reactor; thus, the model began with an idealized scenario of perfect flue gas control. In addition, the thin metallic walls of the reactor itself were ignored in terms of thermal inertia and thermal resistance. A basic diagram of the assumed aspects of heat transfer is shown in Figure 6 and Figure 8.

As seen from the diagram, the situation is radially symmetric, and thus only two dimensions are necessary for consideration, being r (radial) and z (axial). Also, the heat loss from the top of the biomass chamber, to the biomass and to the environment, was ignored, as a layer of insulation was placed there to inhibit this heat loss, and practically this heat was small. Ideally, this assumption could be checked, and the heat loss from the top could be included in a later model. Furthermore, it was also assumed that there was no heat transfer from the bottom of the reactor bed, either to the biomass or to the

environment. This heat loss was likewise assumed to be small, and a layer of bricks were placed in the reactor to inhibit conduction from the bottom of the reactor to the biomass.

Lastly, the heat transfer inside the biomass bed can clearly not be assumed to be constant in the radial direction, and thus must be discretized into annular rings, to assess the temperature at each of these distance points. This assumption was verified by calculating the Biot number according to the equation below:

$$Bi = \frac{h * L_C}{K} = \frac{h * V}{K * A_s}$$

where h is the heat transfer coefficient from the heating gases to the biomass, inside the chimney, V is the volume of the biomass bed, k is the cumulative thermal conductivity of the biomass, and A_s is the surface area of the chimney wall (as this is the surface area of heat transfer). This was calculated to be 11.7. Only Biot numbers of less than 0.1 can be treated to have a lumped capacitance with uniform temperature profile(Wiley 2008). In the present biomass bed, the temperature can thus not be treated as uniform.

3.4.A.2   Transient Condition

The transient condition of the reactor was treated assuming constant heat transfer coefficients, assuming these were mostly stable throughout the torrefaction process. However, this needed to be verified. As discussed by van den Akker (van den Akker and Mudde 2014), two different theories for transient heating can be applied, depending on the case. If the Fourier number is less than 0.05, then penetration theory should be assumed, with the global temperature gradient being constant and a varying heat transfer coefficient. Conversely, if the Fourier number is greater than 0.1, the long-term heating can be assumed, with a constant heat transfer coefficient and a varying temperature gradient. Thus, the latter condition needed to be verified. The formula $Fo = \frac{a_{air}*t}{D^2}$ was used, where a_{air} is the thermal diffusivity of air, t is some time in seconds after the heating is begun, and D is the distance for the heat to penetrate, in this case the width of the biomass section. The thermal diffusivity of air was used as an estimate, giving a high estimate of the penetration time. If the actual diffusivity of the porous biomass were used, an even shorter time estimate would be found. Therefore, upon calculation, a Fourier number of 0.05 exists at time t=14.1 seconds, and a Fourier number of 0.1 is achieved after 28.2 seconds. Thus, long term heating is achieved very early in the torrefaction process, thus permitting the assumption of constant heat transfer coefficients since the torrefaction process will occur in minutes, not seconds.

3.4.A.3   Energy Balances

The entire reactor was discretized, being split into small, differential regions (annuli), in order to determine the temperature gradients in each region, and subsequently to calculate the mass loss and gas production. For each region, the heat transfer into and out of the region was calculated, based on the various applicable heat transfer coefficients (discussed below). These were then used in an energy balance for each region of the form:

$$\frac{dT(i,j)}{dt} = \frac{(Qr_{i-1,j} - Qr_{i,j}) + (Qz_{i-1,j} - Qz_{i,j})}{\rho c_p * V_{i,j}}$$

where T is the temperature within a differential annular region of index (i,j), Qr is the radial heat flow out of point (i,j), Qz is the axial heat flow out of point (i,j), ρ is the density of the region (either biomass or insulation), c_p is the specific heat capacity of the same, and $V_{i,j}$ is the volume of the specific section of the annular region. The variables i and j denote the index of a given row and column respectively. This notation of i for row and j for column was maintained throughout the model, with row 1 being the bottom, and column 1 usually referring to the chimney or the most-inner section of biomass. Ultimately, a matrix of 4x20 elements was used in modeling the biomass region (only 4 were used in the axial direction due to small temperature gradients in this direction). This discretization, for the biomass region, is shown below in Figure 8, while a similar discretization was performed for the insulation region on the outside of the reactor.
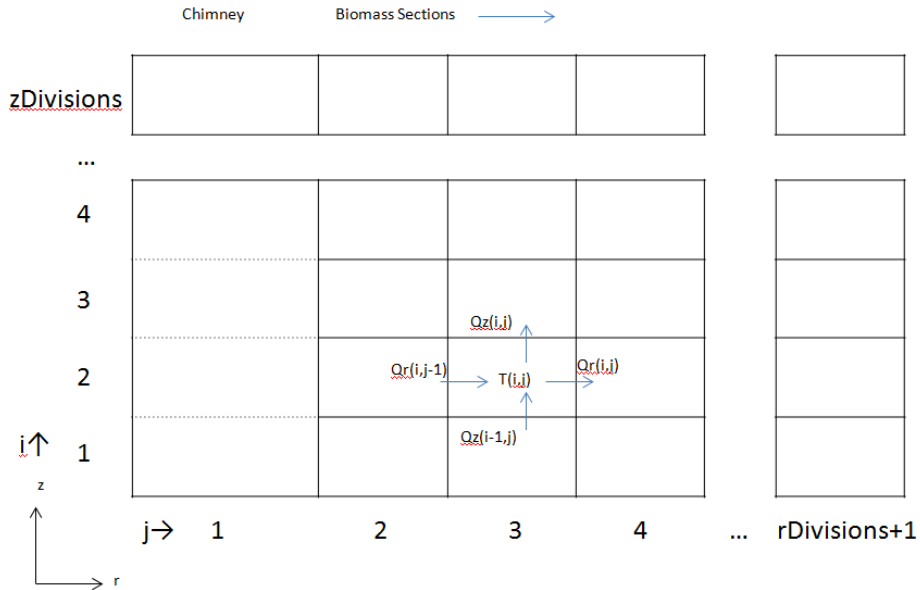
Figure 8 - Heat Transfer Model Schematic

For the chimney section, heat transfer for each (cylindrical) section was considered only in the radial direction, outwards via forced convection, as heat transfer axially was assumed to be negligible compared with the flow of energy in the moving gases. Thus, the mass balance for the chimney is as shown below:

$$\frac{dT(i,j)}{dt} = \frac{v_{fg} * (T(i-1,j) - T(i,j))}{dz} - \frac{Qr_{i,j}}{\rho c_p * V_{i,j}}$$

where v_{fg} if the velocity of the flue gas through the chimney, dz is the height of the differential annulus, and the ρc_p corresponding to air properties.

The values of heat transfer $Qr_{i,j}$ and $Qz_{i,j}$ were constantly changing in time, depending on temperatures with $Qr_{i,j}$ determined according to the equation below:

$$Qr_{i,j} = UA_x * \left(T(i-1,j) - T(i,j) \right)$$

Where, again $Qr_{i,j}$ is the heat **leaving** the annular region at (i,j), $T(i,j)$ is the temperature of the region, and UA_x is the appropriate overall heat transfer coefficient. UA_x was calculated for each annular region, both in the axial and radial directions, and reflected the mode of heat transfer: either forced convection, conduction through biomass, conduction through insulation, or natural convection and radiation. The discretization of UA for the biomass section is depicted in the figure below.
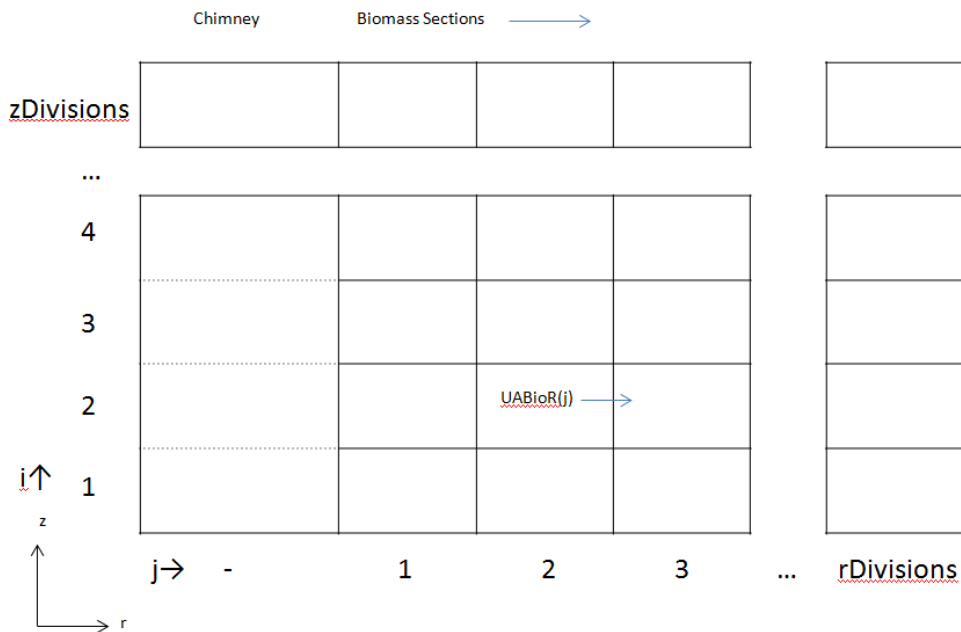
Figure 9 - Discretization of UABio

The values for UA were calculated according to the equations in the table below:

Table 15 - Overview of UA Equations

Section	Radial	Axial
Chimney (Internal)	$UA_{int} = \frac{Nu_{int}*k_{air}}{L} * \pi d_1 dz = h_{int} * \pi d_1 dz$	-
Biomass	$UA_{bioR\,(j)} = \frac{2\pi dz * k_{bio}}{\ln\left(r_{j+1}/r_j\right)}$	$UA_{bioZ\,(j)} = \frac{k_{bio}}{dz} * \left(\pi(r_{j+1}^2 - r_j^2) \right)$
Insulation	$UA_{insR} = \frac{2\pi dz * k_{ins}}{\ln\left(d_3/d_2\right)}$	$UA_{insZ\,(j)} = \frac{k_{ins}}{dz} * \left(\frac{\pi}{4}(d_{j+1}^2 - d_j^2) \right)$
External Surface	$UA_{ext} = (h_{extConv} + h_{extRad})\,\pi d_3 dz$	-

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3.4.A.4   Heat Transfer Parameters

Four separate regions of heat transfer were considered: 1. forced convection from the flue gas to the biomass, 2. axial and radial conduction through the biomass, 3. axial and radial conduction through the insulation, 4. natural convection from the outer surface of the insulation. For each of these sections, different aspects were considered.

1. Internal

For the first region, inside the chimney, the velocity was first estimate using the equation shown below:

$$v_{fg} = K * \sqrt{2 * g * H * \frac{T_{fg} - T_a}{T_{fg}}}$$

found to be 1.13 m/s, corresponding to a Reynold's number of 17,013, indicating turbulent flow. However, as the gas temperature varies, assuming a varying heat input as seen in India and as modelled here, the Reynolds will fluctuate, dropping to 5,900 (v=3.5 m/s) when the combustion gases reach 960°C in the early phases of the heating process, which lies in the transition flow regime between laminar and turbulent.

The normal assumption for this flow is to assume forced convection, as there is a clearly defined flow with a bulk velocity. However, according to Mills, natural convection can involve flows up to 2 m/s which could include the present case(Mills and Ganesan 2009). Also, the phenomenon driving the flow in the chimney is the result of density differences between the gases in the combustor and the ambient, analogous to the situation of natural convection. However, the heat transfer mode would not be considered natural convection, as it is not the temperature difference between the surface of heat transfer (in this case the chimney wall) and the bulk temperature (of the flue gases) that is driving the flow. Rather, the wall temperature is assumed to have little impact on the flow of the chimney gases, whereas the temperature in the combustor drives the flow(Hanby 1994).

Thus, the appropriate correlation for forced convection with turbulent and transition flow in pipes was found from Perry's Handbook(Perry, Green, and Maloney 1997):

$$Nu_{int} = \frac{\left(\frac{f}{2}\right) * (Re_{int} - 1000) * Pr_{int}}{1 + 12.7 \left(\frac{f}{2}\right)^{0.5} \left(Pr_{int}^{\frac{2}{3}} - 1\right)} \left(1 + \left(\frac{D}{L}\right)^{\frac{2}{3}}\right)$$

This formula was used for its applicability in both transient and turbulent flows (2300<Re<10[6]), the relevant Prandtl numbers (0.6<Pr<2000), but especially being applicable for the entry region of the tube (0<D/L<1). In this chimney, D/L=0.3/2.0=0.15, considered in the entry region by most authors, thus not fully developed turbulent flow.

The friction factor f in the equation above is calculated according to the following equation (Perry, Green, and Maloney 1997):

$$f = 0.25 * (1.82 \log{(Re_{int})} - 1.64)^{-2}$$

Due to the mixing from the turbulent flow, difference in viscosity between the bulk and the wall were ignored. Thermal values for the flue gases and external air were derived internally from the stock code *airProp*, including thermal conductivity, density, specific heat, and other values. Thus, the convective heat transfer coefficient *h* and the overall heat transfer coefficient UA were calculated from this Nusselt number based on the chimney diameter.

2. Biomass

In the region containing the biomass, again, conduction was assumed. However, the proper values for thermal conductivity, density, and specific heat were required. This was dependent on properly combining the thermal properties for the solid phase and gas phase within the reactor bed, functioning essentially as a porous medium. Values for the particle density, thermal conductivity, and specific heat of pine needles were taken from literature (McAllister et al. 2012). These are shown in Table 16 below:

Following the method outlined by Nield (Nield 2013), the overall thermal conductivity and ρc_p were calculated. First, from measurements taken in India for the reactor tested, the packing density of the reactor bed was calculated.

The volume occupied by the pine needle particles was found by dividing the loaded mass by the particle density. The porosity of the bed was calculated as follows:

$$\varepsilon = \frac{V_{bed} - V_{particles}}{V_{bed}}$$

It was assumed that the bed porosity will not change over the course of the process. This is based on observations made in India that the overall bed volume did not decrease significantly. Thus, the biomass particles are assuming to follow the "Decreasing Density" model, where the overall particle size does not change, and thus the bed porosity remains constant(de Jong and van Ommen 2014). The thermal conductivity was calculated using the following equation:

$$k_{bed} = (1 - \varepsilon) * k_s + \varepsilon * k_{air}$$

where k_s and k_{air} are the thermal conductivities of the solid phase (pine needles) and gas phase (air) respectively, and ε is the porosity. The ρc_p was calculated similarly:

$$(\rho c_p)_{bed} = (1 - \varepsilon) * (\rho c_p)_s + \varepsilon * (\rho c_p)_{air}$$

These values are shown below in Table 16. Thus, with these values, the heat transfer via conduction in the bed could be calculated.

Table 16 - Biomass Parameters

Parameter	Value (units)
Particle density	567 (kg/m^3)
Particle specific heat	1800 (J/kg K)
Particle thermal conductivity	0.169 (W/m k)
Packing density	55.85 (kg/m^3)
Bed porosity	0.902 (-)
Bed thermal conductivity	0.062 (W/m k)
Bed ρc_p	1.01*10^5 (J/ m^3 K)

3. Insulation

For the section of fiberglass insulation, the thermal properties were obtained from literature (Ayugi, Banda, and Ujanga 2011) (The Engineering Toolbox 2015). These numbers are given below:

Table 17 - Insulation Parameters

Parameter	Value (units)
Density	30 (kg/m^3)
Thermal conductivity	0.034 (W/m K)
Specific heat	960 (J/kg K)

The heat transfer in the insulation was taken to function similarly as in the biomass, with heat conduction in the axial and radial directions.

4. External

Lastly, natural convection on the outer surface of the insulation was considered. For this, the following correlation was found in literature for natural convection on a vertical cylinder (Totala et al. 2013):

$$Nu_{ext} = 0.59 * Ra_{ext}^{0.25}$$

where Nu_{ext} is the Nusselt number for the external surface, and Ra_{ext} is the Raleigh number for the corresponding surface, calculated by $Ra = Gr * Pr$. Thus, the convective heat transfer coefficient was calculated. In addition, radiation on the external surface was included, using empirical estimates given in Perry's Handbook, and extrapolated to the dimensions required for the reactor here(Perry, Green, and Maloney 1997). Thus, an equivalent heat transfer coefficient h for the external radiation was estimated. This process can be seen in more detail in Appendix L.

Thus, all of the necessary equations to complete the energy balances for each annular region were implemented into the MatLab code. All of these equations were put into a basic program script employing a single ODE (ordinary differential equation solver). Initially, a solver for partial differential equations was considered, solving for variation in multiple dimensions simultaneously (r, z, and t), but upon reconsideration, it was discovered that an ODE solver, solving for variation in time, could perform the same task. The temperature of each differential region was treated as a separate variable, in addition to the gas concentration and the solid mass, and these were all implemented into a large

concatenated matrix in order to be able to utilize an ODE solver. The details of using concatenated matrices to achieve this are discussed in Appendix M.

3.4.A.5   Chimney Inlet Temperature Model

In order to simulate the actual heat transfer conditions and results observed in the reactor tested in India, it was necessary to apply a realistic heating scheme. As seen from the data presented in the report by Mohan, the temperature in the combustor of the reactor fluctuated considerably. Thus, a model with a constant temperature input was deemed unrealistic.

To model the temperature at the inlet of the chimney, the experimental data was taken and divided into time regions. Then linear functions were fitted to each of the 5 time regions of the form y=m*t+b. The parameters for these regions are given in the table below.

Table 18 - Combustor Inlet Temperature Model Parameters

t (min)	m (deg C/min)	b (deg C)
0 to 8	0.00	50.00
8 to 16	106.25	-800.00
16 to 34	-22.22	1255.56
34 to 151	0.00	500.00
151 to 158	-64.29	10207.14

On top of the linear functions, a sinusoid variation was also imposed, with a period and amplitude taken from the experimental data, in order to simulate to fluctuations observed in the tests. The final equation for the imposed sinusoid is given here:

$$y = 152.752 * \sin 2 * \pi 7.33 * t$$

With 152.75 and 7.33 arbitrarily chosen from the data in order to produce a reasonable simulation of the combustor data. The combustor temperature data and the model are shown in the figure below.
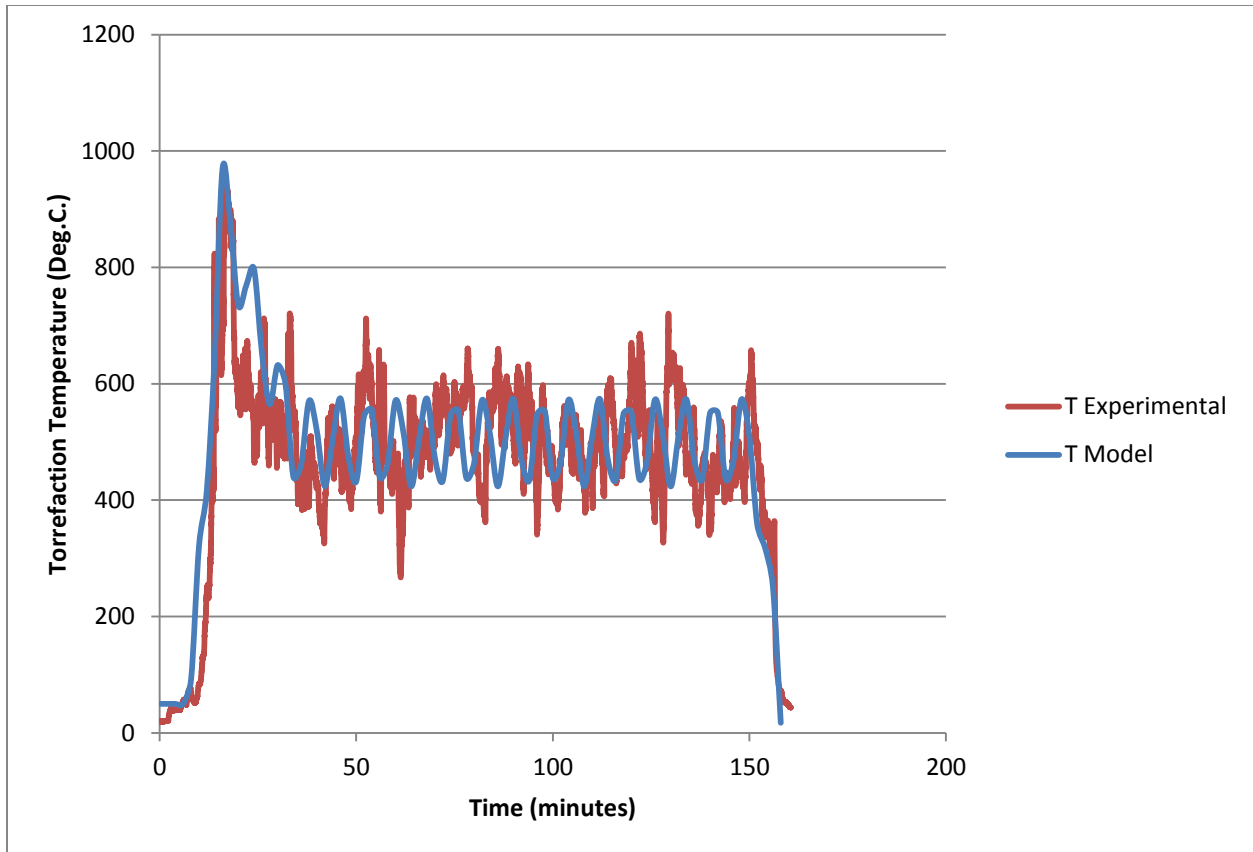
Figure 10 - Combustor Inlet Temperature Empirical Data and Model

3.4.B   Results and Discussion

The heating pattern of the combustor, is one of the primary parameters of the heat transfer model. As discussed before, this was based on experimental data, and the simulate curve in Matlab is shown below. The jagged curve, instead of a smooth curve, is due to finite sampling points (50 in this image).
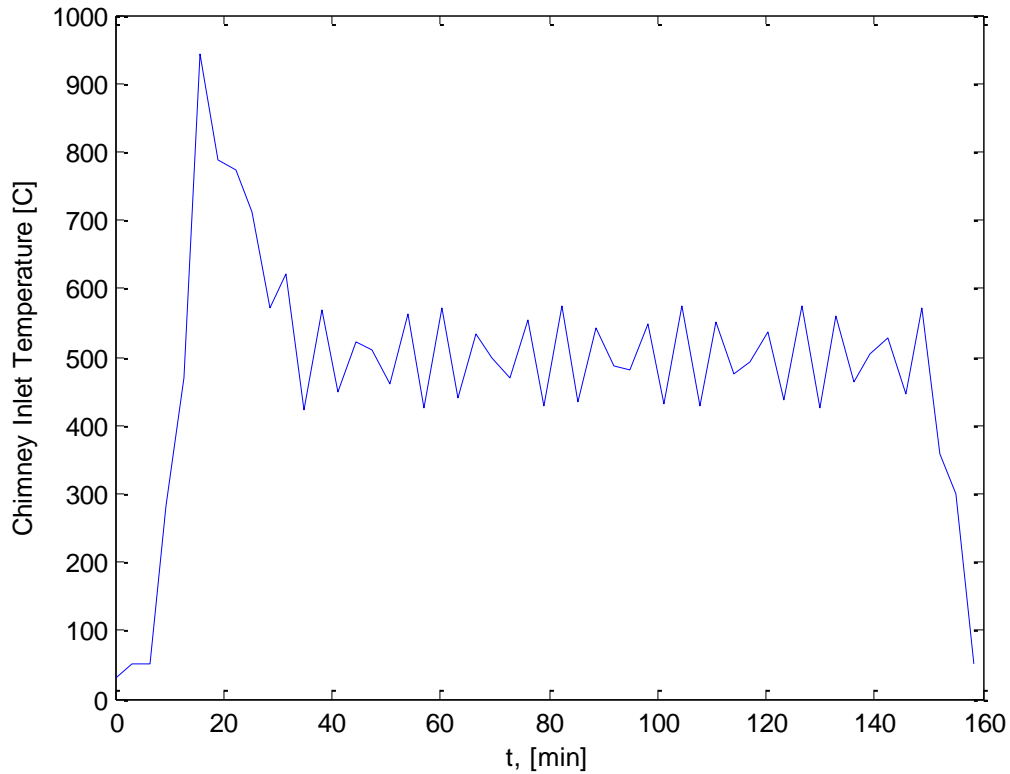
Figure 11 - Chimney Inlet Temperature Function in Matlab Simulation

Temperatures as various points in the reactor are presented here, having the same position as the thermocouples in the testing done in India in order to allow comparison of the heat transfer model to the experimentally observed temperatures. The positions of the selected temperatures in the graph below are explained in the table below.

Table 19 - Spatial Position of Temperature Data

Position	r (m)	z (m)
Bottom Inner (BI)	1 cm	10 cm
Bottom Middle (BM)	7 cm	10 cm
Bottom Outer (BO)	13 cm	10 cm
Top Inner (TI)	1 cm	80 cm
Top Middle (TM)	7 cm	80 cm
Top Outer (TO)	13 cm	80 cm

The temperatures calculated by the model at these temperatures are shown in the figure below.
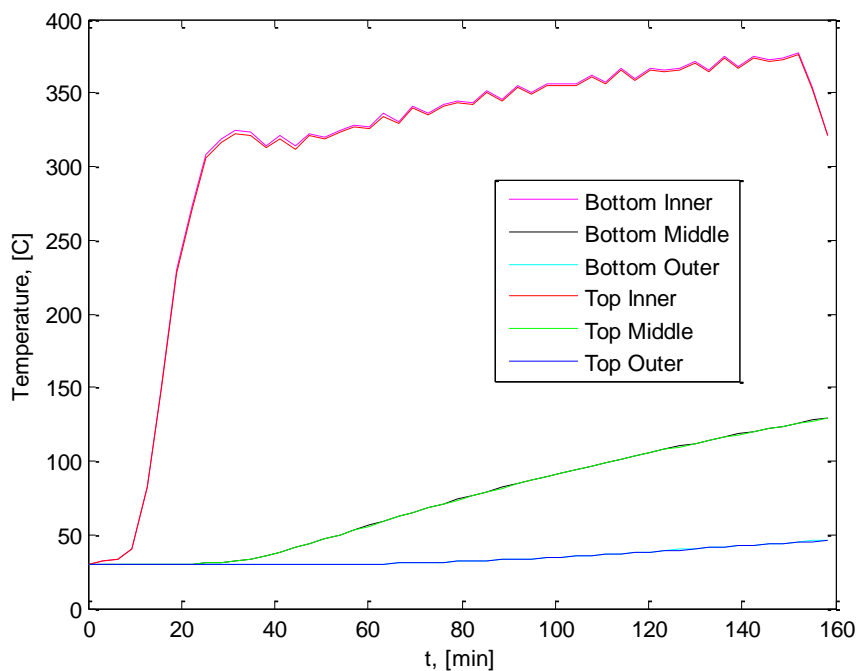
Figure 12 - Model Temperature Data throughout the Reactor Bed

The results for the test in India, repeated from Mohan's report, are shown in the figure below.
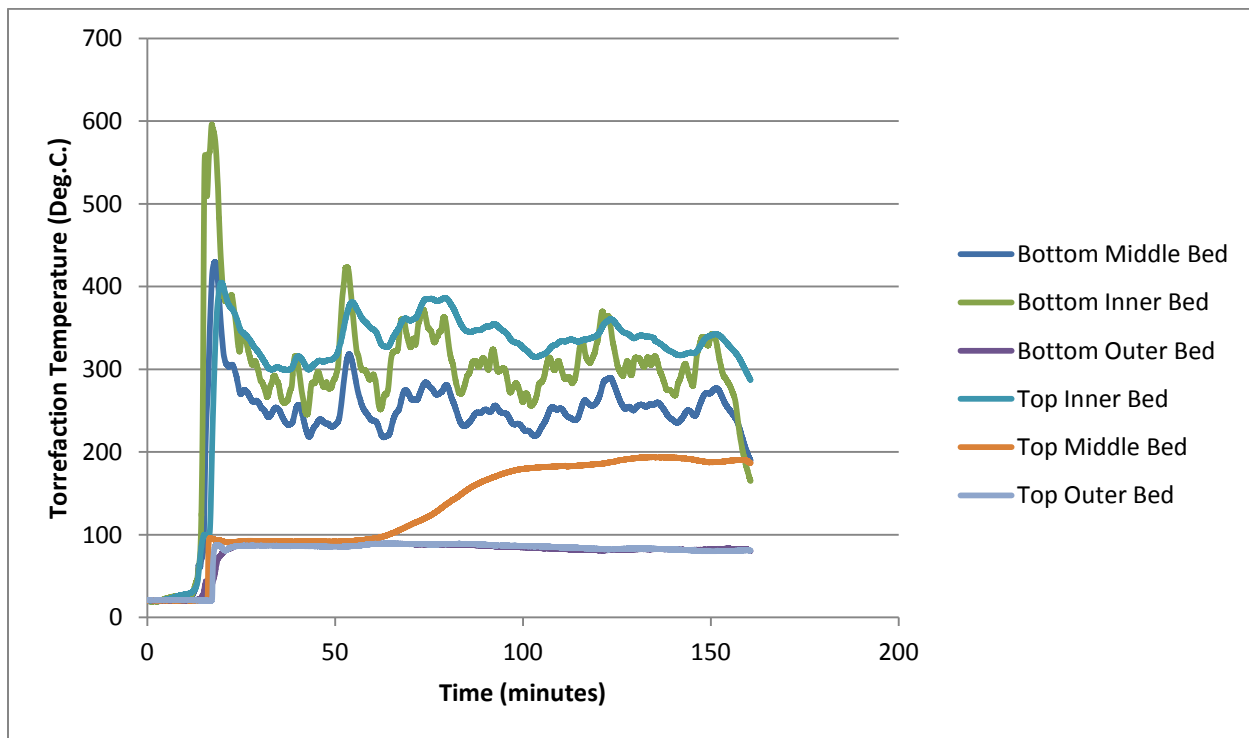
3.4.B.1   Convection in the Chimney

As seen in comparing the model results and the experimental results, the inner temperatures of the biomass rise much more quickly in the actual testing. These temperatures quickly rose to above 400 degrees within 5 minutes, with the bottom temperature rising to almost 600 °C. After the input heat in the chimney began to decline, there is also a decline in the inner temperatures in the biomass to between 250 and 350 °C. This decline after the initial heating spike in the experimental results is not seen in the model results. Rather the temperatures in the model rise quickly to around 250°, when the combustor temperature begins to drop. Then, it continues to rise, albeit more slowly, to around 340°C before the process is ended. This would indicate that the convective heat transfer in the chimney in the actual reactor is much higher than that modelled in the simulation. (As a side note, this would then indicate a chimney flow even faster than predicted, supported the assumption of forced convection. Were the flow natural convection, the heat transfer would tend to be lower.)

3.4.B.2   Thermal Resistance in the Bed

In addition, it appears as though the bed in the actual reactor has a much higher thermal conductivity than that modelled in the simulation (0.062 W/m K). The middle temperature at the bottom of the reactor passes 300°C in the first 20 minutes, whereas in the model this temperature never rises above 150°C over the course of the whole heating process. Similarly, the top middle temperature in the experimental results rises from 100° (following drying) to around 180°C in half an hour, reaching this temperature before t=100 minutes. Again, this temperature in the model, identical to the bottom temperature, never crosses 150. Thus, clearly, the conductive heat transfer, dependent on the thermal conductivity, is higher in the actual reactor than in the model.

3.4.B.3   Axial Differences

Furthermore, the temperatures at the bottom and top of the reactor for the same radial position are almost equal in the model, showing less than 5 degrees of difference, following each other quite closely. This indicates that in the model, axial heat transfer is minimal, as expected, since there is no driving force for heat transfer in this direction, but primarily radially, coming from the heated chimney. However, in the experimental results, not only is a large difference of approximately 50 °C observed, but furthermore the top temperature is higher than the bottom temperature for the large part of the process. This could result from several possible reasons. First, it is possible that, due to the high temperature gradient in the biomass in the first 3 centimeters, the top thermocouple is placed slightly closer to the chimney wall than the bottom thermocouple. In this section of the bed, several millimeters of difference could result in a temperature difference of tens of degrees. This was tested in the model, by setting the Top Inner temperature to 1 cm from the chimney wall, and keeping the bottom temperature at 2 cm. This corresponds with notes from the actual reactor experiment in India, that top thermocouple was apparently placed 1 cm closer to the chimney wall. The model result is shown below. It is clear that even this slight shift of 1 cm can easily cause an increased temperature reading of 100°C, even though, as seen in the figure above, the actual temperature is almost the same. Thus, this test shows that this irregularity in the experimental graphs is likely due to inexact placement of the thermocouples.
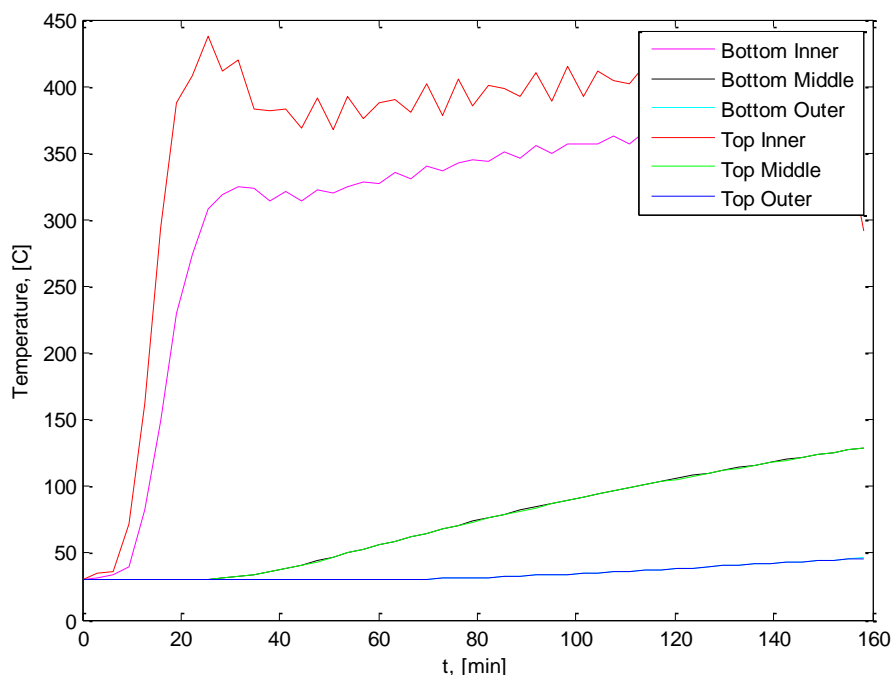
Figure 13 - Temperature Data throughout the Bed with TI Thermocouple shifted

Secondly, there are clearly axial heat transfer modes that should be considered in the model which currently are not, predominantly the heat transfer due to internal convection (natural convection) and condensation. The slow, natural flows of the torrefaction gases in the bed may additionally heat the biomass, effectively taking heat from the bottom section and transferring it to the top section. Furthermore, condensation of the torrefaction gases will also raise the temperature of the biomass, as the heat of fusion is released from the gas to the environment. Condensation was observed in the reactor, and thus this could be significantly affecting the temperatures in the top of the reactor. This would cause the condensing gases to cool down, but the average temperature may increase. The scale of this affect would need to be evaluated in more detail.

Lastly, there is always the possibility that, due to poor sealing, oxygen entered the reactor and caused oxidation of the biomass, released more heat in the top section than desired. Lastly, the heat loss from the top and bottom of the reactor was not considered. This is assumed to be negligible, but nonetheless a more complete model would implement these modes of heat transfer to verify this. These drivers of axial heat transfer should be implemented and checked in future models to verify their impact on the temperatures.

3.4.B.4 Drying

Also, very importantly, the model does not involve any sort of drying, which clearly will play a large role in the industrial operation. The temperatures in the middle and outer regions of the bed, in the experimental results, show plateaus around the drying temperature (approximately 95°C due to altitude). Thus, this drying phase creating a large inhibition to the biomass reaching torrefaction

temperatures, and results in large gradients in the bed. Furthermore, as the largest section of biomass is the most distant from the reactor (the outer annular region), and is the last to absorb the heat from the chimney, drying in this region takes place very slowly. In practice, the outer thermocouples never rose above 95°C. Clearly, a more realistic model would need to incorporate drying in the heat transfer process.

The final temperature gradient in the bottom of the reactor, as calculated in the model, is shown below. To note, the region from r=0 to r=0.14 represents the chimney, assumed to be well mixed and have a uniform temperature radially. The three major regions of the temperature profile are described in the table below. As seen in this curve, the temperature gradient in the biomass at the end of the process reaches around 400°C, with the inner temperatures of the biomass at around 450°C and the outer temperatures below 50°C. This temperature gradient, due to the low thermal conductivity of the bed, is the primary inhibitor to uniform torrefaction throughout the bed, and resulting in the inconsistent product seen in the experimental results.

Table 20 - Radial Ranges of Reactor Model Regions

Model Region	r (m)
Chimney	0 to 0.14
Biomass	0.14 to 0.30
Insulation	0.30 to 0.32
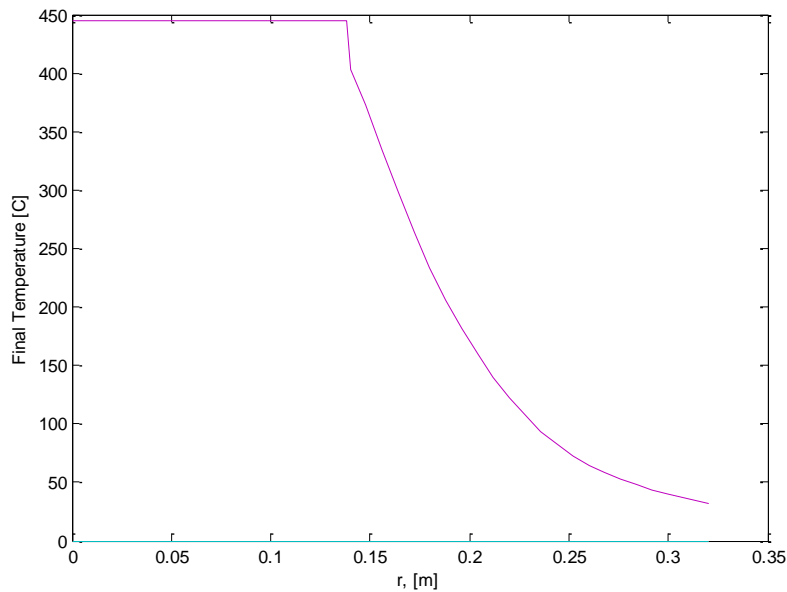
Figure 14 - Final Temperature Gradient in the Bottom of the Bed

In addition, a simulation of the temperature gradients in time was generated in Matlab, and the final frame from the simulation is shown below. To note, the region in the chimney (from 0 to 0.14 m) has already been cooled down to ambient temperature, and the biomass has also begun to cool down.
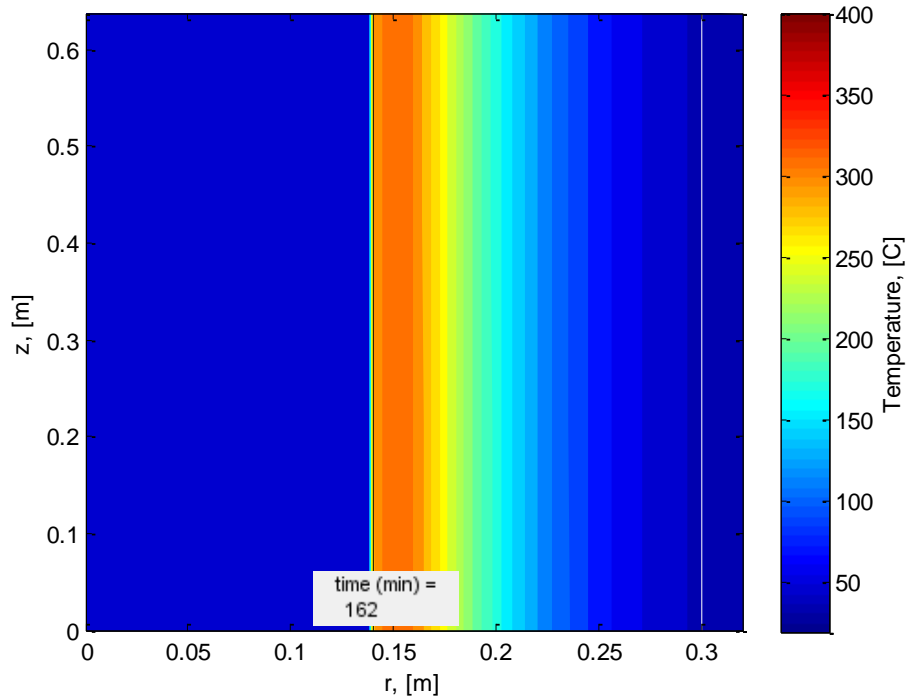
Figure 15 - Final Screenshot from Temperature Animation

In all, a reasonable estimate for the torrefaction process is generated by the model, although various aspects of heat transfer would need to be adjust and included. However, it is important to note that the general trends of temperature radial temperature gradients are observed in both the model and the experimental results. The thermal resistance of the biomass in the bed is very high, seen in both sets of results, and this is the primary hindrance to consistent torrefaction throughout the biomass bed

3.5   Solid Decomposition Model

Following the development of the heat transfer model, the solid decomposition was to be modelled. This, in addition with the subsequent gas production model (discussed below), were much less straightforward to develop, as the chemical reactions in torrefaction are only vaguely known presently, and thus it is not a simple task to attempt to characterize these reactions throughout the process.

3.5.A   Torrefaction Models in Literature

Currently, the predominant model for torrefaction devolution has been that proposed by Prins (Prins, Ptasinski, and Janssen 2006a). This model, applied to woody biomass, employs a 2-step reaction model

with pseudo-components of the solid and gaseous products, which claims to somewhat represent the two main stages of torrefaction, being the volatization of hemicellulose and the decomposition of cellulose. The model parameters were based on experimental data of solid decomposition (from thermogravimetric analysis (TGA) data) for non-isothermal temperature rise from 230°C to 300°C, without considering the isothermal regions in the estimation of the parameters. His model appears to give reasonable results for long residence times; however, for residence times shorter than 45 minutes, as considered for this project, the results do not give adequate accuracy. Furthermore, model results for temperatures below 270°C are not presented.

Bates later built on this model by simulating the production of gases, both permanent gases and condensable volatiles (Bates and Ghoniem 2012). In this research, the same two-step reaction model was used, but adding data for the gas production. The cumulative production of permanent gases and volatiles were collected and measured, and from this the composition of the gaseous pseudo components from Prins' model were estimated. However, the data for the volatiles estimation is only for the heat up period from 200°C and the isothermal period, for torrefaction temperatures from 230°C to 300 °C. Thus, this model is not based on differential data in time, with data at different points in the torrefaction process, but rather cumulative production. Thus, the gas production in time was quantitatively validated, and the cumulative results match reasonably with the model prediction.

Shang also applied Prins' model for the solid decomposition of wheat straw during torrefaction, with similar results as Prins (Shang et al. 2013), and no inclusion of a model for gas production. Lasode applied a model free technique to gain insights into the activation energy of the torrefaction process, without a quantitative model, but was able to confirm the use of a multi-step model for torrefaction (Lasode, Balogun, and McDonald 2014). Peng applied a one-step, first order model to torrefaction on Canadian Wood, which gave good results for long residence times (above 10 hrs). A second model, of a two-component, single step model, gave better results for shorter residence times, but this was still limited mainly to times above 30 minutes, and was only applied during the isothermal period of torrefaction, excluding the heat up time (Peng et al. 2012).

Lastly, Carrasco applied a single step reaction model, with one reactant component (wood) and two product components (torrefied material and volatiles) (Carrasco et al. 2014). Here, a reaction rate with an Arrhenius relationship with temperature was applied. This was fit to experimental data from 250-325 °C, from residence times of 20 to 80 minutes. However, this only provided a solid decomposition model, with not gas production model, and was based on cumulative mass yields for the various torrefaction experiments, as opposed to mass yields in time (such as from TGA).

In this project, due to the difficulty of matching the two step model to results for shorter residence times (less than 45 minutes), this approach was not adopted. As no previous work in literature has developed an effective model for mass loss in torrefaction, it was deemed beyond the scope of this project, to allow for more focus on the gas production kinetics. Therefore, true reaction kinetics for solid decomposition were not derived in this project. Rather, simple equations of mass loss vs. temperature were fitted to TGA data, described in the next section. The complete TGA data and the mass yield results are presented in the accompanying report by Mohan.

3.5.B Methods for the Solid Decomposition Model

Data from the testing of pyrolysis in the TGA apparatus was used for the Solid Decomposition model. In this experiment, the temperature of the biomass was increased steadily at a rate of 10°C/min until over 600 °C; however, for the model, data from 100°C to 550°C were used. This then excludes mass loss due to drying, as this model assumes already dry pine needles. (Note: in an industrial reactor, some amount of drying would be necessary, but the modelling of this process was deemed beyond the scope of the project, and not relevant for determining the usefulness of the torrefaction gas produced in the reactor.) Furthermore, as seen in the heat transfer model above, no temperatures of the biomass reach above 500°C. Thus these limits of the mass decomposition model were chosen. The temperature profile and weight loss in time are shown in Figure 16 below.
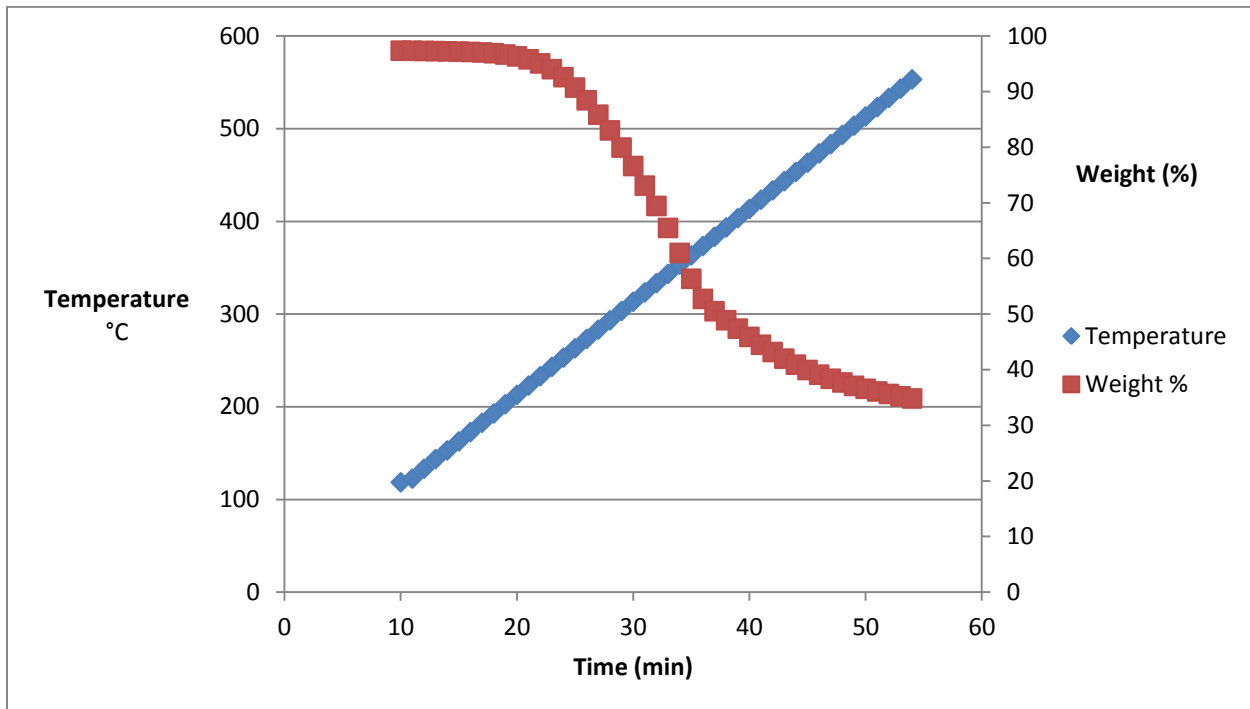
Figure 16- Temperature and Mass Yield from TGA experiment (constant ramp)

In accordance with first-order exponential decay, the decomposition rate at a given point in time was assumed to depend on both the mass and the temperature, as seen in the equation below:

$$\frac{dm_x}{dt} = m_x * f(T)$$

where m_x is the mass of component x at a given moment in time, and f(T) is a function dependent on the temperature of the mass m_x Thus, a data fit for the function f(T) was found by calculating the differential mass loss rate $\frac{dm_x}{dt}$ for each time step, and then dividing this mass loss rate by the mass yield for that time step. Then, a curve was fitted to the data to obtain an equation for f(T). Note: this equation for f(T) does not attempt to represent mass loss kinetics, but merely a data fit. This data is shown below

in the figure below. As seen in the figure below, no one equation could be used to model the mass loss, thus, according to the data trends, the model was divided into four temperature regions: 120°C to 290°C, 290° to 360°C, 360°C to 400°C, and 400°C to 550°C. Due to the varying curvature of the data, differential orders of polynomials were used to model f(T), shown in the table below.

Table 21 - Solid Decomposition Model Equations

T Range (deg C)	Equation	R²
120 to 290	$y = 1.060157196106470E\text{-}10x^4 - 9.416651575039170E\text{-}08x^3$ + $+2.842620902725070E\text{-}05x^2 - 3.577882654575320E\text{-}03x +$ $+1.605497667363730E\text{-}01$	0.997799
290 to 360	$y = -6.774831817669070E\text{-}04x + 1.682861057122920E\text{-}01$	0.955468
360 to 400	$y = 1.363321014297400E\text{-}03x - 5.747339156383470E\text{-}01$	0.91774
400 to 550	$y = 1.311122498070620E\text{-}10x^4 - 2.642886132993150E\text{-}07x^3$ + $+1.983381490748260E\text{-}04x^2 - 6.551707727055310E\text{-}02x +$ $+7.999105610878530E\text{+}00$	0.99952

The mass loss model is graphed, shown in the figure below, underneath the values calculated from the TGA data. As seen, the model for f(T) follows the empirical data very closely.
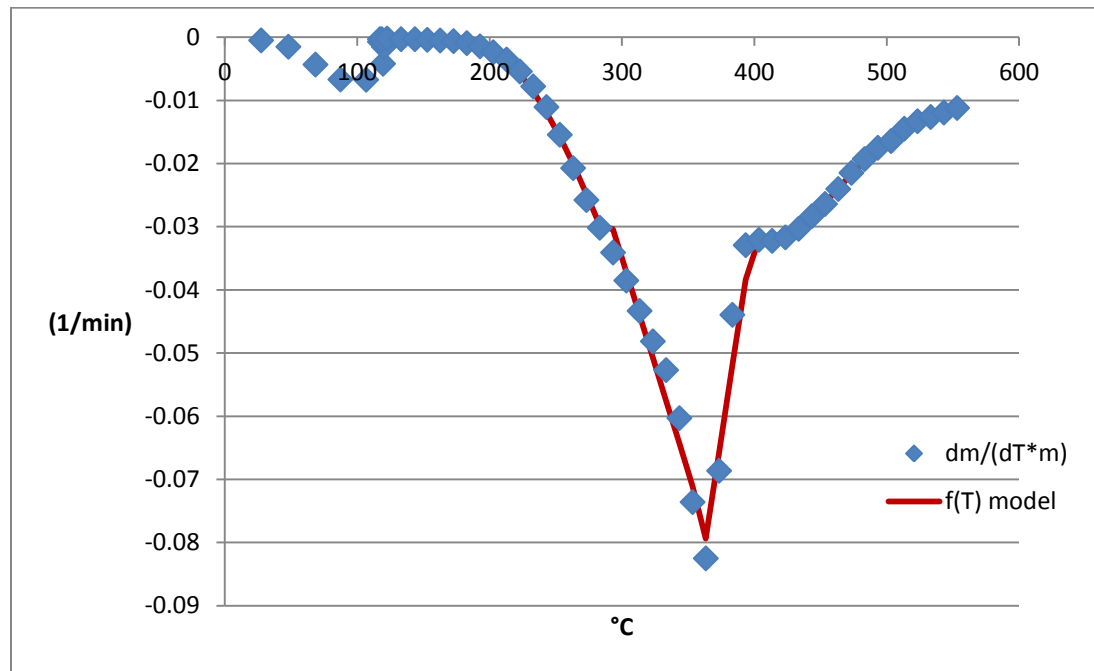
Figure 17 - Empirical Mass Loss Rate (dm/dt*min) and f(T) Model

As a side remark, with the given reactor design, no region of the biomass maintains a constant temperature for any significant period of time. For reasonable operational times (<5 hrs for the entire heating process), steady state is not reached in the reactor, and thus the isothermal period of the

torrefaction process is effectively not achieved. This phenomenon was seen in both the model as well as being observed in tests of the reactor in India. Thus, even though the target process conditions at 250°C for 15 minutes were chosen, no special mass loss rates for this region, or any isothermal region, were modeled.

3.5.C   Results and Discussion

The overall mass yield, in the modelled reactor, in time, is shown in the figure below. The yield steadily declines, after the initial period, to a point of finally reaches 0.811. The initial period corresponds to the initial phase before the combustor is ignited. The steady decline indicates that, even though the overall mass loss rate is not linear, the gradual increase in temperature throughout the reactor is constant, as seen above. This combined with slower heating rates at larger distances from the chimney, results in a balanced mass loss rate, and thus a steady decline. The 81% mass yield is reasonable when compared to the actual mass yield of the test performed in India, giving a mass yield of 73.08%. The model does not include the mass loss from drying the pine needles, which can be around 25%. Noting that, in the experiment, the large outer sections of the reactor did not finish drying, it may be reasonable to assume that only around 8% of the 25% of moisture content was released from the biomass, which would drop the mass yield from 81% to 73%. Thus, these mass yield results seem reasonable.
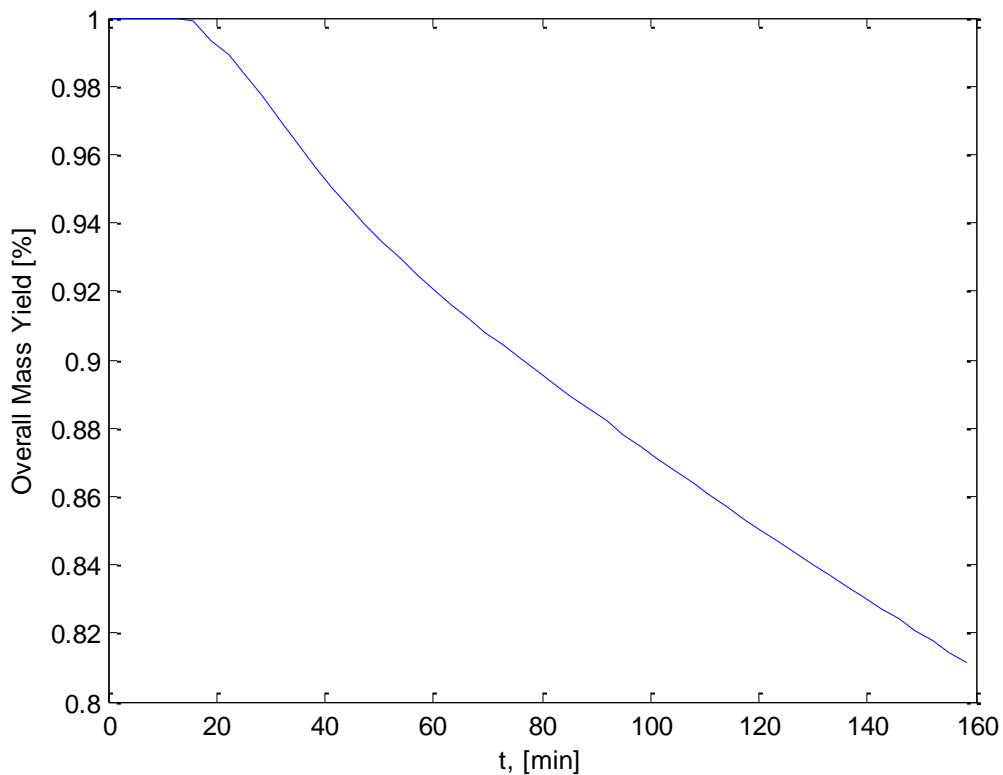
Figure 18 - Overall Mass Yield Results

Next, the mass yield and temperature curves versus time were plotted for the three thermocouple locations in the bottom of the reactor (BI, BM, BO). These are shown in the figures below. As seen in all three graphs, the mass does not begin to decrease below 120°C, as defined by the model. This corresponds with the mass that occurs after drying as seen in the TGA results. In the inner ring of biomass, the high temperatures result in a 0 mass yield. As the temperature steadily climbs from around 250°C to 350°C, the mass yield drops to zero by around t-100 min. This is obviously unreasonable, as at these temperatures, the fixed carbon will not decompose, nor will the ash fraction of the biomass. Thus, for the higher temperatures experience in the inner annular region of the biomass, the mass loss model equations overestimate the mass loss. However, this region contains a relatively small portion of the bed, compared to the size of the larger annuli, and thus the impact of this mass loss will not greatly affect the overall mass yield.
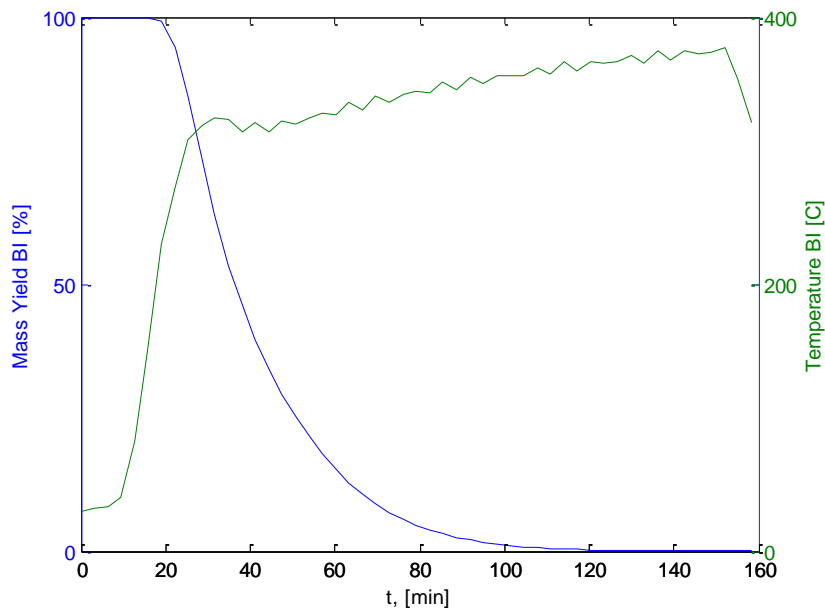
Figure 19 - Mass Yield and Temperature in time - Bottom Inner

For the middle region, very little mass loss is found in the model. This is due to the lower temperatures, which as seen above, do not exceed 150°C. The mass loss between 120°C and 150°C is nominal, and thus the final mass yield of the middle annulus does not fall below 99%. For the outer ring, the biomass does not rise about 50°C. The mass loss model does not engage before 120°C, as drying is excluded, and thus the mass yield for the outer ring remains at 100%. These results are shown in the figures below.
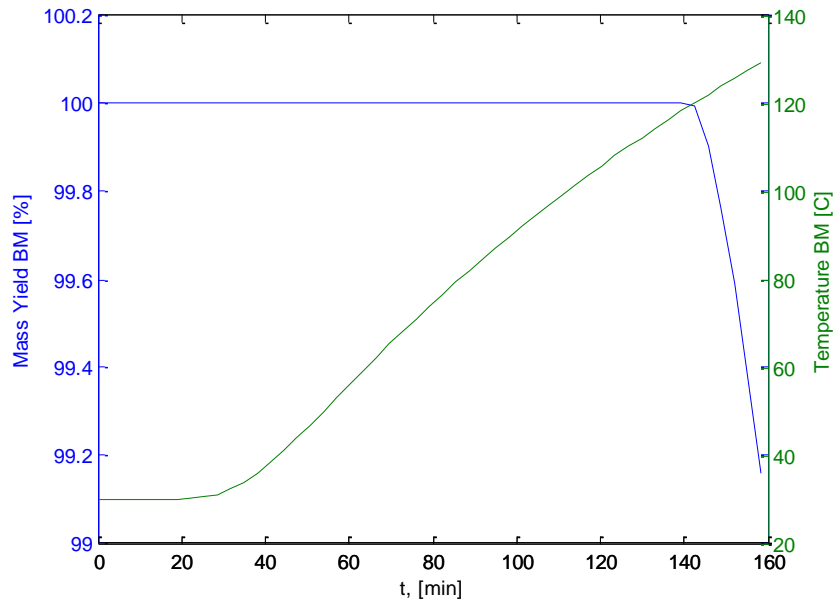
Figure 20 - Mass Yield and Temperature in time - Bottom Middle
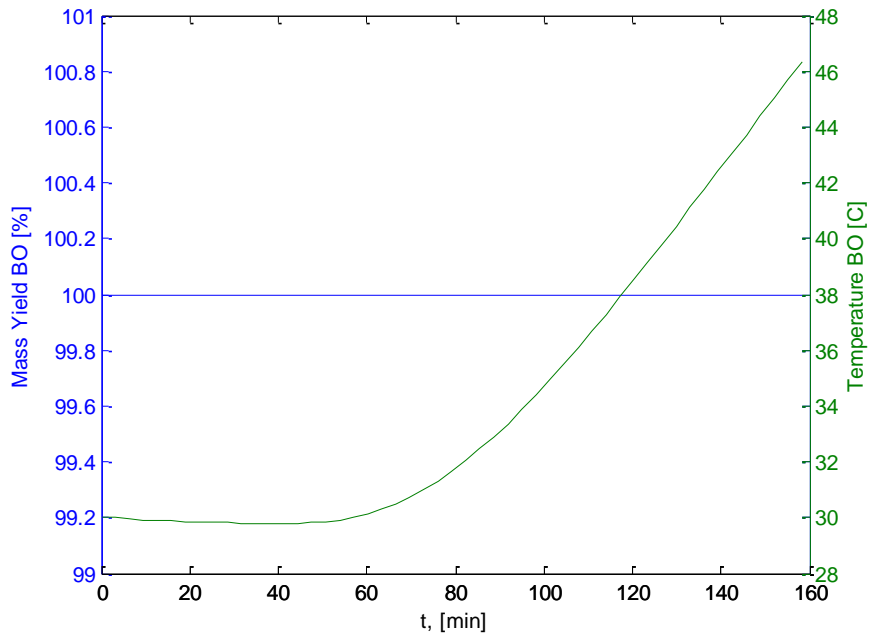
Figure 21 - Mass Yield and Temperature in Time - Bottom Outer

The relative mass loss curves for each of the three chosen biomass sections (BI, BM, and BO), are shown below. Clearly, the mass loss percentage in the inner ring is much greater than the other rings, due to the much higher temperatures, while the other two regions remain at 100% mass yield, on the top border of the graph.

78
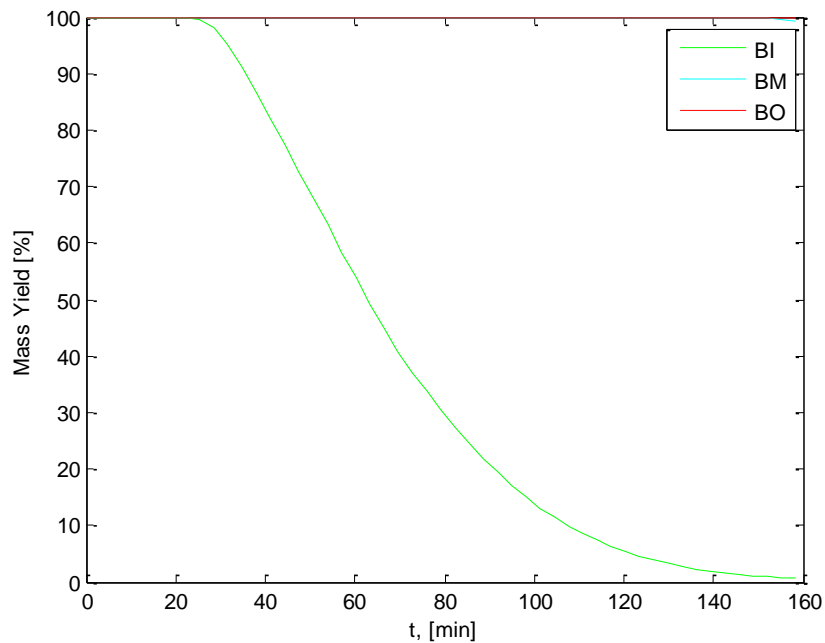
Figure 22 - Mass Yield in Time for Three Positions

Lastly, a simulation was generated from the Matlab code of the mass yield in time for the reactor volume. The final screenshot of this simulation is shown below. As seen in the image, effectively no mass loss is experience at a distance of more than 6 cm from the chimney wall (the chimney wall being 14 cm from the centerline of the chimney). Furthermore, extensive mass loss, almost 100%, is experience in the region from the chimney wall to around 3 cm from the wall. Given the large temperature gradient in this region, this mass loss gradient also seems logical. In a more realistic model, with a higher thermal conductivity of the pine needles, and a lower temperature gradient in the bed, the mass loss gradient would be more evenly distributed across the radial distance of the bed.
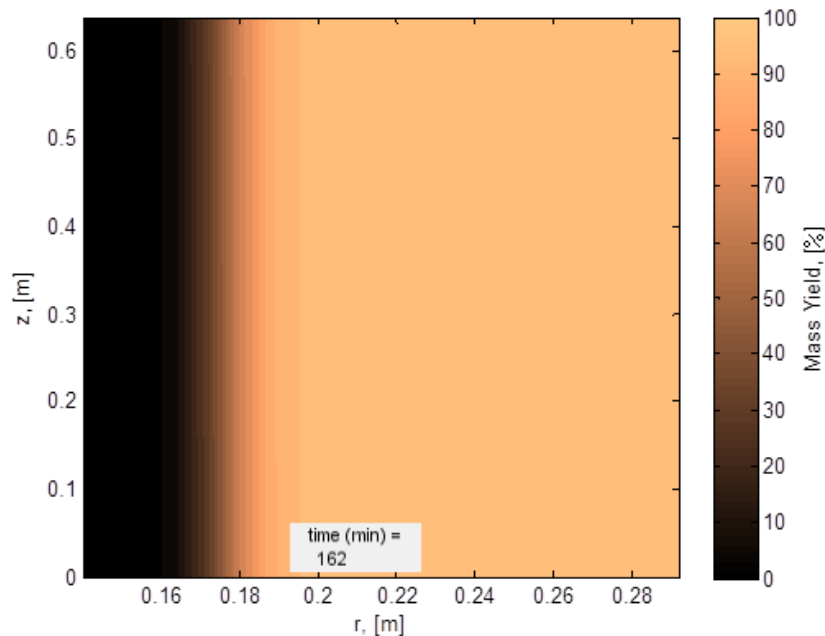
Figure 23 - Final Screenshot from Mass Yield Animation

3.6   Gas Production Model

With the models for the temperature profiles and mass yields of the biomass in the reactor defined, the gas production model could be thus built upon these. In order to achieve this experimental data on the production of the various gaseous components needed to be obtained. The permanent gases needed to be measured and analyzed separately from the volatiles, as it was not possible to measure both in the same device. Ideally, the gas production data could be acquired in time, as opposed to a cumulative result, in order to acquire precise information as to which components were being produced at different points in time and different temperatures. However, this was only possible for permanent gas analysis. Continuous sampling of the volatiles produced was attempted, but experimental complications resulted in abandoning this approach for a simpler, cumulative approach to collecting volatiles. These methods are discussed below.

3.6.A   Permanent Gases Model

Torrefaction was thus carried out in the bench scale reactor, aiming to achieve a ramping rate of between 5-10°C/minute, a constant nitrogen flow of 60 L/min, a torrefaction temperature of 250 ±2°C, and a 45 minute isothermal period. The flow through the gas analyzer was adjusted to 50-60 L/hr, and this operated constantly at a temperature of around 68 °C. Spacers were inserted into the torrefaction bed, in order to only use a small section of the bed. This was done to simulate a thin slice of the bed where the temperature in the slice is more or less uniform. In this section, 10 g of raw, uncut biomass was loaded for the experiment.

The permanent gases were analyzed using an Emerson Xstream XEGP gas analyzer. This was connected to the exhaust of a bench scale torrefaction reactor, utilizing direct convective heating via nitrogen flow,

from which a portion was diverted to the gas analyzer, while the bulk flow was sent to the exhaust. The analyzer recorded the concentration of CO, CO_2, CH_4, and O_2 in the flow. The oxygen was recorded only to ensure the quality of the measurement, to ensure that no leakages in the line were contaminating the data. The methane concentration was recorded as well, but the production was erratic and low, remaining within the range of measurement error. Thus, it was not modeled.

For the other components, the gas analyzer data was matched in time with the data from the torrefaction reactor, to match the concentrations recorded to the temperature of the biomass in the reactor and the flow rate of nitrogen going through the reactor, which did vary to some extent. The delay in the gas stream (the time from leaving the reactor to the gas analyzer) was calculated to be 5.2 s, and thus was ignored as measurements were only taken every 5 seconds, and thus this delay is insignificant for a reaction time on the scale of hours.

After matching the data, the gas analyzer (GA) data was smoothed via a MatLab function smooth, and then the data was adjusted to eliminate any negative concentrations. After this, an Arrhenius correlation for the reaction rate was sought. The basic equation for gas production was assumed to be of the form below:

$$\frac{dX}{dt} = [X] * \phi_v = m_y * k(T)$$

where dX/dt is the mass of component X produced, in g, per minute, $[X]$ is the concentration of component X in the exhaust gas in g/L, ϕ_v is the flow rate of nitrogen in the reactor (assumed to be almost equal to the exhaust gas flow), m_y is the mass of the biomass source in grams, and k(T) is the reaction rate coefficient in g X per g biomass per minute.

For this model, as pure components are being produced, an Arrhenius relationship was sought for the gas production of each component, having the form here:

$$k(T) = A * exp\left(\frac{-E_a}{RT}\right)$$

where A is constant, E_a is the activation energy for the hypothetical reaction, R is the universal gas constant, and T is the temperature in Kelvin. Thus, the parameters A and E_a needed to be estimated. However, no single relationship could be obtained from the experimental data to fit the entire range of temperatures. This is again due to the fact that this reaction is not composed of a single reaction of pure components, but an agglomeration of numerous reactions. Thus, similar the solid decomposition model, the permanent gas production models were divided into three regions according to the table below. 215°C was set as a breaking point for the ramp section as a peak in the gas production occurs at this temperature, likely due a peak in hemicellulose decomposition. The gas production on either side of this temperature followed different trends, as seen in the graphs of k vs. 1/T below. The breaking points at 248°C and 273°C were chosen arbitrarily, giving a better fit to the experimental data. 288°C was chosen as the fourth breaking point, as this was the limit of the experimental data for the torrefaction experiments (the highest experiment consisted of an isothermal region at 290°C, and no higher).

Thus, as the temperatures of the biomass in the model exceed 288°C, it was deemed important to model gas production for these temperatures another way. Based on experimental data of torrefaction of woody biomass by Wannapeera, the CO and CO_2 production appear to increase somewhat linearly beyond 290°C until 325°C. At this point, the production peaks, and then falls to a nominal value at 350°C (Wannapeera, Fungtammasan, and Worasuwannarak 2011). Thus, the model estimated the experimental rate of increase of the reaction rate before 290°C, and this slope was then maintained (assuming a linear type correlation) until 325°C. From 325 to 350 °C, the kinetics were assumed to fall linearly to zero. This trend for the reaction rate seems also to be confirmed by Bates, as he discusses that the composition of gases produced above 260°C is dominated by condensable volatiles, such as organic acids, not permanent gases like carbon monoxide (Bates and Ghoniem 2012). Similar to the mass loss model, no separate kinetics were modelled for the isothermal regions, as the temperatures in the reactor never reach stability for any substantial period of time.

Thus, in order to find the parameters A and E_a, k was calculated for every point in time (every 5 seconds) from 180°C till 288°C, by the following formula:

$$\frac{[X] * \phi_v}{m_y} = k(T)$$

As concentration and flow rate were measured during the entire experiment, and pine needle mass was estimated by applying mass yield curves from TGA, the value of k(T) could be calculated. Thus k was plotted against 1/T for each component, for each of the 3 temperature regions, and an exponential curve was fitted to each data set. An example graph of CO production between 215 and 248°C is shown in Figure 24 below. The other graphs, with the associate equations and R^2 values, can be seen in Appendix N.

k CO (215-248) $y = 5.769720854250670E+05e^{-1.214549037799540E+04x}$
$R^2 = 9.960838996490110E-01$
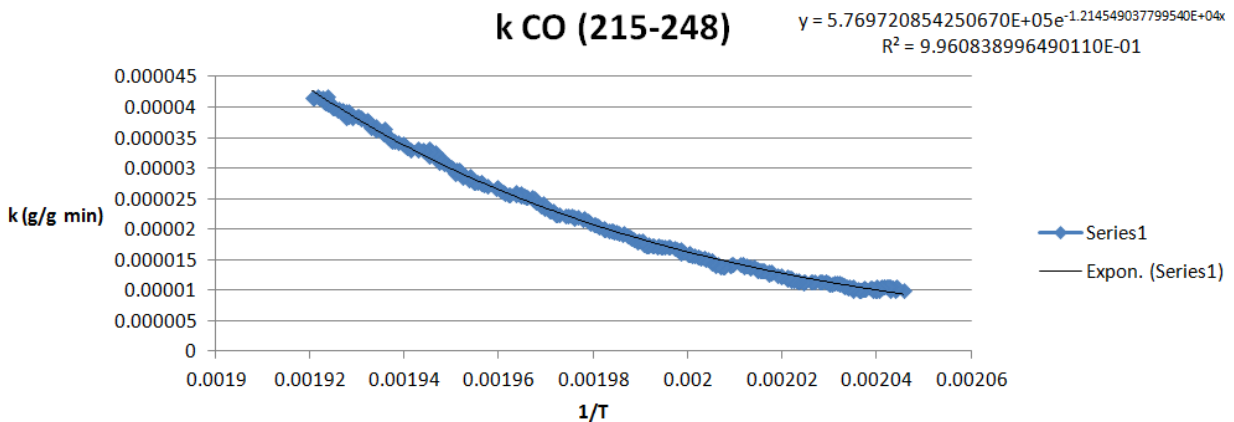
Figure 24 - Reaction Rate vs. 1/T (CO)

Thus, the parameters of A and E_a were found for both CO and CO_2 for the three temperature ranges. These relations and the associated parameters, are shown below in Table 22. To note, the number of significant digits retained for these constants was found to be highly crucial, as rounding to only a few decimal places produced large errors in the model. Thus, all digits were retained.

Table 22 - Kinetics Constants (CO)

CO Production

Range (°C)	-Ea/R (1/K)	A (g X/g biomass *min)
T: 180-215	-1.852648795828730E+04	4.291253644390620E+11
T: 215-248	-1.214549037799540E+04	5.769720854250670E+05
T:248-273	-1.372205817964490E+04	1.250205865052110E+07
T: 273-288	-7.545719704344710E+03	1.121309388162950E+02

Table 23 - Kinetics Constants (CO2)

CO2 Production

Range (°C)	-Ea/R (1/K)	A (g X/g biomass *min)
T: 180-215	-9.457674776212580E+03	4.482720921818850E+04
T: 215-248	-6.403231733858230E+03	1.077385688185970E+02
T:248-273	-6.958152072919520E+03	3.956374697156560E+02
T: 273-288	-6.233769988459170E+03	7.033174733294510E+01

For the regions above 288°C, the rate of increase of k was maintained, so that it rose linearly to a max at 325°C. After this temperature, it was modelled to fall linearly to zero at 350°C. Thus, the model for each of these regions has the following form:

$$k = m_i\, T + b_i$$

where m and b are constants for a given temperature range, T is in °C, and k is in g/(g pine needles *min). The parameters for these equations are given below.

Table 24 - Kinetics Constants above 288°C (CO)

CO Production

Range (°C)	m (dk/dT)	b (k)
T: 288-325	5.480750369436740E-06	1.822399552895100E-04
T: 325-350	-1.540110875834680E-05	3.850277189586690E-04

Table 25 - Kinetics Constants above 288°C (CO_2)

CO_2 Production

Range (°C)	m (dk/dT)	b (k)
T: 288-325	2.444173326065040E-05	1.150618933936710E-03
T: 325-350	-8.219852258323100E-05	2.054963064580770E-03

The graphs of the kinetics constants vs. temperature are shown below. The discontinuities are due to the natural of the curve fitting for each temperature range separately, resulting in a piece wise function. Overall, the general trend of k, as shown by Wannapeera, is followed.
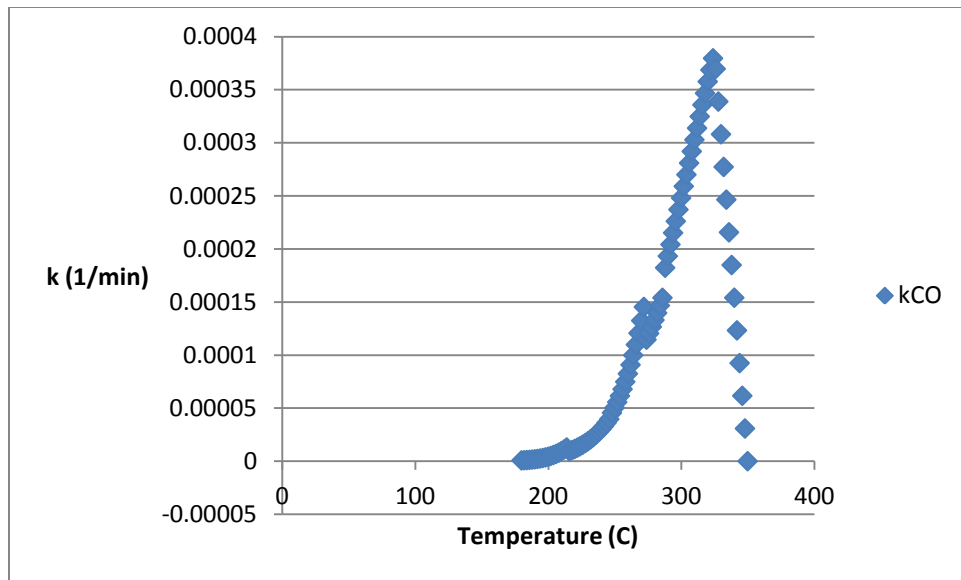
Figure 25- Graph of k Model for CO
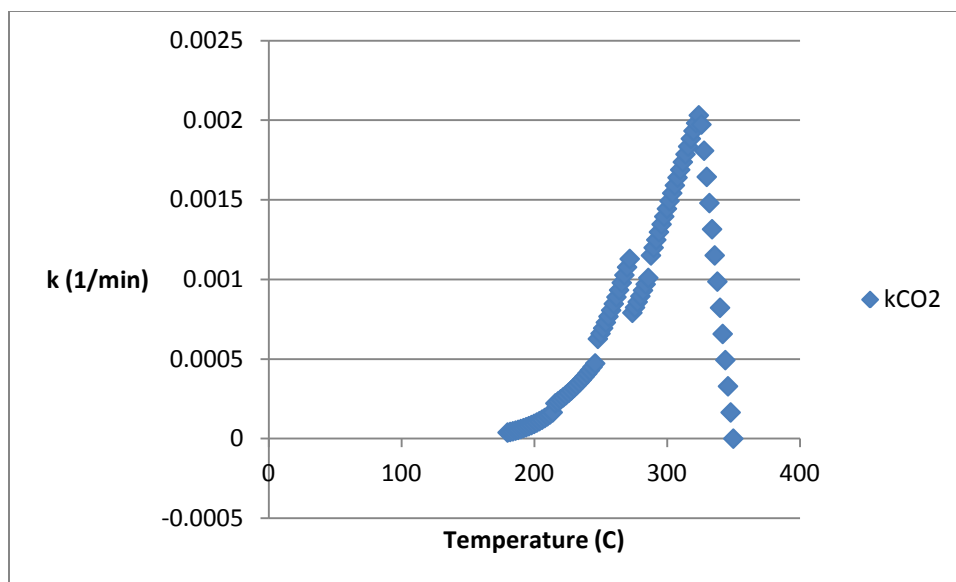
Figure 26 - Graph of k Model for CO$_2$

3.6.B   Volatiles Model

As mentioned above, the volatiles model was based on data for the cumulative production of condensable components, instead of continuously sampled data. Thus, a different approach was taken to model this production than that of the permanent gases. For this, a different experimental set up was used, that allowed for the collection of all volatiles produced. The bench scale reactor from the permanent gas experiments only allowed for a small portion of the flow (roughly 1/60) to be extracted, due to limitations of the gas analyzer. This resulted in very low concentrations of volatiles, insufficient to be well detected later analysis methods.

3.6.B.1   Experimental Set up

Thus, a new set up was constructed according to the schematic shown in Figure 27below. Torrefaction was carried out by loading a sealed chamber with powdered pine needles inside a muffle furnace, which controlled the temperature of the air surrounding the biomass chamber. From the biomass chamber, the volatile gases were lightly blown through a series of bubblers to condense and capture the volatiles, which were then analyzed. A more detailed description of the laboratory set up is given in Appendix Q. Thus, after the experiment, the liquid in the bubblers were combined and mixed, and a clear increase in volatiles concentration was observed visually by the increase in brownish hue in the liquid collected as seen in
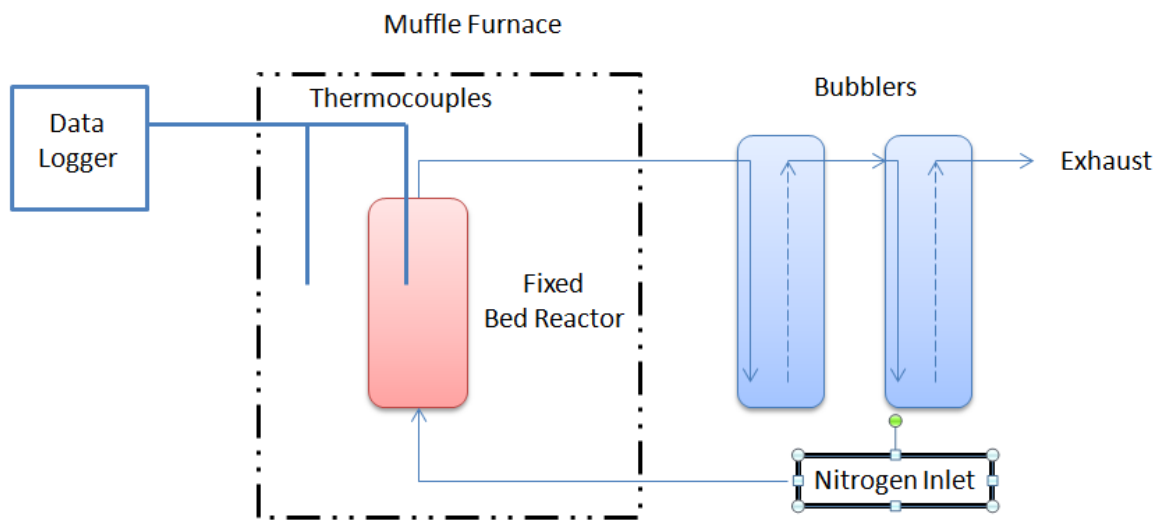
Figure 27 - Schematic of Experimental Setup for Volatiles Collection

Figure 28 - Image of Condensed Volatile Samples

In this method, a cumulative sample was taken. In order to estimate the parameters A and E_a from the Arrhenius equation, assuming an Arrhenius relationship could be obtained, the volatiles were only collected from the isothermal period, since the reaction rate constant k is assumed to a function only of T. Thus, during the isothermal period, k(T) is constant. Thus, k(T) was estimated by the following equation

$$\frac{m_x}{m_y * t_{tot}} = k(T)$$

where m_x is the cumulative mass of volatile component x produced during the isothermal period, m_y is the average mass of the pine needles during torrefaction, and t_{tot} is the total isothermal residence time in minutes. As the overall production does depend on the mass of biomass, an average mass was assumed during the isothermal period, based on applying the mass yield curve from TGA to the initial mass loaded into the reactor. In addition, the bubbles were only connected to the exhaust of the reactor when the isothermal period was reached. Before and after the isothermal period, the gases were sent directly to the exhaust. This experiment was performed for the same four torrefaction temperatures tested by Mohan in the accompanying report (230, 250, 270, and 290 °C). Ideally, this isothermal test would be performed also at temperatures between 180°C and 230°C in order to have data on the entire range. However, due to time constraints, the production in the range from 180°C to 230°C was estimated by separately sampling the volatiles produced in this ramp phase from the isothermal phase, during the experiment for torrefaction temperature of 230°C.

3.6.B.2   HPLC characterization and kinetic parameters

After collection of the volatiles, the condensed gases were analyzed and characterized in High Pressure Liquid Chromotography (HPLC) setup. As the column use in the setup was limited to separation of organic acids predominantly, and time constraints, not all components were characterized. Focus was given here to Lactic Acid, Formic Acid, Acetic Acid, and Methanol, as these are reported in literature to be the dominant volatiles for other biomass types, aside from water (Prins, Ptasinski, and Janssen 2006b; Bates and Ghoniem 2012; Shang et al. 2013). Lactic acid was not detected in the sample, and is thus not presented here. In addition, Furfural was detected, and this shall be discussed below. Water was assumed to comprise the remainder of all mass lost by the solid fraction, excluding the 5 other gas components produced (CO, CO_2, Formic acid, Acetic Acid, and Methanol. The procedure for characterization of the samples via HPLC is presented in Appendix O.

In order to obtain a relation between k and T, ln(K) and (1/T) were plotted, as shown in Figure 29below. Linear relations were fitted to the data, and from these relations, the parameters A and E_a were estimated; these are shown, with the R^2 accuracy measurement for each curve, in Table 26below.
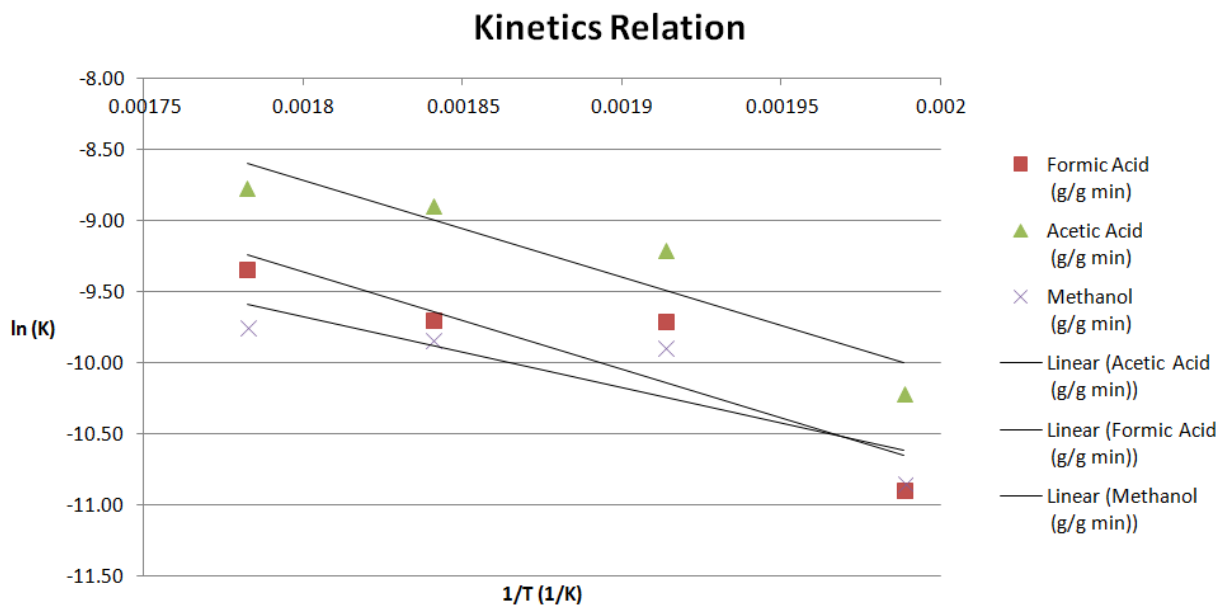
Figure 29 - ln(k) vs. 1/T (Volatile components)

Thus, the required kinetics parameters for the volatiles production were obtained. It is clear from the R^2 values above that the reaction rate constants do not fit precisely with the data. This is due to several factors, including the limitations of the experimental method (not being able to sample the volatiles continuously or measure the mass of the biomass during the experiment, but rather using cumulative estimates. Furthermore, in some of the experiments, the temperature fluctuated by several degrees during the isothermal region, further affecting the isothermal assumption. Lastly, further testing with the HPLC of the gathered samples would likely improve the values slightly as well.

Table 26 - Parameters from Kinetics Curve Fitting (Volatiles)

Parameter	Formic Acid	Acetic Acid	Methanol
-Ea/R (K)	-6.843190806752710E+03	-6.827121246687870E+03	-4.943411476739980E+03
Ea (J/mol)	5.689428836734210E+07	5.676068604496300E+07	4.109952301761620E+07
A (g/g *min)	1.925824613964100E+01	3.556337665939760E+01	4.560621651060780E-01
RSQ	0.811	0.871	0.745

Furfural was also detected, although it was not rigorously characterized, nor were kinetics parameters found, due to time constraints. After characterizing the samples in similar, although less robust, method as the components discussed above, a production ranging from 0.65 to 1.03 mg/g of pine needles was estimated (for the isothermal period only), roughly half of the production of methanol (approximately 2.0 mg/g) and one fourth of the production of acetic acid (approximately 4.0 mg/g). However, more rigorous testing is needed to confirm this estimate.

These correlations were used for all temperatures above 230°C. It was assumed, due to lack of experimental data, that the production would continue above 290°C (the limit of the experimental data)

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as, according to Bates, gases produced in this range are dominated by condensable components, such as organic acids(Bates and Ghoniem 2012). For the region from 180°C to 230°C, a simplistic relation for a linear reaction rate dependency with temperature was derived, based on the empirical data. The methodology for deriving this relation and the resulting values are shown in Appendix R.

3.6.C   Results and Discussion

The above kinetics relations were implemented into the Matlab software to simulate gas production. As this model did not look into the fluid flow patterns of the torrefaction gas in the bed, a simple assumption for the mass balance is taken. Since the bed is fitted with pipes allowing for the escape of the torrefaction gases to the combustor, the pressure will not increase significantly. Thus, the overall mass of gas will not accumulate within the reactor, and outflow of gas will be directly linked to gas production. As the time scales for equalization of pressure in a fluid are low relative to reaction kinetics, it is assumed that gas produced effectively becomes gas outflow from the reactor. This assumption is valid for models where the time step in the simulation is large relative to the residence time in the reactor, which was not measured from the tests in India.

3.6.C.1   Volume Fraction and Calorific Value

The gas mass yield, relative to the initial mass of pine needles loaded into the reactor, is plotted below, with the solid mass yield, all versus time. In addition, the gas production, being the gas leaving the reactor in grams per min, is plotted below with the solid mass yield. The rise in the gas yield matches exactly with the solid mass yield decrease. The final values of 81% solid yield and 19% gas yield show that the mass balance essentially closes. Also, the gas production matches with the mass yield, which begins to drop at the same moment in time when the gas production rises, above 120°C. Furthermore, the gas outflow correlates with the slope of the graph of mass yield. The mass yields drops most quickly where gas production is highest, as the solid mass lost is due to gas production. Thus, the overall gas production matches mass loss.
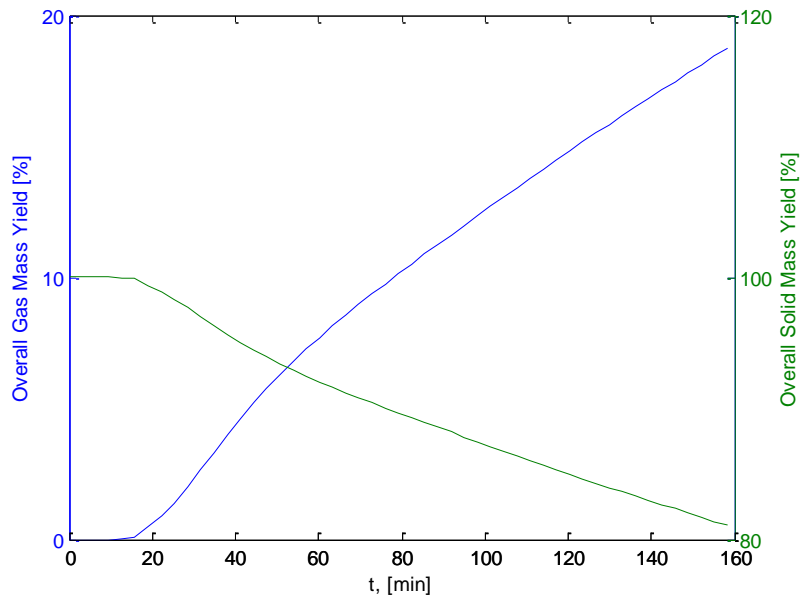
Figure 30 - Overall Gas Mass Yield and Overall Solid Mass Yield in Time
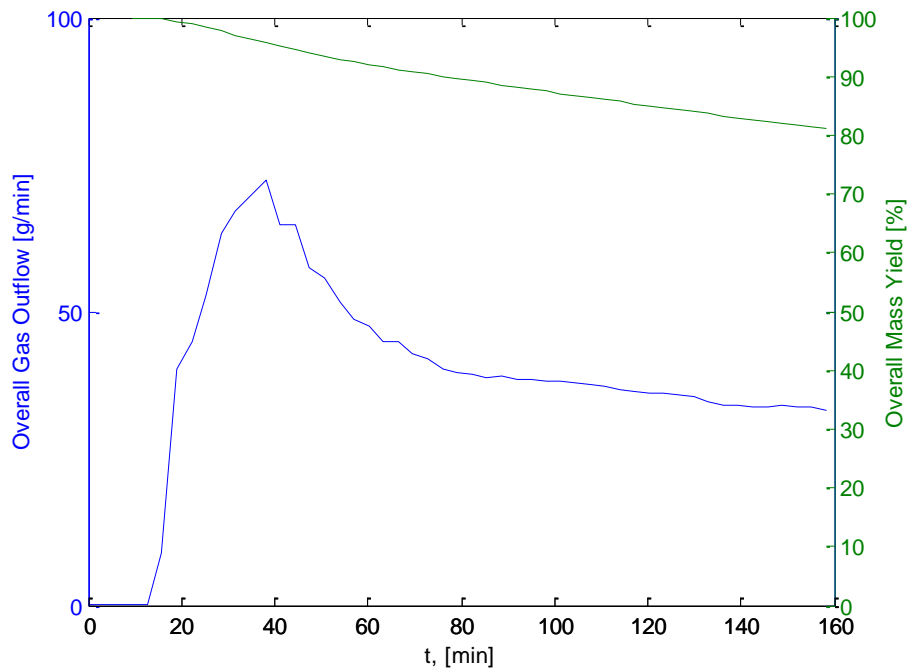
Figure 31 - Gas Outflow and Solid Mass Yield in Time

The final mass yield for each component is shown in the table below. (Note: the mass balance is missing 0.17% of the original mass of the pine needles, which is lost due to an unknown in the Matlab simulation.)

Table 27- Mass Yield per Component

Component	Mass Yield (%)
CO	0.072
CO2	0.609
Formic Acid	0.101
Acetic Acid	0.185
Methanol	0.057
Water	17.727
Total Gases	18.751
Total Solids	81.079
Total	99.830

The mass yield per component of the gases in time is shown in image below. Clearly, water dominates the production of gases, forming around 95% of the mass of the gas produced. In Figure 32 below, the component wise mass yield is plotted without water, showing in detail the mass yields of each component. water comprises 17.7 of the 18.8% mass yield of the gases, while all of the other gases comprise less than 1% each of the total mass yield, which carbon dioxide being the largest among them at 0.609%.
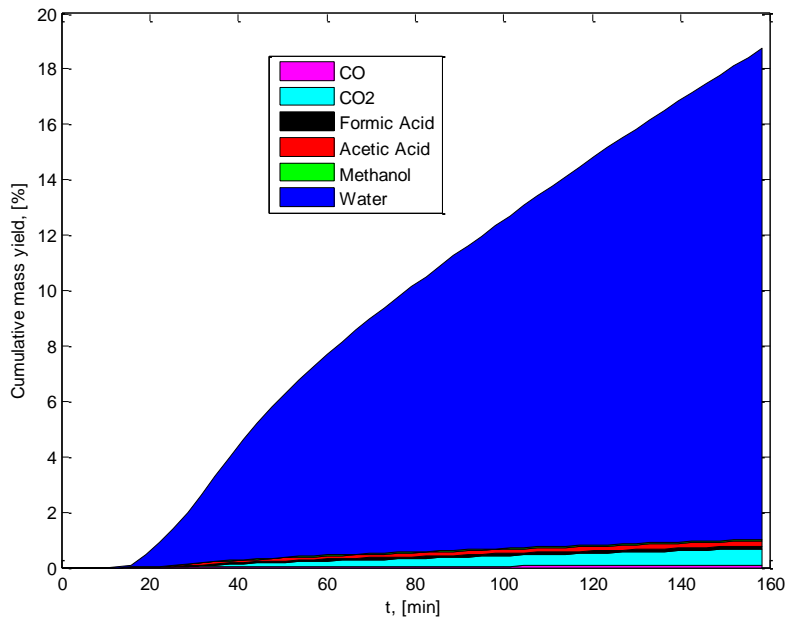
Figure 32- Cumulative Mass Yield of Gases
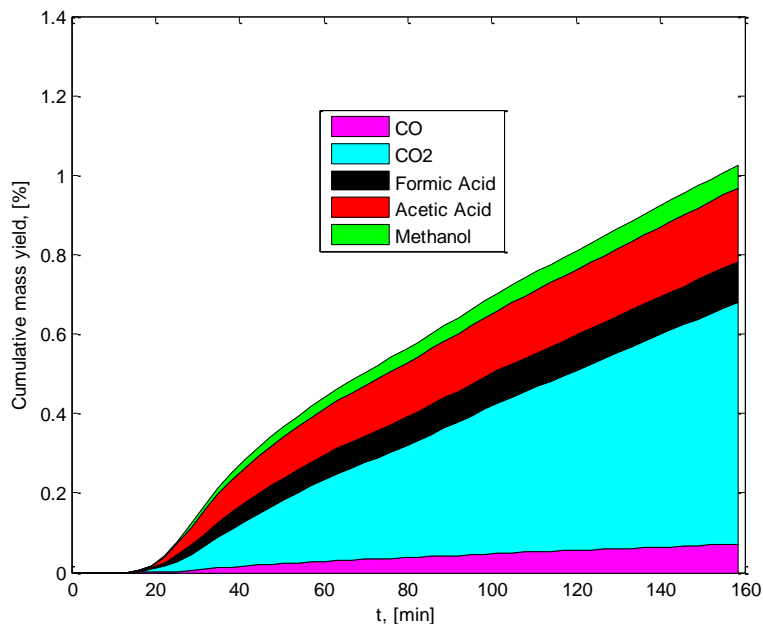
Figure 33 - Cumulative Mass Yield of Gases - Water Excluded

These relative quantities of the gases, excluding water, appear to make logical sense, when compared to results in literature(Bates and Ghoniem 2012). Concurring with Bates' results, carbon dioxide production is much larger than carbon monoxide production. Furthermore, acetic acid, formic acid, and methanol production are on the same order of magnitude, with acetic acid being the larger, even though Bates' model focused on woody biomass. However, the largest difference is in the water production. In Bates' model, no more than 30% of the gas yield is water vapor, much less than the 95% found in this model. In the work by Wannapeera on torrefaction of leucaena, water production reaches around 40% of the mass produced, with other condensables compromising another 40% and carbon dioxide comprising the bulk of the remainder (Wannapeera, Fungtammasan, and Worasuwannarak 2011). Thus, this model appears to overestimate on the water produced. However, it could very well be that, pine needles, not being woody biomass nor a very grassy type of biomass, behave fairly differently in terms of gas production. It is likely that in reality, water does not make up 95% of the gas yield, but it could very well be much higher than for other types of biomass. To prove this, experimental methods of measuring the water produced would be necessary. However, according the results of this model, the produced torrrefaction gas does not appear to be highly useful due to the low amounts of combustible gases.

3.6.C.2   Volume Fraction and Calorific Value

In order to address one of the original research questions of the project, the utility of the torrefaction gas for combustion within the process was assessed. Before so doing, it is important to understand how much of the water produced will stay in the vapor phase. Assuming the torrefaction gas is cooled to 25°C, the amount of water in the gas phases would not exceed the saturation vapor pressure, being 3.2 mbar at this temperature, or a volume fraction of 3.2%. Thus, the bulk of the water produced in the process will not be in the vapor phase, and this liquid will be assumed to be separated from the gas

mixture. In the graph below, the volume fraction of the torrefaction gas per component is presented, assuming only 3% of the mixture is comprised by water. (Note: here it is assumed that the liquid phases will be separated in a condenser or other equipment. However, the design of this equipment within the process is beyond the scope of this project.)
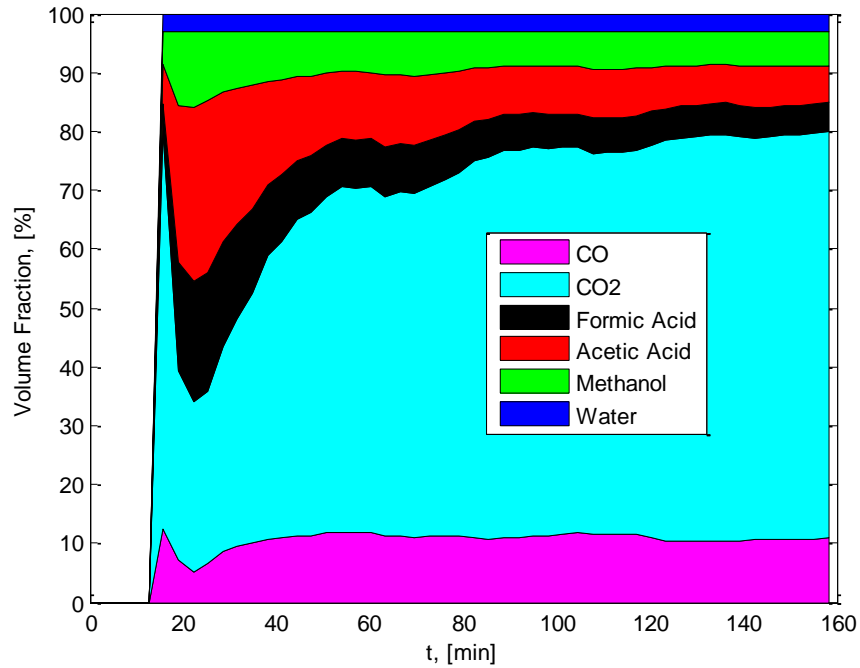
Figure 34 - Torrefaction Gas Composition in Time

Next, the fuel value of the torrefaction gas was calculated, based on the previous assumption of saturated water vapor and the volume fractions above. This value for LHV, again varies in time, and is plotted in the graph below. In Figure 36, the LHV for the dry gas mixture, excluding all water is shown. As the fraction of gas phase water is nominal, there is little difference between the two graphs (8.29 MJ/kg maximum for the wet mixture vs. 8.39 MJ/kg maximum for the dry mixture). Compared to the LHV of methane of 50 MJ/kg, propane at 49.9 MJ/kg, or pure methanol at 22.7 MJ/kg, the maximum value of 8.29 MJ/kg is rather low. Moreover, the average value of the LHV of the torr gas is around 4.5 MJ/kg. Thus, overall, the torrefaction gas is limited in its usefulness for use in heating the biomass and thus reduce the energy input of the whole process.
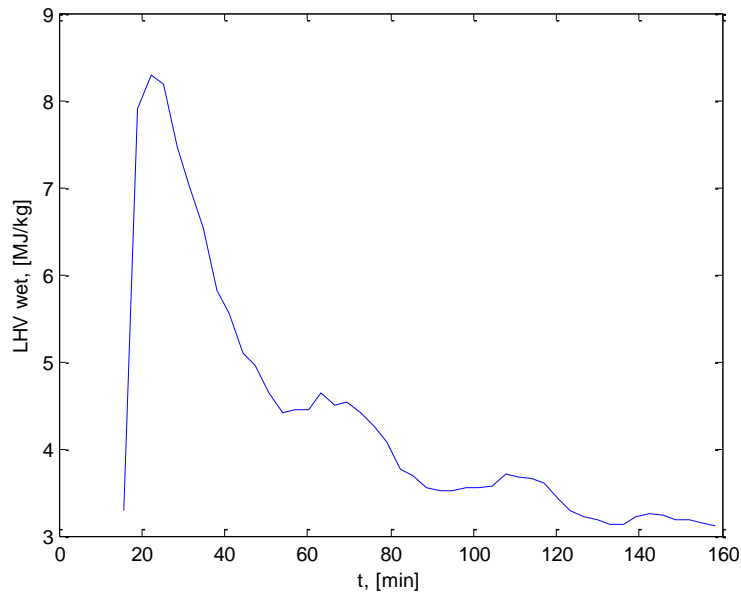
Figure 35 - Torrefaction Gas Calorific Value (Wet)
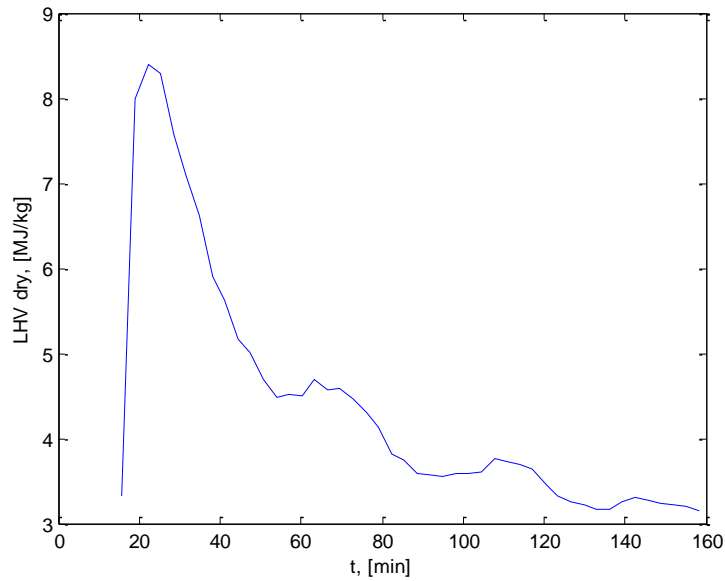
Figure 36 - Torrefaction Gas Calorific Value (Dry)

3.6.C.3   Flammability Limit

Furthermore, to fully address the usefulness of the torrefaction gas, the flammability of the torrefaction gas was assessed, to ascertain whether it would be useful to collect and use it for combustion within the process itself and reduce the energy input of the system. According to Le Chatelier's principle, the lower limit of flammability for a mixture of gases is calculated according to the formula below (Coward and Jones 1952)

$$LFL_{mix} = \frac{1}{\sum \frac{x_i}{LFL_i}}$$

Where LFL is the lower limit of flammability, i denotes a given component of the mixture, and x is the volume fraction of the component in the mixture. In this estimate, it is again important to comment that the water content in the gas phase will not exceed 3%, assuming saturated vapor at 25°C. Although the volume fraction of the component gases varies throughout the process, the flammability was estimated by taking an upper estimate of the concentrations of the flammable gases (CO, formic acid, acetic acid, and methanol) as shown in the table below, with the LFL of each component:

Table 28 - Flammability Limit for Torrefaction Gas

Component	Final Volume Fraction (-)	LFL (%)
CO	0.108	12
Formic Acid	0.049	18
Acetic Acid	0.063	4
Methanol	0.058	6.7
Total	1.000	27.7

Using Le Chatelier's formula, the LFL was found to be 27.7%, implying that a mixture of the torrefaction gas of 28% in air (with air comprising the remaining 72%) will be flammable. Thus, it is flammable under certain conditions. Compared, to methane, however, with an LFL of 4.4%, and propane at 2.1%, the LFL of the torr gas is rather high, and proper combustion of the gas would require special equipment, although the design of this equipment is beyond the scope of this project. Nonetheless, the gas is flammable, after separation from the liquid phase.

3.7   Sensitivity Analysis

The model was also tested for variations in various important parameters, to test how much the results of the model fluctuated. For this, three different aspects were varied: mesh size and time step, porosity and thermal conductivity, and internal heat transfer coefficient.

3.7.A   Mesh Size and Time Step

The model has three relevant dimensions: radial distance r from the center of the reactor, axial distance z from the bottom of the reactor, and time. Thus, each of these varied to see if the results varied as well. Above all, it was assumed that the overall process results, such as mass yield, would not vary much, but rather the precision of the graphs and the reduction of discontinuities in the gas production results.

The standard mesh size used for the model was set to 20 steps for r, 4 steps for z, and 50 steps for t. Only 4 steps were used for z in order to simplify the computations since there was little observed variation in temperature in the z direction. The varied increments are shown in the table below.

Table 29 - Mesh Size/Time Step Variations and Simulation Results

Iteration Number	Radial Divisions	Axial Divisions	Time Divisions	Simulation time (min)	Mass Yield (%)
1	20	4	50	45.1	81.08
2	10	4	50	45.2	79.53
3	20	8	50	90.0	81.07
4	20	4	20	48.0	81.08

As seen in the table, the run time only significantly changed when the axial steps were increased to 8, almost doubling the simulation time. Otherwise, more steps did not increase the run time of the simulation. In addition, the mass yield only changed when the radial divisions were decreased, resulting in larger annular regions. The mass yield thus dropped slightly to 79.53.

When comparing the results of the temperature profiles, it was noticed that a decrease in radial steps to 10 decreased the resolution of the results, as seen in the figures below.
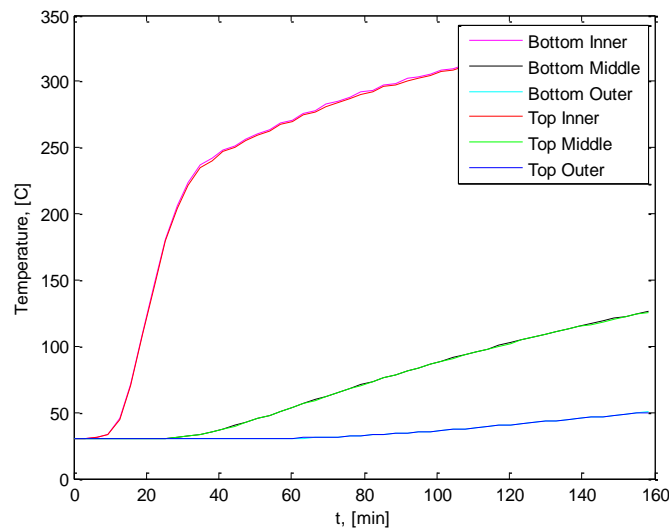
Figure 37 - Temperature results for reduced radial steps (r=10, z=4, t=50)

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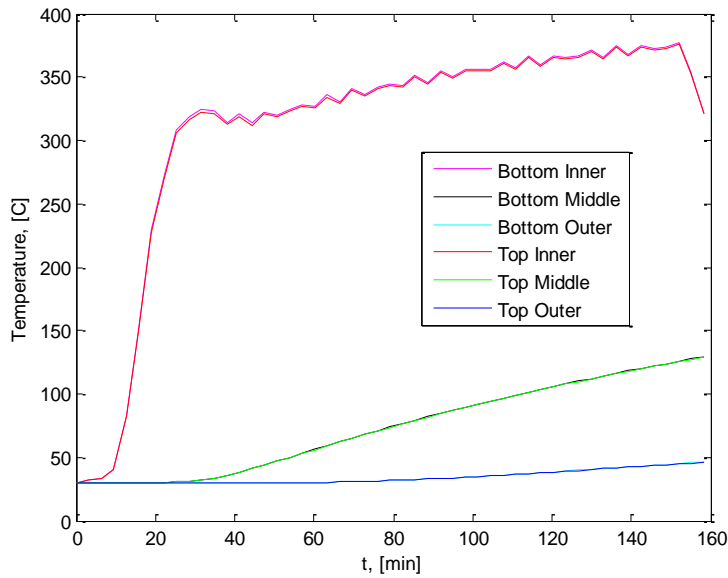
Figure 38 - Temperature results for a standard mesh size (r=20, z=4, t=50)

In addition, there is a large impact on the gas production. The increased size of the sections in the mesh cause a large impact whenever the temperature goes from one kinetics regime to another (for instance when crossing the threshold of 180°C). The larger mass in each section results in larger jumps. Thus, 20 radial steps appear to be an appropriate step size.
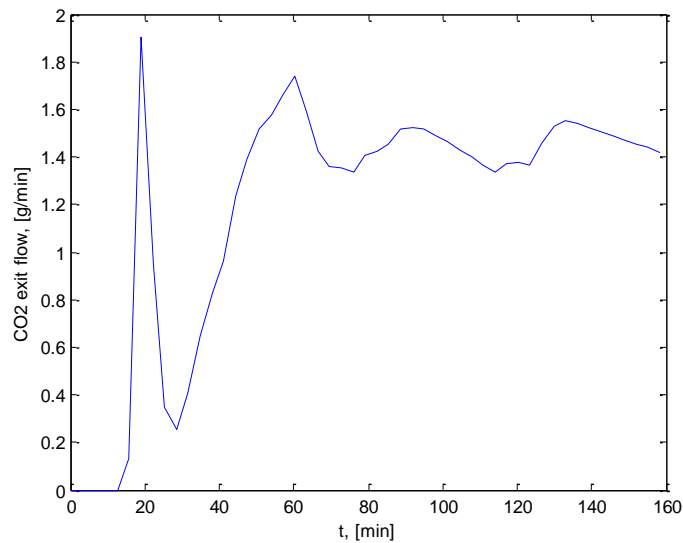
Figure 39 - Gas Production for reduced radial steps (r=10, z=4, t=50)
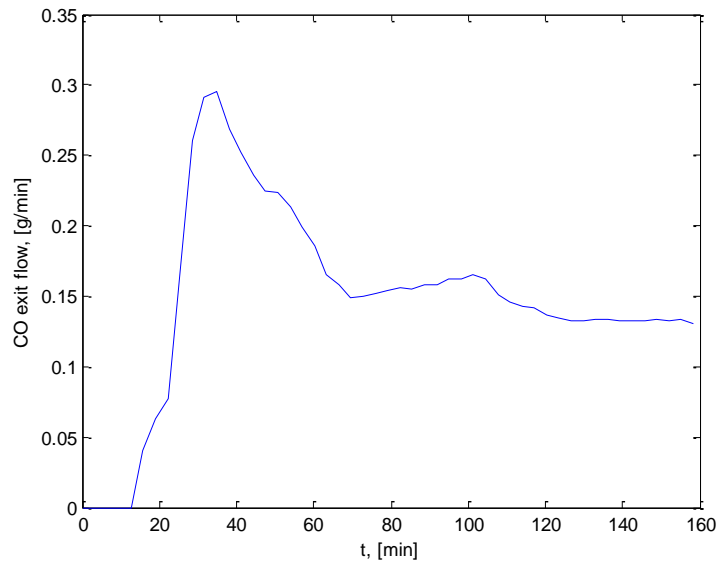
Figure 40 - Gas Production for a standard mesh size (r=20, z=4, t=50)

When checking the impact of increasing the axial step size, no increased resolution was noticed. All graphs of temperature, mass loss, and gas production appeared exactly identical. Thus, the reduction of axial steps to 4 sections is justified.

Lastly, when the time step was reduced to 20, the resolution also dropped. The temperature curves and gas production curves lose much of the detail and precision when the time steps are reduced, as would be expected. Thus, a step size of 50 seems adequate.
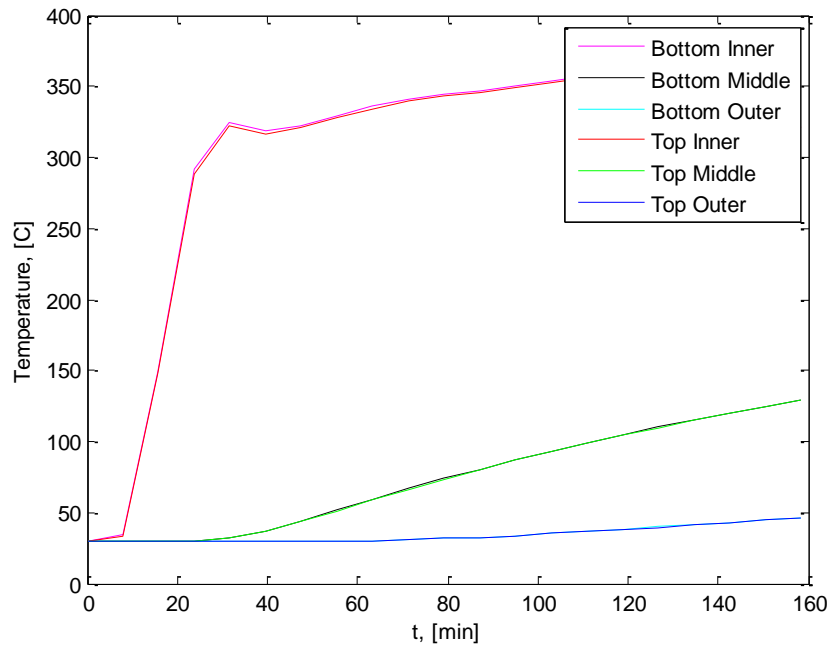
Figure 41 - Temperature Results for a reduced number of time steps (r=20, z=4, t=20)
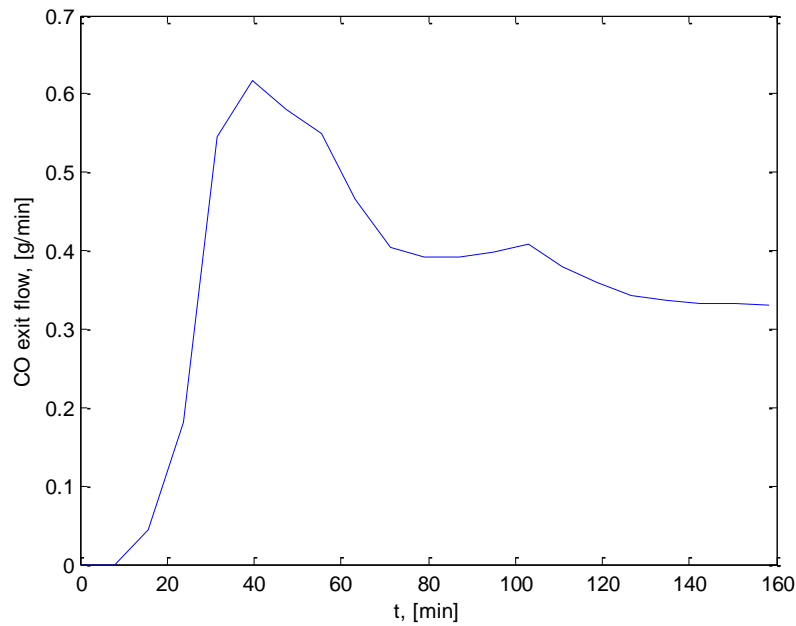
Figure 42 - Gas Production for reduced number of time steps (r=20, z=4, t=20)

3.7.B   Porosity and Thermal Conductivity

As discussed above, the thermal conductivity is directly linked to porosity. With less porosity, and a higher packing density, the bed is filled with more solid mass instead of gas, and the solid mass will allow

for conduction much more than the gas phase. Therefore, the sensitivity of the heat transfer model to porosity was checked, varying according to the table below:

Table 30 - Bed Porosity Variation and Simulation Results

Bed Porosity	rho cp (kJ/m3 K)	k (W/m K)	High Temperature (deg C)	Low Temperature (deg C)	Mass Yield
0.901	101.6	0.0405	403	43	81.08
0.8	205.1	0.0549	367	34	87.31

As seen in the table, reducing the porosity by 10% reduces the maximum temperature in the biomass to 367°C, in addition to dropping the lowest temperature. It is clear that the biomass bed is much more able to transfer heat from the chimney to the ambient air. The reduced temperatures result in a higher mass yield then, rising from 81 to 87%, which is logical due to higher mass loss at higher temperatures. It thus appears that from a change of 10% to the porosity, the model is substantially affected. Therefore, the estimation of this value, and thus the resultant thermal conductivity, are important for accurately modelling the reactor.

3.7.C   Internal Heat Transfer Coefficient

Due to the discussion on the proper selection of the internal heat transfer equation, depending on forced/natural convection, entry flow/fully developed, and turbulent/transition flow, it was justified to verify the sensitivity of the model to this parameter. In using different correlations for the internal Nusselt number in the chimney, for forced flow in a tube, the standard value for the heat transfer coefficient h of 1.728 W/m^2 K could vary up to 1.772 or 1.976, depending on the equation chosen. For the sensitivity analysis, the standard h value was doubled to 3.456. This is shown in the table below.

Table 31 - Chimney Heat Transfer Variation and Simulation Results

hInt (W/m2 K)	High Temperature (deg C)	Low Temperature (deg C)	Mass Yield
1.7281	403	43	81.08
3.4561	431	47	77.50

As seen in the table, the increased value of h increases the temperatures in the bed, particularly near the chimney wall. This clearly will have an impact on the mass yields which resultantly drop to 78%. This impact is thus minimal, considering the value of h has been doubled. Therefore, any minor errors in estimating the heat transfer coefficient will not affect the model significantly.

3.8   Conclusions of the Technical Aspects

In this chapter, several aspects of the reactor development have been presented, namely construction method, design calculations, and a computerized model of the reactor. Regarding construction methods, the most important aspect to consider in the context of Kumaon is that local manufacturing is

not very precise, and thus training would be crucial for the technicians constructing the reactors with moderately precise components, such as doors that need proper fit to seal well. The basic design calculations were useful in giving an accurate perspective on the most important aspects of the design, namely the temperature gradient and the flow in the chimney, Both of these were well predicted in the preliminary calculations. Lastly, a computerized model of the torrefaction reactor has been developed and tested, and subsequently compared with experimental results of tests performed in India. The overall trends of temperatures relatively follow the trends of the experimental data, but it is clear that certain estimates of heat transfer parameters, such as the internal convection coefficient, need to be refined, to produce the temperature gradients observed in the tests in India. The high level of thermal resistance to conduction is shown in both the reactor model and the experimental results with roughly a 300°C radial temperature gradient shown in both. This is likely the largest inhibitor to successful torrefaction in this design of reactor, as a uniform product is very difficult to generate with such high temperature gradients.

In addition, it appears as though other factors are causing axial temperature gradients in the actual reactor, possibly due to internal convection and/or condensation, and these would need to be modelled to improve the accuracy of the simulation. Also, the drying phase of the biomass is very important, and was another of the aspects that greatly inhibited the uniform torrefaction of the biomass. Thus, this also would need to be included in the model.

The mass yields produced by the model seem very reasonable, when compared to the field results, differing by only 8%. As only part of the pine needles dries during the process, the 8% difference seems highly plausible.

Lastly, it appears as though the gas produced by the torrefaction process is of little industrial use, other than for process heat. The combustion utility of the gas is low, showing a low calorific value of around 8 MJ/kg. Furthermore, the flammability limit of the gas is around 27%. Thus, special equipment may be required to combust the gas, which is primarily composed of water (95%) according to the model. Therefore, the torrefaction gas would likely not be used for combustion, but used internally possibly for pre-drying of pine needles before being loaded into the reactors.

Above all, the current design of reactor is inadequate. With a poor fuel product, being far from uniform, and a very high energy input, a new design must be tested and implemented before the business can take off.

4.0   Conclusions

In this project, torrefaction technology has been applied to the context of Kumaon in rural, Himalayan India. From the research conducted, both in literature and in personal field experience, there is a place for a business based in biomass fuel to make a positive impact in this region. A business of this sort can not only be a driving force in enabling a transition to a more healthy local ecology, but can also promote the growth of the local economy in Himalayan India. The business outlined in this report and the accompanying report by Mohan has the capacity to provide meaningful employment to local workers, offering a healthy income in a positive working environment. Efforts have been taken to structure a business culture that respects and equips local workers, and aiding them to adapt to the demands of a modern professional context. Above all, it will provide empowering opportunities to locals to provide for themselves and their families in a meaningful, sustainable way.

4.1   Summary of Methods

For the social research, literature was consulted on culture theory to shape the development of the business structure. The perspectives of experts such as Hofstede and Tromenaars were applied to observations and information gathered via personal experience in Kumaon. Field data was collected primarily by three means: interviews, demonstrations of cookstove/fuel technology, and Generative Design sessions. The cultural theories were then used to analyze the data, and recommendations were for the proper managerial structure of the company. Apart from the managerial structure, the systems of operations, maintenance, and plant overview were outlined based on knowledge of the local context. The costs of these systems were estimated, and, combined with results from Mohan's research, the overall finance balance of the company was ascertained. These profits were estimated for the onset of the company and for the short term-future, outlining plans for growth and expansion. Lastly, the risks of the company were qualitatively assessed, and the environmental impact of the business was estimated.

For the technical research, a reactor was designed, constructed, and tested, in tandem with Mohan. This report has outlined the construction methods for this reactor. In addition, the technical performance of the reactor was modelled, in terms of heat transfer and temperature, solid decomposition and mass yield of the biomass, and production and composition of the torrefaction gas. Various experiments were performed to develop the various aspects of the model, including estimating kinetics coefficients for gas production. This model was then simulated in Matlab, with a brief assessment of sensitivity to certain parameters also performed.

4.2   Summary of Results

The business shows strong promise. A managerial structure has been developed which thoroughly considers the local culture of Kumaon. Specific measures have been proposed to develop a positive, productive working environment and healthy interactions among all persons working there, which will be crucial in sustaining the long term growth of the company. In addition, the operations and maintenance systems rely significantly on local assets, further promoting the longevity of the business. In terms of financial outlook, the business is able to pay off its capital costs within 6 years, and thereafter begin producing reasonable profits, all the while maintaining its social and environmental

goals. Although various risks and obstacles would need to be overcome in the process, such as the influence of new competitors or competition for the biomass source, the strengths of the company will allow for these to be addressed. Lastly, the environmental benefits of the production and use of torrefied fuel from pine needles over LPG for cooking have been demonstrated, having less than one tenth the eco-costs of LPG use.

The technical system, after rigorous testing and exploration, has shown that significant further work is needed before realization of the business. The model has demonstrated that the thermal conductive resistance of the packed bed of pine needles is very large, and it may be very difficult to develop reactor based on conductive heat transfer that torrefies the biomass consistently and uniformly. The model has several limitations, which cause a significant deviation from experimental data, particularly lacking a model for drying or for internal convection within the biomass bed. However, the general trends of temperatures seen in experiments are produced in the model, with similar temperature gradients on the order of 300 degrees Celsius in the radial direction in both. The mass yield results seem very reasonable, taking into consideration that drying is not considered in the model. Lastly, the fuel value of the torrefaction gas was assessed, showing meager potential for use in combustion for the goal of process integration. The produced may likely be better use for heating for drying of the pine needles.

4.3   Outlook

Therefore, the potential shown in the business research then calls for the continued development of the project as a whole, particularly in regards to the technology. Further modelling and testing of various reactor designs would be necessary to come to a suitable design for commercial production, potentially looking in a continuous design reactor. Also, the model itself could be further improved and adapted to different reactor designs in order to estimate the performance of these options. In addition, the business case for other potential markets could be further developed, given more field research with local stakeholders. The possibilities for this project are still wide open, with the next steps in the process already cut out.

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Appendix A

Division of Tasks

Technical Areas of Research

- Shared
  - Literature Survey
    - Torrefaction overview
    - Process parameters
    - Design Options
    - *Individual: Experimental details/ Modelling literature*
  - Reactor Design
    - Vidyut
      - Description of design process and selection
      - Idea sketches of each of the 2 finalist designs
      - CAD Drawings of final 1 design
    - Ryan
      - Basic Calculations (Chimney, Temperature)
      - Construction of final design (BOM)
      - Possible Improvement of design
- Vidyut
  - Testing Results from Torrefaction experiments of local biomass (pine needles)
    - Temperature gradients, graphs
    - Mass and energy yields (Calorimetry)
    - Rough Composition (TGA)
    - Testing of our reactor – temperature gradients, graphs
    - Thin slice experiments for use in the reactor model
    - Gas analysis experiments
- Ryan
  - Modelling
    - Volatiles Production Kinetics Experiments
    - Reactor Model: heat transfer, temperature distribution, solid decomposition, and gas evolution
    - Sensitivity Analysis

Social Areas of Research

- Shared
  - General Research
    - Cultural Theory and Dimensions
    - Social context - larger context of country, state
    - Market Overview (desk research and field research)
  - *Service System Idea Generation*

- - - *Research in possible Business Models/ Service Systems*
    - *Possible designs, general stakeholders*
- Vidyut
  - Stakeholder Analysis and SS Design
    - Research possible stakeholders
    - Analyze motivations, value propositions, contributions
    - Final Business model design – Business Model Canvas
    - Policy research relevant to business model
    - Marketing – reach potential customers, create a market
    - Cultural Implications??
  - Logistics
    - Collection, Distribution, Storage
    - Outline options, detail each option (costs, etc)
    - Evaluation of the options
    - Policy research?
    - Cultural Implications/Considerations
  - Market Analysis
    - Porter's 5 forces
- Ryan
  - Business Structure
    - Research options and Evaluation
    - Policy research
    - Cultural considerations
  - Operations and Maintenance
    - Outline necessary tasks for Torrefaction production
    - Policy research – environmental restrictions
  - Finances
    - Costs, Revenues, etc.
  - Risk Assessment
    - SWOT
  - LCIA
    - Torrefaction production via predefined methods
  - Roadmap
    - Outline a 5 year plan for the business

Appendix B

Sample Interview Questions

Questions for Rajnish

These questions are subdivided into the major categories. If the questions overlap, as many may, just answer once and skip redundant questions. Thanks for the help!

Social Issues

1. In your perspective, what are the largest social/environmental issues in this area? Why are they an issue? What is the impact of the problem?
2. Why did you come to this area? What drew you to work in this area?
3. How has your perspective on development work changed over the years? What do you know now that you wish you knew 20 years ago?
4. Why are you still working in development? Why still in this area? What is your goal? What do you hope to accomplish?
5. What are the social issues that Avani is hoping to address? What is the core focus of Avani?
6. What makes Avani unique in its approach to development work?

Business Structure

1. How is the organization of Avani structure? What are the various divisions, and who is supervising each division?
2. How is the vision and direction of the Avani organization decided on?
3. Where does Avani receive its funding?
4. How do you motivate your employees?
5. What do you look for in employees? Any specific attributes or qualities?
6. To what extent are your employees able to make independent decisions? Do they need constant input and supervision?
7. How does Avani function well as an organization (in terms of execution, communication, growth, etc.)? What are ways that Avani could improve?

Pine Needles Project

1. What does he see is the future of the pine needles/gasification project?
2. What are the biggest challenges that the gasifier project has faced?
3. How crucial is maintenance to the operation of the gasifier? Does it have a larger influence? How so?
4. What challenges do you see in the logistics of pine needle collection and how do you foresee to tackle them?
5. Where would you see a Torrefaction plant fit in the upstream chain between pine needle collection and its utilization in the plant?

6. Where else do you think torrefied pine needles could find applications in this area?
7. What issue do you hope to solve with using pine needle charcoal for cooking? Why is it good?
8. What are the biggest challenges to the charcoal taking off?
9. What is your vision for the charcoal? Where do you see the charcoal finding an appropriate market?
10. Are there other sources of biomass that you think could supply energy locally?

Culture

1. What kind of issues does the caste system present?
2. What kind of problems do gender roles create?
3. Is the society very hierarchical? Clear leaders and clear followers?
4. To what extent do people plan ahead and think of the future (make goals)? Are they willing to take risks?
5. Are locals willing to accept change (in their jobs/daily lives)?
6. Is communication very direct, or more indirect?
7. What are the biggest challenges you have faced in terms of work habits of your employees?

Appendix C

Design Sessions Instructions

Icebreaker activity: have the participants sit in a circle, and, taking turns, each person talk about their name. They each have 2 minutes (or some other allotted time) to share anything about their name: the history behind it, why their parents gave it to them, any stories associated to it, if they like it or not, any nicknames they have, etc.

Collection Session - Chechrith

Activity 1 and Activity 2- Map making (1.5 - 2 hr max)

Materials: White A3 (per person), Image Materials (pencils, erasers, sharpeners, colored pencils, cut out images, glue, scissors)

In this activity, I want each of you to draw a map of the journey of carrying the pine needles. Think about the important points in process of carrying the pine needles to the plant. What do you do while taking the pine needles? What places do you pass by? In the map, include the places on the mountains where you find and collect the pine needles, the path you walk while carrying them, and the place you leave them. Also include other important points, like the road, the houses, the gasifier plant, or any other places that you think are important. Also, draw the path you walk, and mark the places you come to and the things you do along the way, giving them numbers in order (1,2,3, etc). Feel free to draw these points on the map, or the images to represent them. Use any of the materials provided. At the end, we will gather together as a group and all of us will explain the maps we have made. (Note: Emphasize that we know very little about the process, and we want to know even the simple things that they think are obvious)

Now, I want each of you to explain the maps you have made. Explain the points on the map, and most importantly, explain the journey. What are the places you come to? What do you do along the way? Who wants to go first? (Note: for the first activity, ask for volunteers. For later activities, pick out people who haven't spoken much.)

Next, I want you to think your past experiences in collecting pine needles. Take five minutes, and think about the following. What are 1 or 2 bad memories you have about moving pine needles? (Frustrating moments, tiring experiences, lonely moments, etc). Also, what are 1 or 2 good memories you have? (Rewarding moments, fun experiences, etc.) After 5 minutes, we will come together as a group and share these memories. Feel free to act or draw the memories if you want.

Activity 3 (1.5 hr)

Materials: Drawing materials (sheets of poster paper per group, crayons, colored pencils, images of simple tools); Construction Materials (popsicle sticks/twigs, small nails/hammer, string/needle, al foil, tape, plasticine/mud/clay, construction paper, balloons/rubber bands, metal pieces, spoons/forks, ping

pong balls, tacks, newspaper, post its?, pine needles, pebbles, current collection tools, box cutter, plastic bottles, buckets)

For this last activity, we will split into two groups (Note: we can just quickly divide them into two groups after the instructions). We want you to create the ideal or perfect way to take the pine needles to the plant.

Group 1 will design a tool or device to use to take the pine needles. It can be anything, from something you carry in your hand or on your head, or something that two people use together, or something with an engine or battery, or a machine that you operate. Use the materials provided to build a small model of what it would be like. Think creatively!

Group 2 will design a process to take the pine needles. Think of several things: what is a better way for the pine needles to move? how will you move them? what people will be needed in the process? how many people? what tools or machines will be needed? How is this better than the current process?

After designing these, we will come together afterwards and explain our designs to the whole group, explaining what it is, how it works, and how it is better than the current system.

Design Session Instructions

Daily Life and Cooking Session - Murari

Activity 1 - Illustrative Timeline (1/2 hr)

Materials: Image Materials: (3 sheets of A4 per person, pencils, erasers, colored pencils, cut out images)

In this activity, I want you to make a timeline of the things you do in a day in January, starting with waking up, and ending with going to sleep. Put down whatever activities you think are important, and illustrate them. You can draw them, or use the images to represent them. At the end, you will explain your timelines. However, I want you to make three timelines - one for a normal day in January, but also one for a day in May, and one for a day in August. Thus, in total you will make three timelines. (If there are things that they will put on all three timelines, they don't have to illustrate these on all three timelines, but can just illustrate them on one timeline (i.e. January), but on the other they should at least make a note of the activity, if not illustrate it)

Now, we are going to explain the timelines we have made. Talk about the following: what is the activity? how do you do it? why do you do it? how long does it take?

Activity 2 - Collaging Cooking (1 hr)

Materials: Image Materials: (1 sheet of A3 per person, pencils, erasers, colored pencils, cut out images)

Next, we are going to make a collage, or a collection of pictures, to represent our experiences in cooking. Take a few minutes to think of 3-5 memorable moments you have experienced in cooking in your life. These can be when you were a child, a teenager, a student, or even yesterday. Think of at least 1 good memory (such as the first time you cooked something or a special meal that you helped

prepare), and at least 1 bad memory (maybe a frustrating day where the meal did not work out right). Then, after thinking of these, illustrate these on the paper, either drawing them or using the images provided. Afterwards, we will discuss them.

Now, let's get together and discuss our memories. Each person choose 1 good memory and 1 bad memory, and we will share those to the group. Talk about the following: What happened? How was cooking involved? How did you feel? Why was it good or bad?

Activity 3 - Kitchen Design Game (1.5 hr)

Materials: Image Materials: (1 poster paper per group (3 total), pencils, erasers, colored pencils, cut out images)

For the last activity, we are going to have a design game. You will be divided into 3 teams. (Quickly group them into teams after the instructions). Each team will have the task of designing the ideal dream kitchen. Each team will be given a "credit card" with a limit of 50,000 Rupees, and you cannot use more money than that. There will also be a store with different things to purchase for your kitchen. First, take a look at the options in the store, then discuss with your team the design of the kitchen. Then, draw the kitchen on the poster, arranging things how you want within the kitchen, and choosing which items you want to place in the kitchen. Illustrate it as you want, and place the images of the purchased items within in. At the end, you will explain the kitchen.

Now, let's explain the kitchens. Talk about the following things: What items are in your kitchen? Why did you choose those items? How did you arrange things in the kitchen? Why did you arrange them that way? What are the most important things for your team in the kitchen?

Kitchen Item	Cost (Rs)
Cooking Appliances	
Gas Stove	3500
Charcoal Stove	2500
3 Stone Stove	1000
Kerosene Stove	3000
Electric Stove	5000
Wood oven	3000
Electric oven - large	6000
Electric oven - small	2500

Gas oven	5000
Charcoal oven	3500
Biogas based cooking system (stove and digester)	3000
Microwave oven	8500
Electric Toaster/Grill	1500

Cooking Utensils

Pressure cooker	200
Kadhai	100
Tawa	100
Electric rice cooker	400
Pateela	150
Microwave containers	500
Frying pan	300

Eating Utensils

Ceramic plates+ bowls + cups	500
Steel plates+ bowls +cups	200
Plastic plates+ bowls +cups	250
Glass plates+ bowls +cups	350
Clay plates+ bowls +cups	150
Steel spoons and forks	75
Plastic spoons and forks	60

Decoration/Utility

Tiles for decoration	800
Chimney/Hood	500
Exhaust fan (hood not included)	800
Refrigerator	1500
Manual grinder (mortar and pestle)	75
Electric Mixer/Blender	800

Storage	
Modular Kitchen Drawers	1000
Basic Wood Cabinets	800
Simple Racks for keeping crockery and cutlery	500
Simple Rack for keeping freshly washed vessels	500
Simple Racks for spices , dal, rice, wheat and vegetables	500
Drums for dry storage	200

Design Session Instructions

Business Structure Session (Chankana, Bana, Avani)

Introduction:

These activities are about the people you interact with often, in daily life and at work, either now or in the past. To be clear, this information is just for us to understand preferences and norms, and no details of what you say will be reported back to Avani or our professors. This is just for our own understanding. We are doing this for our own research, to understand how people interact in a business environment.

Also, have fun with these activities. Don't take them super seriously, but just express what you think. They may seem kind of childish, but it's good to have fun like a kid at times. So enjoy!

Activity 1 - Daily Life/Coworker Collage (1 hr)

Materials: Image Materials: (2 sheets of A4 per person, pencils, erasers, colored pencils, cut out images), Crayons as well

To start, I want you to make two collages of the people you interact with in your lives. I want one collage to be focused on the people you interact with at work, whether frequently or not, and one focused on the people outside of work you talk to, especially on a regular basis. Place yourself at the center of the paper, and show the other people around you. You can draw them, or use the pictures given to represent them. Also, draw a line between the image of yourself and each person, and describe your relationship on the paper with them in 5 words or less. As you do the activity, think about the following questions: Who is the person? How do you know them? How do you interact with them (what do you talk about, where do you talk with them)? What is your relationship like with them? Are they the same gender as you? Are they the same caste as you? After making the collages, we will discuss them.

Now, let's discuss the collages. First, let's discuss the non coworkers collage. Pick two people in this collage and talk about the following: Who is the person? How do you know them? How do you interact with them (what do you talk about, where do you talk with them)? What is your relationship like with them? Are they the same gender as you? Are they the same caste as you?

Now, let's discuss the coworker collage, again choosing two people: Who is the person? How do you know them? How do you interact with them (what do you talk about, where do you talk with them)? What is your relationship like with them? Are they the same gender as you? Are they the same caste as you?

Activity 2 - Experience Discussion (15 min)

As we are thinking about work experience, I want to talk about past work experiences. Now, in this time, I don't want you to use specific names of people, and I don't want you to think only about your current job, but also other working experiences you have had. If you haven't had another job, that's fine too, but we don't need to know who exactly you are talking about.

So take a few minutes and think about a 2-3 memories you have had about interacting with a supervisor, coworker, or subordinate at your work. Include both good memories (such as an encouragement given, acknowledgment of hard work, etc) and bad memories (a frustrating situation, an ignorant supervisor, etc). Afterwards we will discuss them.

Now, I want to discuss your experiences. For each experience, think about the following: What happened? What did each person say? How did you treat each other? How did you feel during and after the interaction?

Activity 3 - Business Scenarios (50 min)

Materials: Image Materials: (1 sheet of poster paper per session, pencils, erasers, colored pencils, cut out images), Crayons as well

In the last activity, I want you to work as a group to resolve the following scenarios. We have written these imaginary situations that you may encounter in the workplace, and we want you to discuss what is the best way to solve the situation. After 10 minutes, you will present your proposed solution, and then we will move onto the next one. There will be 4-5 scenarios in all. Feel free to act out your proposed solution, illustrate is on the chart paper, or use bullet points to explain it. When presenting, discuss why you think the proposed solution is the best.

Scenarios: see attached Scenarios document

Appendix D

Sample Design Session Analysis

Chankana Design Session – at the SHG meeting (Daily Life Collages)

April 17, 2015

- Observations
    - Avani women are much more proactive, stone-willed, and especially confident with strangers and in group settings
        - Probably due to professional training, guidance and experience
        - Much more so than the village women
        - Outgoing as well
    - Time perspective of women in the village is very lax, no urgency to start/finish at a certain time for public gatherings. Little sense of time
        - Likely much more structure with daily activities (grass cutting, cooking, etc) and individual activities
        - They don't work in a very specific, time-bound way, but have a general sense of time based on the cycle of the day, not on the clock
        - Geeta and Santoshi are much more punctual
    - Neutral response from the women when asked/pushed to do the activity, not reluctant or sceptical but also not excited – just accepting and compliant
        - Maybe previous activities have been done with them by volunteers
        - Initially slow to engage, not necessarily reluctant, but okay once Santoshi pushed them. Maybe they thought it was an obligation for the SHG meeting.
    - Need for motivation, push, and encouragement to start the activity
        - Need for clear instructions but no need for repeated instruction
        - Collaborative working
    - Education level of older women: can't read or write
        - Older women were sitting idle while the younger women worked on the collage
    - Older women were sitting idle – this may indicate a low value of time for them, that it wasn't a big deal that they were wasting time.
        - Conversely, maybe for them it was not a waste of time, but they were just valuing/enjoying the chance to gather with other women, which they do not do frequently?
    - Diffuse culture, multi tasking, many interruptions, various people talking. Simultaneously, the SHG was happening while the participants were working on the collage.
    - After beginning, they were very focused on finishing the task
        - Overall they worked collectively, but they worked independently at times. Most of the time they were discussing and taking suggestions from others
        - Very accepting of Santoshi's help and encouragement

- o They do hard work, not fun tasks, with little thanks or appreciation or recognition
    - ▪ They seem to accept tough working conditions without complaint which a manager or owner could take advantage of
  - o At home, the women are more active decision makers than in strange contexts, especially more able than men to take initiative in the home.
  - o Different flow to the session than in Chachret – they followed the instructions and finished the task as directed, and did not leave early.
    - ▪ Not so dedicated to task in Chachret.
    - ▪ The women were less literate there and didn't know how to read and write.
    - ▪ They are likely more educated than the women in Chachret
    - ▪ Santoshi strongly led the activity, inciting compliance and obedience
    - ▪ Are the villagers in Chankana of a higher caste than Chachret? At least we are sure that the village is more prosperous than Chachret, as seen by the living conditions
    - ▪ Chachret, like Murari is also away from Berinag, and thus there may be less economic opportunities available there.
  - o In a new context/new task, they are not so proactive or independent, as opposed to house work. Thus they would need training in a new job situation.
- Activity Results – Daily Schedule
  - o January:
    - ▪ In general they have more time in January – go shopping and to the market, weaving, dancing for holidays, collecting wood, breaking stones, care for the cattle and give fodder, Avani dye material collection and earn more money in this month because of this, do weaving, lots of weddings, plant banana trees- have more time, dehusk rice and grind wheat
  - o May
    - ▪ In general less time in May: Harvest dal, barley ,wheat, mustard, peas, planting rice, maddua and various crops, weddings, cutting leaves, work the whole day in the fields, buy clothes sometimes, cut grass, clean the house for a special festival in May, plant corn and weed, go to the markets to buy clothes, sow daal, dance in the weddings, cut leaves, and fodder for animals
  - o August – harvest rice, maddua, corn, soyabean, bhatt, marijuana, cut grass (most grass is cut during this time and hung on wooden poles, after monsoons), collect pine needles for cow bed, plough fields, school holiday/festivals, pay off debts
- Summary
  - o Difficult for women to find the time in May for collecting pine needles and working a plant if we want to encourage traditional lifestyle/activities. We would need to be more flexible/creative if we want to include them.
  - o May not be able to work so much in May. Might have to employ men as Avani tried to do by hiring labour.
  - o The money they earn can help them pay for their debts.

Appendix E

Operational Costs in Detail

Here the operational costs, and the assumptions made, are shown in the tables below. All of the calculations a made on a per reactor basis here. In the last table, this is converted to per cubic meter of cumulative reactor volume, and this is converted to total Operational Costs by multiplying by 21 cubic meters.

Here the labor costs for the Year Round Labor (working in the office, briquetting, etc.) is calculated, according to assumptions discussed in chapter 2.

Business Weeks/Year	Business Hours/Week	Working Hours (hr/yr)	Worker Wage (Rs/hr)	Number of Workers	Year Round Labor Costs (Rs/yr)
48	50	2400	40	0.0236	2264.150943

Here the labor costs for seasonal labor (operators of the reactors, not collectors) is estimated.

Working Hours (hr/yr)	Worker Wage (Rs/hr)	Number of Workers	High Season Labor Costs (Rs/yr)
1008	35	0.133	4692.24

Here the electricity costs of the motor for the cable car are estimate, assuming an electricity cost of 4 Rs/kWh, as found in the Kumaon area. Note, these costs will only exist after retrofitting the cable car in year 6.

Rating of motor (kW)	Number of times it has to run (runs/day)	Number of running hours (h)	Energy usage (kWh)	Electricity Cost (Rs/year)
52.5	10	4	210	183.2176836

Next, the electricity costs for heating are calculated. These are taken from the assumptions shown in the table below. The pine needles will be heating from 20 to 250°C, and have a moisture content of 25%. Thus, the specific heat from heating and the latent heat from drying are taken into account. Resulting in 7.2 MJ per reactor per batch.

Energy Input (MJ)	Energy Input (kWh)	Energy Cost (Rs/batch)	Heating Energy Cost (Rs/yr)	Max Power Needed (kW)
7.175	1.994692353	7.978769411	2297.88559	1.99

The assumptions for packing, size, and thermal values are shown below, taken from the reactor model and literature.

Reactor Volume (m3)	Mass Input (kg)	Packing Density (kg/m3)	Reactor Output (kg)
0.064	6.1	95.9	3.948225

Rho Cp (kJ/m3 K)	Energy Input (kJ)	Energy Input (MJ)	
173.1	7175.152348	7.175	

Next the maintenance costs for various parts of the plant are esimated, assuming 7.5% of the capital cost is spent per annum on maintenance.

Plant Maintenance Costs (Rs/yr)	Briquetting Maintenance (Rs/yr/reactor)	Vehicle Maintenance (Rs/yr/reactor)	Cable Car Maintenance (Rs/yr/reactor)	Total Maintenance Costs (Rs/yr)
580.2094912	65.43488698	113.6022343	954.2587685	1599.903147

Next, the electricity costs for the briquetter are calculated, according to specifications from the manufacturer, discussed in Chapter 2.

Electricity Costs (Rs/kg)	Binder Costs (Rs/yr)	Briquetting Cost (Rs/yr)
0.27	175.68	390.39

The assumptions for the briquetting machine are shown below.

Briquetting Machine				
USD	INR	Output (kg/hr)	Power (kW)	Workers
4500	288000	450	30	2

Lastly, the electricity costs for the electricity consumed by the computers was added.

Power Consumption (W)	Total Energy Consumption (kWh/yr)	Computer Electricity Cost (Rs/yr)
10	10.08	40.32

The total operational costs, total, per cubic meter, and for the entire plant, are shown below.

Total Operational Costs (Rs/yr)	Total Operational Costs Per m3 (Rs/m3 yr)	Total Operational Costs for 21 m3 (Rs/yr)
11581.71	182052.9903	3823112.795

Appendix F

Capital Costs in Detail

The capital costs are summarized in the tables below. The methodology of calculation and estimation in discussed in Chapter 2. First, the costs dependent on the number of reactors were totaled, and normalized per cubic meter of reactor.

Component	Cost(Rs/Cu.m)
Land Cost	286.28
Materials (sheet metal, etc)	4180.00
Labor	5220.00
Heating Tracer	45902.64
Insulation	135.50
Computer	392.98
Storage Shed	19028.43
Reactor Shed	46458.40

The assumptions for the heating tape are shown below.

Heating Tape per Reactor					
Cost (Rs/m)	Max Temp (C)	Power (40 W/m)	Estimate Length (m)	Power Total (kW)	Total Cost (Rs)
310	290	40	9.42	0.3768	2920.2

The assumptions for the insulation are shown below.

Insulation				
Cost (USD/m2)	Cost (Rs/m2)	Thickness	Total Area (m2)	Total Cost (Rs)
0.5	31.95	10 Cm	0.8482300165	135.5047451

The assumptions for the land calculation are shown below.

Land Calculation				
Per Reactor (m2/reactor)	Number of Reactors	Land Area Needed (m2)	Cost	Cost per m3 (Rs/m3)
3	330	1981	2970892.271	286.2776306

The assumptions for the storage shed are shown below.

Density of storage (kg/m2)	Torrefied PN at the end of season (kg)	Space occupied by Torrefied PN (m2; ft2	Specific Cost of	Total cost of shed pace (Rs)	Total cost of shed space per reactor

		below)	Warehouse Storage (Rs/m2)		(Rs/reactor)
1822.600243	383318.6918	210.3141889	11009.72053	399596.959	1210.536197

The assumptions for the reactor shed are shown below.

Reactor Shed Cost					
Per Reactor (m2/reactor)	Number of reactors	Shed area needed, m2	Cost of shed construction (Rs/m2)	Cost(Rs)	Cost (Rs/m3)
2	330	660.1982825	1900	1254376.737	46458.39765

Additional costs, calculated specifically for 21 cubic meters, were calculated. These were not normalized per reactor.

Briquetter	288000
Bolero	500000
Cable Car	2100000
Tarpualin cost	54540

The assumptions for the briquetting machine are shown below.

Briquetting Machine

USD	INR	Output (kg/hr)	Power (kW)	Workers
4500	288000	450	30	2

The assumptions for the cable car are shown below.

Cable Car				
Length of ropeway (m)	Max Load (kg)	Cable cost (Rs)	Electric Work (Rs)	Total Cost (Rs)
150	150	200000	150000	600000

The financial assumption for annuitizing costs are shown below. Note that the annuity factor for a 10 year life was only used for building costs, due to tax code regulations, as discussed in Chapter 2.

Project Life(years)	6
Rate of interest(%)	10
Anunuity factor	4.355260699
Anunuit factor (10 yr)	6.144567106

The total capital costs are summarized in the table below, with annuitized costs per m^3 and for 21 m^3.

Total Capital Costs (Rs)	Annutized Capital Costs (Rs/yr/m3)	Annuitized Capital Costs (Rs/yr)
43083990.33	699171.5495	1170024.52

Appendix G

Fuel Conversion Method

An estimate was needed of how much torrefaction fuel would be required to replace a given amount of LPG, thus a ratio of mass of torr coal per mass of LPG. Ideally, this could be done by testing torr coal and comparing it to LPG. However, this was not possible, due to not having torr coal there. Thus, comparisons were made between LPG, wood, and charcoal. Here, just the comparisons between LPG and wood are shown, as charcoal comparisons were not used in the end.

First, literature was found comparing different sorts of fuels and cookstoves, applying standardized tests to compare them. In one paper(Visser 2005), a water boiling test was used to compare wood, charcoal, kerosene, and butane on various stoves. The amount of fuel consumed was given, and this was used to get fuel conversion ratios. See the table below.

Consumption in Standard Water Test (kg fuel)				
Wood (3-stone stove)	Wood (Bottom Air Fan Stove)			
1.9	0.609			
Charcoal Stove 1	Charcoal Stove 2	Ratio (kg fuel/kg wood)	Ratio (kg fuel/kg wood)	
0.8	0.55	0.3552631579	1.108374384	
Kerosene Stove 1	Kerosene Stove 2	Ratio (kg fuel/kg wood)		
2.9	4.2	1.868421053		
Butane Stove 1	Butane Stove 2	Ratio (kg fuel/kg wood)	Ratio (kg fuel/kg wood)	
0.4	0.25	0.1710526316	0.5336617406	
			For the business case (using Bottom Air Stove for wood)	
kg Charcoal/kg LPG	kg Charcoal/kg Wood	kg Wood/kg LPG	kg Charcoal/kg Wood	kg Wood/kg LPG
2.08	0.36	5.846153846	1.11	1.873846154

Similarly, another paper made comparisons with a standard water test, and the same method was applied to achieve fuel ratios (MacCarty, Still, and Ogle 2010).

Consumption in Standard Water Test (kg fuel)			
Wood (3 stone)	Wood (Mud/sawdust)	Average	
1.253	0.754	1.0035	

Mali Charcoal		Charcoal Jiko	Charcoal w/ skirt	Ratio (kg fuel/kg wood)
	0.655	0.613	0.657	0.5121042831
Propane (LPG)				Ratio (kg fuel/kg wood)
	0.14			0.1117318436
Kerosene (unpressurized)				Ratio (kg fuel/kg wood)
	0.223			0.1779728651
kg Charcoal/kg LPG		kg Charcoal/kg Wood	kg Wood/kg LPG	
	4.58	0.51	8.95	

Similarly, a study on First Energy Oorja stoves gave similar data:

First Energy Oorja Study	
kg Pellets/meal	kg/month
1	60
kg LPG/meal	kg/month
0.5	30
kg Wood/meal	kg/month
5	300

Giving a ratio of 10 kg wood/kg LPG.

Interviews with locals, and measuring amounts of wood, gave an indication on wood usage per meal. See table below.

Fuel Use from Interviews (kg wood/meal)	
5	Murari Interview 1 - inferred
6.5	Murari Interview 2
4	Chachreth Demo

Thus, around 5 kg of wood per meal was assumed.

Lastly, the authors performed their own tests at Avani, cooking a standard quantity of rice (approx 1 kg) in the same pot, on charcoal, wood, and LPG. The results and fuel ratios are given below:

Wood			
Wood Count (kg)	Rice (kg)	Time (min)	Fuel-Food Ratio (kg fuel/kg food)
1.5	1.2	61	1.25

Charcoal			
Charcoal (kg)	Rice (kg)	Time (min)	Fuel-Food Ratio (kg fuel/kg food)
0.625	1.125	30 min	0.56
LPG			
Gas Count (kg)	Rice (kg)	Time (min)	Fuel-Food Ratio (kg fuel/kg food)
0.3	1.2	27	0.25
kg Charcoal/kg LPG	kg Charcoal/kg Wood	kg Wood/kg LPG	
2.22	0.44	5	

Thus, kg Wood per kg LPG ratios ranged from 1.87 to 8.95. 10 kg/kg was also found, but this value was not used for further calculations, as it appeared to be based on rough estimates, whereas the research behind the ratio 8.95 kg/kg was much more thorough.

Wood was chosen instead of charcoal to further convert to torr coal, as in interviews with experts from Philips, torr coal appears to burn more like raw biomass than charcoal, having a higher oxygen and hydrogen content. Thus, LPG usage was first converted into equivalent wood usage, and then into equivalent torr coal usage.

Wood was converted into torr coal by mere ratio of calorific value. In the tests done by Mohan, the torrefied pine needles have a calorific value of 21.1 MJ/kg. In literature, pine wood is reported to have a calorific value of 14.7 MJ/kg (Hassan, Steele, and Ingram 2009). Thus, in terms of energy equivalence, 0.70 kg of torr coal equates to 1 kg of wood. This ratio, in combination with the LPG/wood ratios above, were used to estimate a range of equivalent torr coal consumption, given a defined LPG consumption (such as a dhaba owner gives in an interview).

Appendix H

Environmental Analysis Method

The eco-cost calculations and assumptions for the various components are shown in the tables below. First, the assumptions and calculations for the reactors are shown.

list of materials				eco-costs data		result	
Reactor				copy paste from 'Ecocosts 2007 LCA data on products and services V2-2, 2010'			
type	qty per reactor	weight (kg)	process step	LCI name in Idemat, Ecoinvent or CES	eco-costs (€)	eco-costs (€)	
Mild Steel Sheets (4 m2)	4 m2*7.2 kg/2 m2 sheet	14.4	production	Idemat2015 Steel beams, pipes, sheet (from market mix 4	0.63	9.096	
	4m	4	gas welding	Idemat2015 welding steel, gas 0.0536 kg electrode per m	0.10	0.414	
Reinforcing Bar	2.5 m*.395 kg/m	0.9875	production	Idemat2015 Steel beams, pipes, sheet (from market mix 4	0.63	0.624	
Steel Mesh	0.25 m2*2.27kg/m3	0.5675	production	Idemat2015 Steel (21% sec = market mix average)	0.68	0.385	
Stainless Steel (Heating Tracer)	0 m * 1 cm dia*8000 kg/m	31.42	production	Idemat2015 Stainless Steel (secondary), average, estir	0.29	9.191	
	51 m * 1 cm dia*8000 kg/m	31.42	forming	Idemat2015 Deep drawing steel	0.10	2.987	
Teflon PTFE (Heating Tracer)	0 m*2mm*3cm*2200 kg/m	6.6	production	Idemat2015 PTFE (Teflon, Polytetrafluoroethylene), estim	1.79	11.818	
Fiberglas Insulation	0.85 m2 * .1m*50 kg/m3	4.25	production	Idemat2015 glass wool	0.47	2.005	
Angle Iron	4 m*1.93 kg/m	7.72	production	Idemat2015 Steel beams, pipes, sheet (from market mix 4	0.63	4.876	
	2m	2	gas welding	Idemat2015 welding steel, gas 0.0536 kg electrode per m	0.10	0.207	
Computer	1 per 10 reactors	0.1	production	Computer, laptop {GLO}| market for	Alloc Rec, S	56.00	5.600	
plus other small components, such as the hinges and latches							
TRANSPORT							
from-to		kg	km				
Shanhai-R'dam	sum of masses	65.94	375	Idemat2015 Truck+trailer 24 tons net (min weight/volume	0.0288	0.713	
plus other transport legs							
USE PHASE							
type		weight (kg)	energy (kWh)				
electricity		1.803 kWh/batch*		Electricity, low voltage {IN}| electricity voltage transforma	0.1000	0.000	
plus materials which are used in the use phase (in this case wheat, water							
END of LIFE							
type	weight (kg)	weight (kg)	process step				
Fiberglass and Teflon	425kg+6.6kg	10.85	municipal wa	Idemat2015 landfill (inert waste, not biodegradable)	0.12	1.278	
Steel	20%*(14.4+.99+.57+7.7)kg	4.732	landfill	Idemat2015 landfill (inert waste, not biodegradable)	0.12	0.557	
Steel	80%*(14.4+.99+.57+7.7)kg	13.7228	scrap	Idemat2015 Scrap (iron)	-0.01	-0.121	
Stainless Steel	20% 31.4 kg	6.28	landfill	Idemat2015 landfill (inert waste, not biodegradable)	0.12	0.740	
Stainless Steel	80% 31.4 kg	25.92	scrap	Idemat2015 Scrap (Stainless st)	-0.02	-0.513	
plus the materials of the use phase							
				Total eco-costs (€)		49.858	
				Specific eco-costs (€/kg fuel)		0.004380425	

Next, the eco cost calculations for the reactor shed are shown

list of materials				eco-costs data		result
Reactor Shed				copy paste from 'Ecocosts 2007 LCA data on products and services V2-2, 2010'		
type	*weight in paper(kg)*	*weight (kg)*	*process step*	*LCI name in Idemat, Ecoinvent or CES*	*eco-costs (€)*	*eco-costs (€)*
Columns	160 m * 202 kg/m	32320	production	Idemat2014 Steel beams, pipes, sheet (from market mix 449	0.64	20794.33507
Beams	160 m * 67 kg/m	10720	production	Idemat2014 Steel beams, pipes, sheet (from market mix 449	0.64	6897.130938
Plain Cement Concrete	n depth * 0.5*0.5 *20 footers*2400 kg	18000	production	Idemat2014 Concrete	0.03	611.057844
GS Sheet	1040 m2* 0.3 kg/m2*1.1 for overlap	343.2	production	Idemat2014 Steel beams, pipes, sheet (from market mix 449	0.64	220.8111323
Fiberglass insulation	1040 m2*0.1 m*50 kg/m3	5200	production	Idemat2014 glass wool	0.75	3879.080088
Bracing	4*160m*2.62 kg/m	1676.8	production	Idemat2014 Steel beams, pipes, sheet (from market mix 449	0.64	1078.834809
TRANSPORT						
from-to		*kg*	*km*			
Delhi to Almora	addition of all mass	68260	375	Idemat2015 Truck+trailer 24 tons net (min weight/volume ra	0.0288	738.1076753
plus other transport legs						
END of LIFE						
type		*value (EUR)*	*process step*			
Office Building		33481.24988	Renovation	30% of value after 40 yrs	-0.300	-10044.37496
plus the materials of the use phase						
					Total eco-costs (€)	24174.98259
					Specific eco-costs	0.001252342

The dimensions of the shed were assumed from http://www.alibaba.com/product-detail/low-cost-industrial-shed-designs-. The Steel beam specifications were taken from http://www.steelexpress.co.uk/structuralsteel/universal-beams.html. The assumptions for concrete were taken from http://hypertextbook.com/facts/1999/KatrinaJones.shtml. The assumptions for galvanized steel sheets were taken from http://www.indiamart.com/niganiasteels/galvanized-steelsheets-coils.html. The bracing for the structure was assumed from

http://www.orrconsteel.com.au/australian-steel-products/building-products/roofing/~/media/Orrcon/Pdf%20Files/Product%20Tables/Orrcon%20Steel%20Purlins%20%20Girts.ashx.

Next, the storage shed eco costs were calculated, using the same assumptions as the reactor shed.

list of materials				eco-costs data		result
Storage Shed				copy paste from 'Ecocosts 2007 LCA data on products and services V2-2, 2010'		
type	*weight in paper(kg)*	*weight (kg)*	*process step*	*LCI name in Idemat, Ecoinvent or CES*	*eco-costs (€)*	*eco-costs (€)*
Columns	64 m * 202 kg/m	12928	production	Idemat2014 Steel beams, pipes, sheet (fror	0.64	8317.734026
Beams	100 m * 67 kg/m	6700	production	Idemat2014 Steel beams, pipes, sheet (fror	0.64	4310.706836
Plain Cement Concrete	pth * 0.5*0.5 *8 footers*240	7200	production	Idemat2014 Concrete	0.03	244.4231376
GS Sheet	0 m2* 0.3 kg/m2*1.1 for overl	184.8	production	Idemat2014 Steel beams, pipes, sheet (fror	0.64	118.898302
Fiberglass insulation	560 m2*0.1 m*50 kg/m3	2800	production	Idemat2014 glass wool	0.75	2088.735432
Bracing	4*100m*2.62 kg/m	1048	production	Idemat2014 Steel beams, pipes, sheet (fror	0.64	674.2717558
TRANSPORT						
from-to		kg	km			
Delhi to Almora	addition of all mass	30860.8	375	Idemat2015 Truck+trailer 24 tons net (min v	0.0288	333.7033892
plus other transport legs						
END of LIFE						
type		value (EUR)	process step			
Office Building		15754.76949	Renovation	30% of value after 40 yrs	-0.300	-4726.430847
plus the materials of the use phase						
					Total eco-costs (€)	11362.04203
					Specific eco-costs	0.00058859

The totals for the eco costs for torrefaction are shown in the table below.

Total Eco Costs - Torrefied Pine Needle Fuel

Component	Life Span (yr)	Total eco-costs (€/p.u.)	Specific eco-costs (€/kg fuel)
Reactor	10	49.86	0.0044
Briquetting Machine	10	33621.21	0.0070
Reactor Shed	40	24174.98	0.0013
Storage Shed	40	11362.04	0.0006
Total		69208.09	0.0132
Distribution	-	-	0.0019
Total			0.0151

The comparison to LPG is shown in the table below.

LPG Equivalent

Esimate	kg Torr Coal/kg LPG	Specific eco-costs (€/kg LPG equivalent)
Low Estimate	1.3	0.0198
High Estimate	15.4	0.2331
Actual LPG	1	2.6741

Lastly, the system diagrams for the eco analysis are given below.
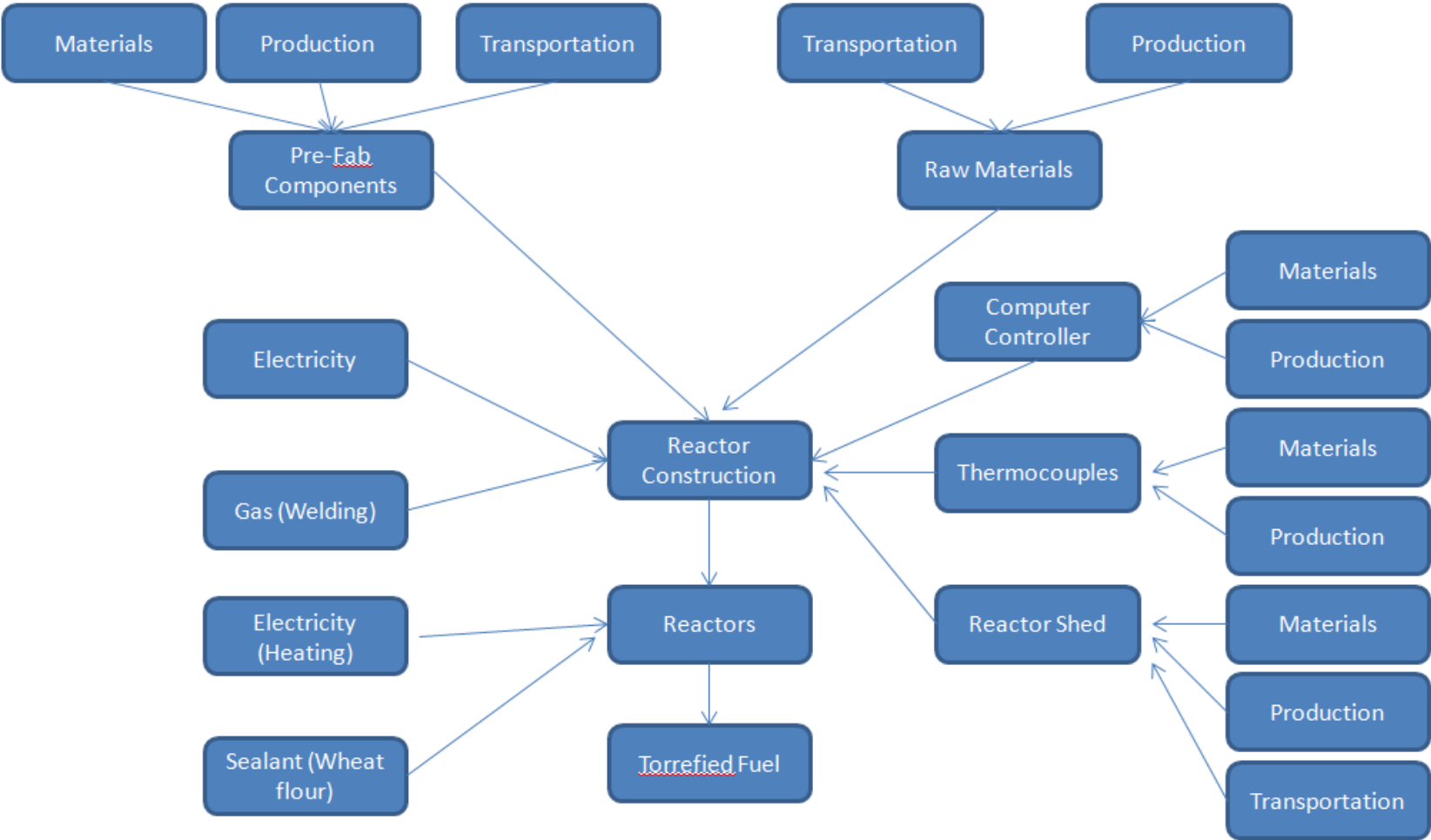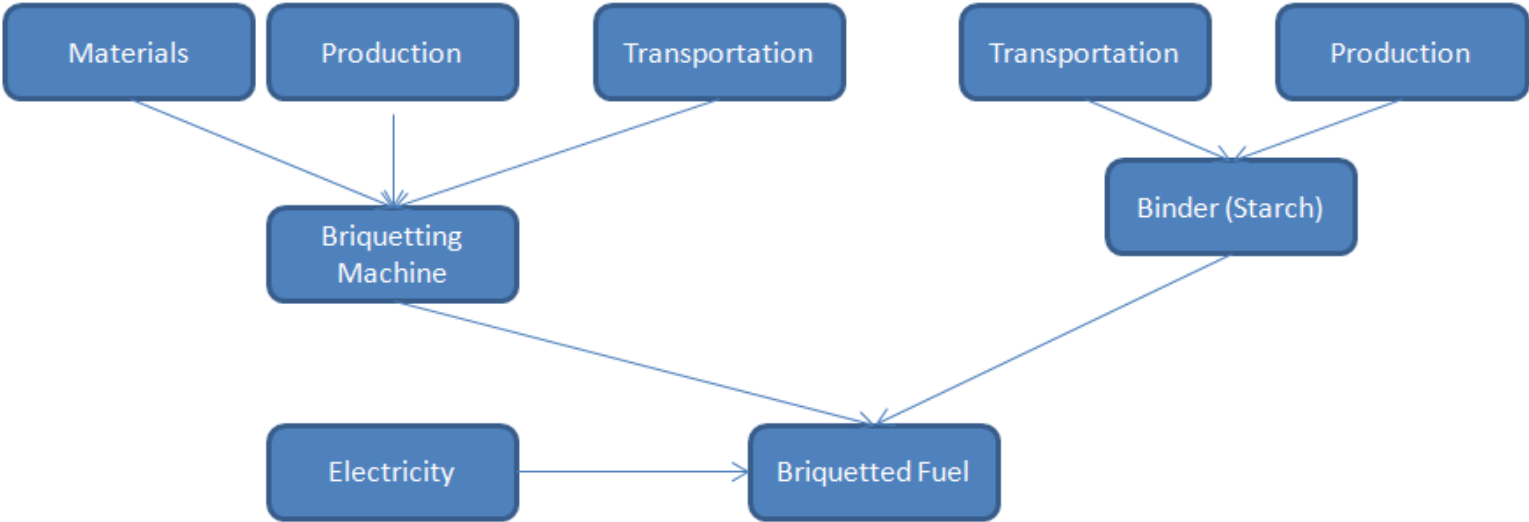
Packaging and Distribuiton

Transportation

Packaging Materials

Packaging

Transportation

Distribution

Long Term Storage

Production   Materials   Transportation

Storage Shed

Storage of Fuel
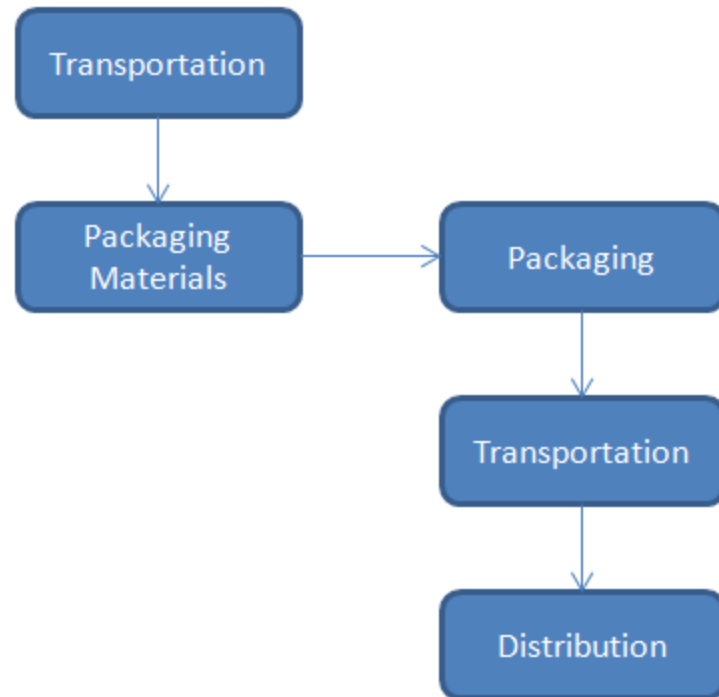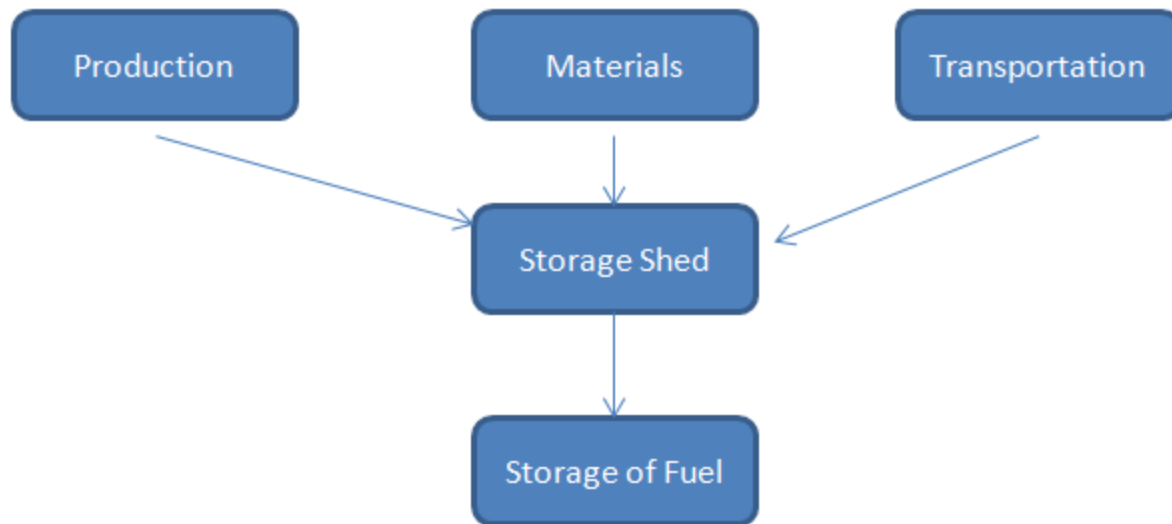
Appendix I

Pressure Calculations

The values used in the pressure calculations are shown below.

Reactor Volume	Density of Charcoal (kg/m3)	Density of Biocoal (kg/m3)	
0.1991	100	300	
Charcoal Mass Yield	Biocoal Mass Yield		
0.5	0.75		
Pyrolysis Packed Density (kg/m3)	Pine Needle Packed Density (kg/m3)		
550	100		
Initial Pine Needles (kg)	Initial Air Volume (m3)	Air Mass (kg)	Air Moles
19.90513105	0.1991	0.2488141382	8.588682712
Charcoal			
Solid Mass out (kg)	9.952565527		

Biocoal		
Solid Mass out (kg)	14.92884829	
Steam produced (kg)	4.976282763	
Gases produced (kg)	4.976282763	
Moles Steam Produced	276.4601535	
Moles Gases Produced (CO2)	113.0973355	
Specific Volume of Steam	0.04	Superheated Steam
Density	25	
Pressure at 250 C	3.97 MPa - 20.0 kg/m3, above this it is liquid	
Specific Volume of Gases	0.04	
Density	25	
Pressure MPa	2.471289261	

Appendix J

Chimney Calculations
The chimney pressure and flow calculation results are shown below.

v0.	0.773264	m3/kg	
Tg	673	K	
Ta	298	K	
		kg dry air/kg a.r.	
m	9.67202	fuel	
A	0.062	m2	
Φv,a	0.04	m3/s	
Re	15173.14		
f	0.007		

H,m	Delta P, Pa	Vg, m/s	Φv, m3/s	Delta Pact, Pa
0	0.00	0.00	0.000	0.000
0.1	0.59	0.68	0.042	0.460
0.2	1.19	0.96	0.059	0.920
0.3	1.78	1.18	0.072	1.379
0.4	2.38	1.36	0.084	1.837
0.5	2.97	1.52	0.094	2.294
0.6	3.57	1.66	0.103	2.751
0.7	4.16	1.80	0.111	3.207
0.8	4.75	1.92	0.118	3.663
0.9	5.35	2.04	0.126	4.118
1	5.94	2.15	0.132	4.572
1.1	6.54	2.25	0.139	5.026
1.2	7.13	2.35	0.145	5.478
1.3	7.73	2.45	0.151	5.931
1.4	8.32	2.54	0.157	6.382
1.5	8.91	2.63	0.162	6.833
1.6	9.51	2.72	0.167	7.283
1.7	10.10	2.80	0.173	7.733
1.8	10.70	2.88	0.178	8.182
1.9	11.29	2.96	0.182	8.630
2	11.89	3.04	0.187	9.077
2.1	12.48	3.11	0.192	9.524
2.2	13.07	3.19	0.196	9.970
2.3	13.67	3.26	0.201	10.416
2.4	14.26	3.33	0.205	10.861

2.5	14.86	3.40	0.209	11.305
2.6	15.45	3.47	0.213	11.748
2.7	16.05	3.53	0.217	12.191
2.8	16.64	3.60	0.221	12.633
2.9	17.23	3.66	0.225	13.075
3	17.83	3.72	0.229	13.516

Chimney Height Calculations
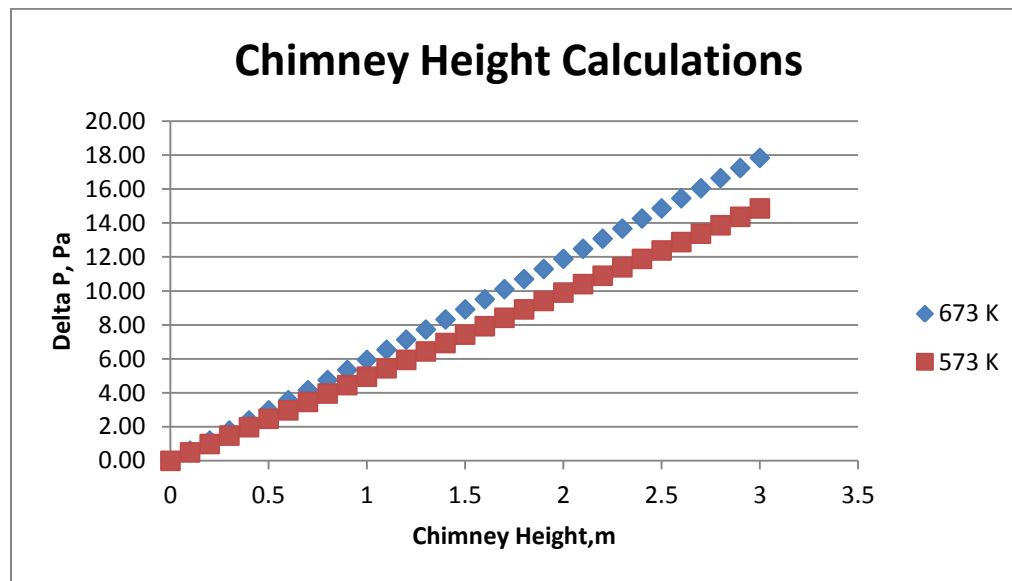
Appendix K

Steady State Temperature Profile Calculations

The results of the Matlab code and the code itself are given below:

Temp (°C)	400	388.917	326.988	218.318	72.090	38.765
D (m)	0	0.1400	0.1933	0.246666	0.300	0.340

Matlab Code:

```
%Air Properties for the flue gas
TinAir=400;% C
TinAirK=TinAir+273;
[aAir, rhoAir, muAir, nuAir, kAir, cpAir, PrAir]=airProp2(TinAirK,{'alpha'
'rho' 'my' 'ny' 'k' 'cp' 'Pr'});
BetaAir=1/TinAirK;

%Air Properties for ambient air
[PrExt, nuExt, kExt]=airProp2(TenvK,{'Pr' 'ny' 'k'});
BetaExt=1/TenvK; %at 20C, 1/K
% BetaExt=3.43e-3;%at 20C, 1/K
% PrExt=0.713; %at 20C
% nuExt=15.11e-6; %at 20C, m2/s
% kExt=0.0257; % at 20C, W/mK

d1=.280; % m
d2=d1;
d3=0.600; %m
d4=0.680; %m
L=0.850; %m
chimneyL = 2; %m

% Pine Needles Correlations from Anderson 1969
% Pine Needles values are from McAllister 2012
SAVRatio=4/0.00076; %For cylindrical geometry, assuming 0.76mm dia PN from
McAllister 2012
rhoPN = 567; %kg/m3 from Mcallister 2012
cpPN=(1.8e3); %J/kgK  from Mcallister 2012
rhoBed=10.5/((pi/4)*(d3^2-d1^2)*(L)); %actual measured in India
Va = (pi/4)*(d3^2-d1^2)*L;% Fuel Bed Volume
Vb = 10.5/rhoPN;% Fuel particles Volume
bedPorosity=(Va-Vb)/(Va);
kBio=1.69e-1*(1-bedPorosity)+(bedPorosity*kAir); %W/mK
rhoCpBio=(1-bedPorosity)*(rhoPN*cpPN)+(bedPorosity)*(rhoAir*cpAir);

% Values for fiberglass
kIns=0.045; % W/mk
rhoIns=35; %kg/m3
cpIns=0.67e3; %J/kg K
```

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```matlab
T4=40; %CHANGE THIS, should be variable, iterative solution
Tenv=25; %C
g=9.81; % m/s2

vFG=0.65*(2*g*chimneyL*(TinAirK-TenvK)/TinAirK)^(1/2);
%http://www.arch.hku.hk/teaching/lectures/airvent/sect03.htm
phiV=0.65*(pi/4)*d1^2*(2*g*chimneyL*(TinAirK-TenvK)/TinAirK)^(1/2);
ReInt=vFG*d1/nuAir; % = 14.703e3

delta=(d3-d1)/2; %penetration depth
tPen=0.05*delta^2/aAir; % time to long term hearting

GrExt=(g*BetaExt*(T4-Tenv)*d4^3)/(nuExt^2);
RaExt=GrExt*PrExt;
NuExt=0.59*(RaExt)^(0.25); % Nusselt - free convection - vertical cylinder
hExt=NuExt*kExt/(L);
UAExt=(hExt*pi*d4*L)

% NuIns=6.3; %Estimated to be close to spherical Nu of 6.6
% hIns=NuIns*kIns/(d4-d3);
UAIns=(2*pi*kIns*L)/(log(d4/d3))

% NuBiomass = 6.3; %Estimated to be close to spherical Nu of 6.6
% hBio=NuBiomass*kBio/(d3-d1);
UABio1=(2*pi*kBio*L)/(log((d1+(d3-d1)*1/3)/d1))
UABio2=(2*pi*kBio*L)/(log((d1+(d3-d1)*2/3)/d1))
UABio3=(2*pi*kBio*L)/(log((d1+(d3-d1)*3/3)/d1))
UABio= UABio1+UABio2+UABio3;

NuInt=0.0243*(ReInt^0.8)*(PrAir^0.4);% assuming the viscosity of the bulk to
be the same as the wall
hInt=NuInt*kAir/(d1);
UAInt=((hInt*pi*d1*L))

UAtotal= 1/( (1/UAExt)+(1/UAIns)+(1/UABio1)+ (1/UABio2)+(1/UABio3)+(1/UAInt)
);
heatFlow=UAtotal*(TinAir-Tenv) % W
% UAtotal= 1/( (1/(hExt*pi*d4*L))+(ln(d4/d3))/(hIns)+(1/hBio)+(1/hInt)  );

T1=TinAir-(heatFlow/(UAInt)) %C
T2=T1-(heatFlow/(UABio1)) %C
T3=T2-(heatFlow/(UABio2)) %C
T4=T3-(heatFlow/(UABio3)) %C
T5=T4-(heatFlow/(UAIns)) %C
T6=T5-(heatFlow/(UAExt)) %C

heatFlowInt=UAInt*(TinAir-T1)
heatFlowBio=UABio*(T1-T4)
heatFlowIns=UAIns*(T4-T5)
heatFlowExt=UAExt*(T5-T6)

d=[0,d1/2,(d1+(d3-d1)*1/3)/2,(d1+(d3-d1)*2/3)/2, d3/2,d4/2];
T=[TinAir,T1,T2,T3,T4,T5];
plot(d,T);
```

```
xlabel('r, [m]');
ylabel('T, [deg C]');
```

Appendix L

External Heat Transfer Coefficient

Here the process for esitmating the equivalent heat transfer coefficient h_{rad} for radiation effects on the outside of the reactor will be summarized. According to Perry, this should not be neglected, and thus a simplistic, empirical method is used here to estimate it. First, values, in English units, for heat transfer coefficients for horizontal pipes of different diameter were given, for varying temperature differences with the environment. An estimate of 100°F was taken between the insulation surface and the ambient during the torrefaction process. Thus, the values taken from Perry's are shown below (Perry, Green, and Maloney 1997).

Diameter (in)	h (Btu/h *ft2 *F)
1	2.5
3	2.25
5	2.15
10	2.07

From this data, an exponential decay curve fit was made, as this appeared to follow the data closely. The curve fit is shown in the plot below.

$$y = 2.483540443654350x^{-0.083522974518998}$$
$$R^2 = 0.985380173146404$$
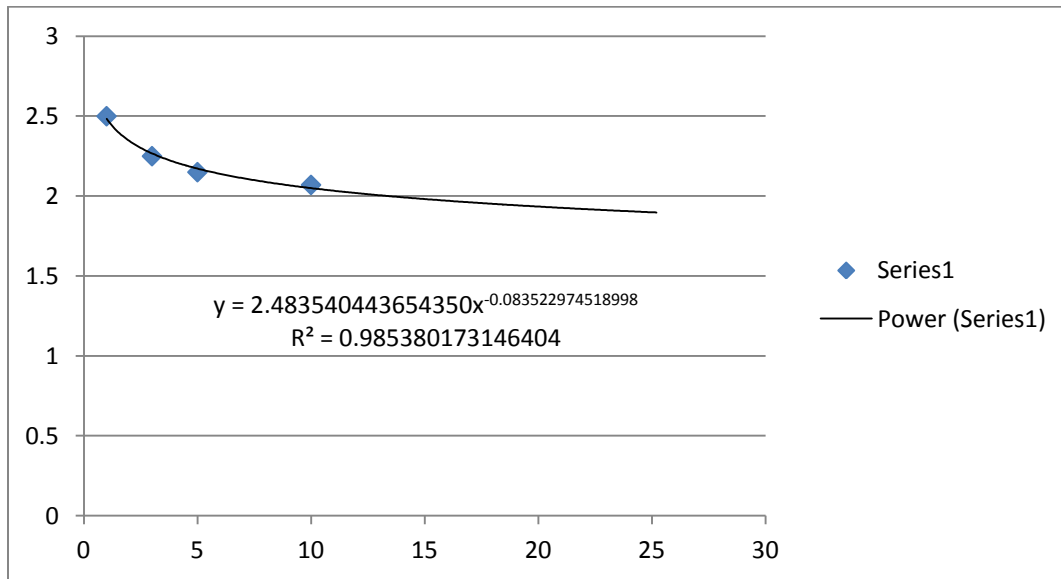
As the diameter of the reactor was not contained in the chart from Perry's, the data curve was used to extrapolate to a diameter of 64 cm = 25.2 in.

inches	h (Btu/h *ft2 *F)	h (J/s*m2*K)
1	2.2517	0.396544741
3	2.265795189	0.399027031
5	2.171156769	0.382360349
10	2.049029742	0.360852674
25.19685	1.896822222	0.334047553

Thus, the external heat transfer coefficient from radiation was estimated to be 0.334 W/m2 K, compared to a convective natural heat transfer coefficient of 1.365 W/m2 K.

AppendixM

Modelling Approach - Matrix Building

Due to familiarity with ODE (Ordinary Differential Equation Solvers in Matlab), it was chosen to use an ODE solver for the model, despite the fact that the system is dependent on multiple variables (r, z, and t), and thus fits the category of partial different equation system. However, the ODE was modified and used due to author familiarity.

The independent variable in the solver was set to be time, and all other variables were dependent on this. The input matrix to the solver consisted of a concatenation of the initial conditions for each of the three models: temperature, solid mass yield, and gas production. Here zDivisions represents the number of divisions axially in the bed, rDivisions represents the number of radial divisions only in the biomass section of the reactor, not the total number of divisions, and tDivisions represent the number of time steps. The temperature matrix contains three extra values for the the chimney, and the inner and outer insulation temperatures. The gas matrix has 6 columns, 1 for each of the gas components. These gas components were lumped together radially in large annular slices, in order to simplify calculations.

Matrix of Temperature Values Throughout the Bed zDivisions x (rDivisions+3)	Matrix of Mass Values zDivisions x rDivisions	Matrix of Gas Values zDivisionsx6

Thus, as depicted above, the three matrices were concatenated together and fed into the ODE solver.

Within the ODE solver, the solver converted the Y matrix into a vector of the following structure:

Temperature Vector: Column 1 Column 2............................ Column n	Mass Vector: Column 1....... Column n	Gas Values CO CO2..... Water

The ODE solver then output a matrix of vectors having this same structure, for each time step:

Temperature Matrix: t1: Column 1 Column 2.......... .... Column n t2: Column 1 Column 2.......... .... Column n	Mass Vector: Column 1....... Column n Column 1....... Column n	Gas Values CO CO2..... Water CO CO2..... Water

This matrix was then separated into individual matrices for temperature, mass, and gas production. The spatial arrangement of the matrices made the calling of various values within the matrix much more efficient and logical
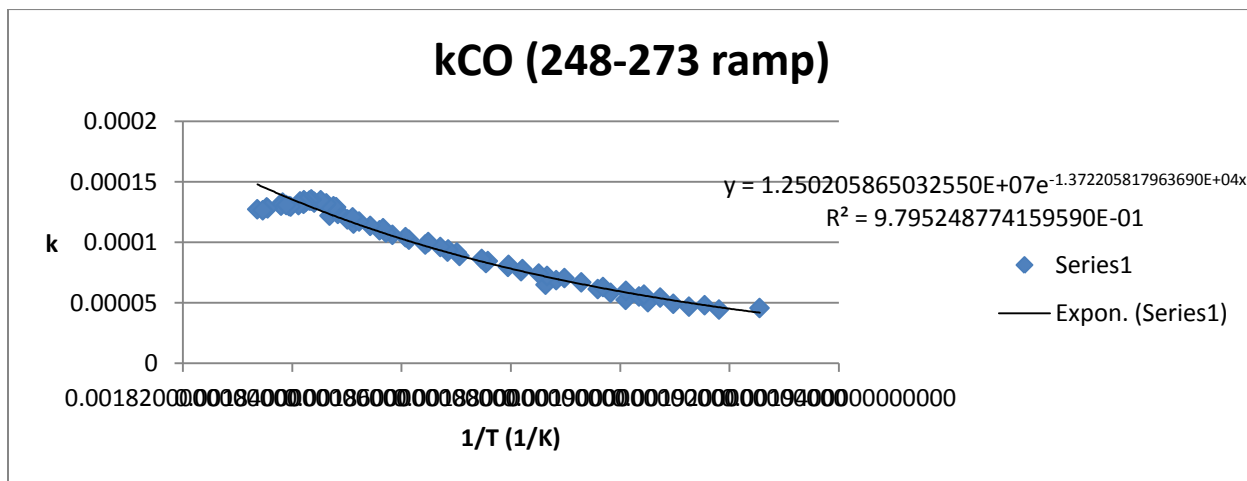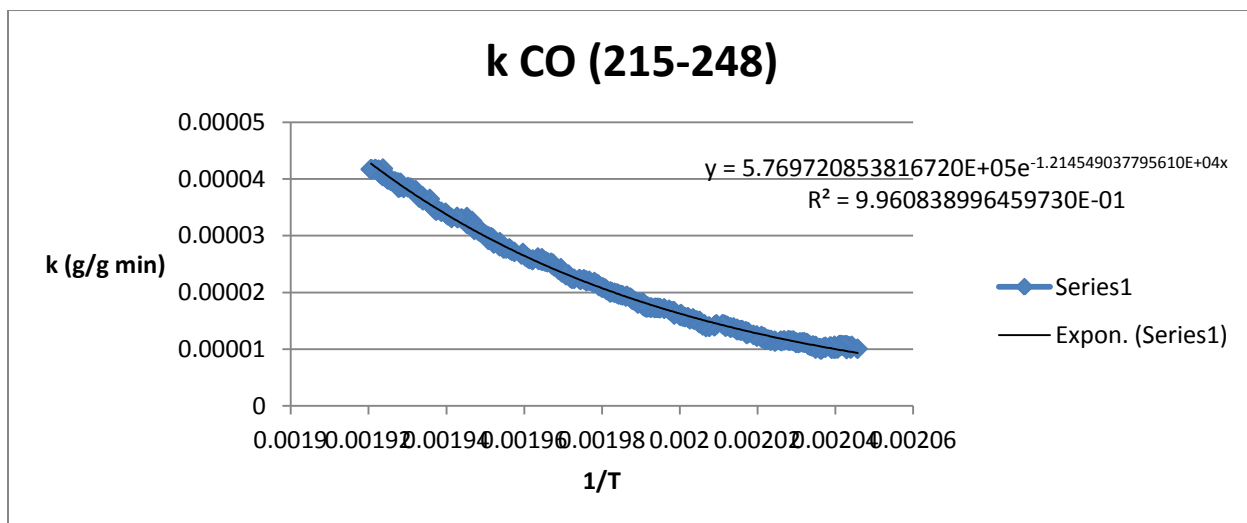
Appendix N

Permanent Gas Analysis

The constants and the equations for the permanent gas modelling are shown below.

CO Production			
Range	-Ea/R (1/K)	A (g X/g biomass *min)	Fitted Curve Equation
T: 180-215	-1.852648795828730E+04	4.291253644390620E+11	$y = 4.291253644390620E{+}11e^{-1.852648795828730E{+}04x}$
T: 215-248	-1.214549037799540E+04	5.769720854250670E+05	$y = 5.769720854250670E{+}05e^{-1.214549037799540E{+}04x}$
T: 248-273	-1.372205817964490E+04	1.250205865052110E+07	$y = 1.250205865052110E{+}07e^{-1.372205817964490E{+}04x}$
T: 273-288	-7.545719704344710E+03	1.121309388162950E+02	$y = 1.121309388162950E{+}02e^{-7.545719704344710E{+}03x}$
Range	m (dk/dT)	b (k)	Fitted Curve Equation
T: 288-325	5.480750369436740E-06	1.822399552895100E-04	y=5.48075036943674E-06*(x-288)+0.00018223995528951
T: 325-350	-1.540110875834680E-05	3.850277189586690E-04	y=-0.0000154011087583468*(x-325)+0.000385027718958669

CO2 Production			
Range	-Ea/R (1/K)	A (g X/g biomass *min)	Fitted Curve Equation
T: 180-215	-9.457674776212580E+03	4.482720921818850E+04	$y = 4.482720921818850E{+}04e^{-9.457674776212580E{+}03x}$
T:215-248	-6.403231733858230E+03	1.077385688185970E+02	$y = 1.077385688185970E{+}02e^{-6.403231733858230E{+}03x}$
T: 248-273	-6.958152072919520E+03	3.956374697156560E+02	$y = 3.956374697156560E{+}02e^{-6.958152072919520E{+}03x}$
T: 273-288	-6.233769988459170E+03	7.033174733294510E+01	$y = 7.033174733294510E{+}01e^{-6.233769988459170E{+}03x}$
Range	m (dk/dT)	b (k)	Fitted Curve Equation
T: 288-325	2.444173326065040E-05	1.150618933936710E-03	y=0.0000244417332606504*(x-288)+0.00115061893393671
T: 325-350	-8.219852258323100E-05	2.054963064580770E-03	y=-0.000082198522583231*(x-325)+0.00205496306458077

Next the graphs, taken from the data analysis, to produce the fitted equations, are shown below.

k CO (180-215)

$y = 4.291253644472940E{+}11e^{-1.852648795829270E{+}04x}$

$R^2 = 4.829707763462380E{-}01$

k CO (215-248)

$y = 5.769720853816720E{+}05e^{-1.214549037795610E{+}04x}$

$R^2 = 9.960838996459730E{-}01$

kCO (248-273 ramp)

$y = 1.250205865032550E{+}07e^{-1.372205817963690E{+}04x}$

$R^2 = 9.795248774159590E{-}01$

kCO (273-288 ramp)

$y = 3.029211005345550E{+}01e^{-6.824717299968860E{+}03x}$
$R^2 = 7.926053106028310E{-}01$

k CO2 (180-215)

$y = 4.482720921861800E{+}04e^{-9.457674776215440E{+}03x}$
$R^2 = 8.988299856502760E{-}01$

kCO2 (215-248 ramp)

$y = 1.077385688179800E{+}02e^{-6.403231733855300E{+}03x}$
$R^2 = 9.322076244332640E{-}01$

Lastly, the combined k models for CO and CO2 are shown plotted over the entire temperature range.
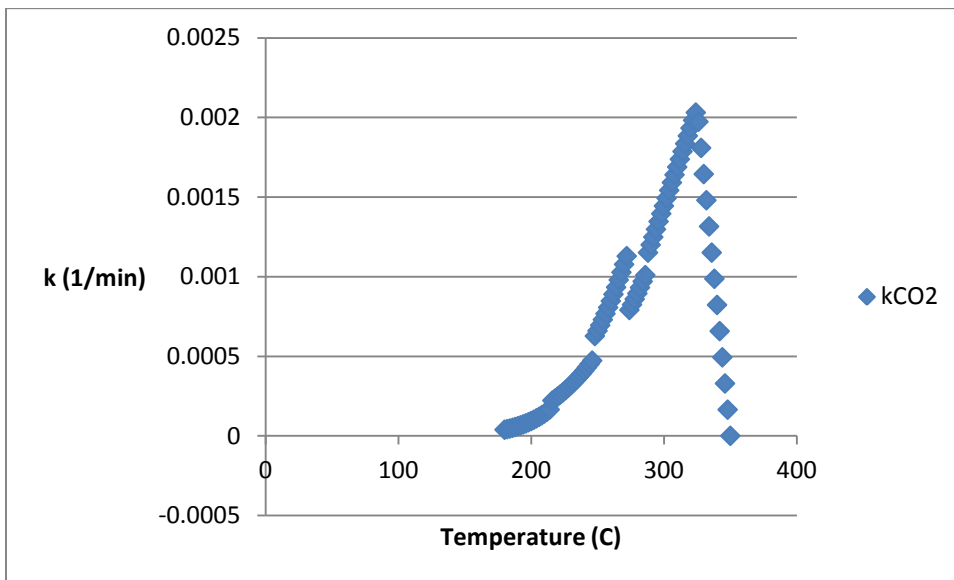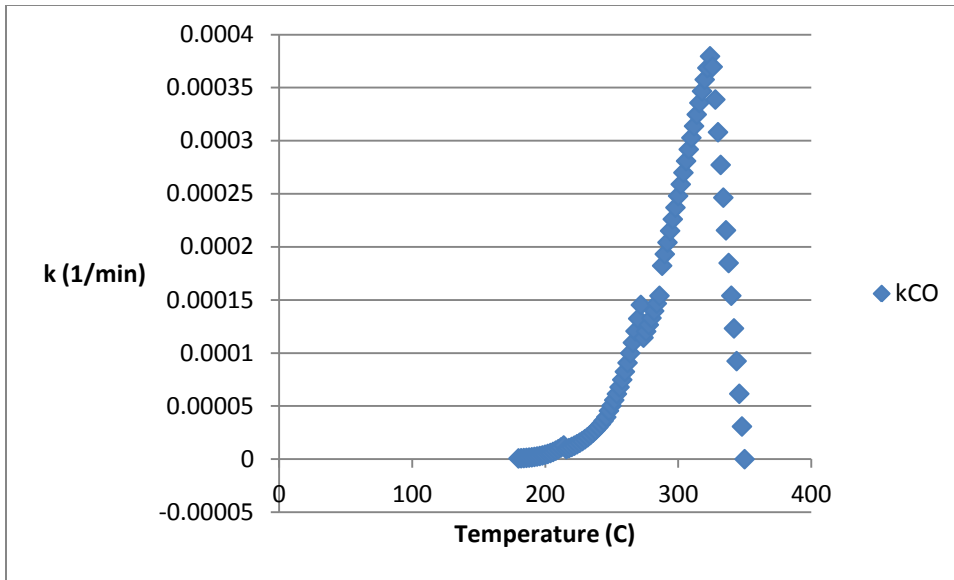
The raw data from the gas analyzer, for the experiment at 250°C for 45 minutes, is shown below.

Ch1 CO

Ch2 CO2

Ch4 CH4

Ch5 O2

kCO2 (248-273 ramp)

$y = 3.956374697125610E+02e^{-6.958152072919520E+03x}$

$R^2 = 7.496147377664660E-01$

1/T (1/K)

kCO2 (273-288 ramp)

$y = 2.624461530941820E+01e^{-5.690716836702810E+03x}$

$R^2 = 8.841379726283190E-01$
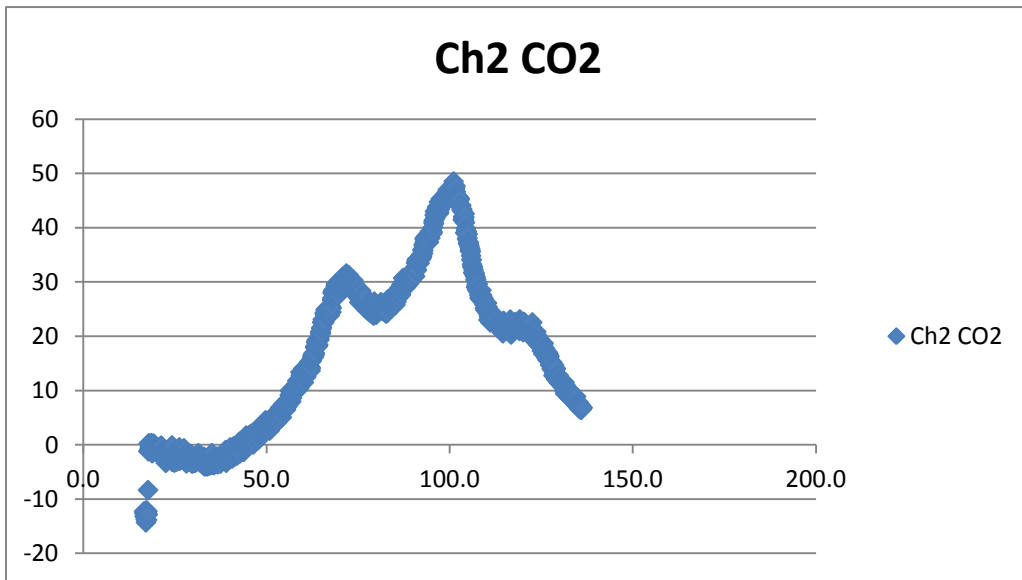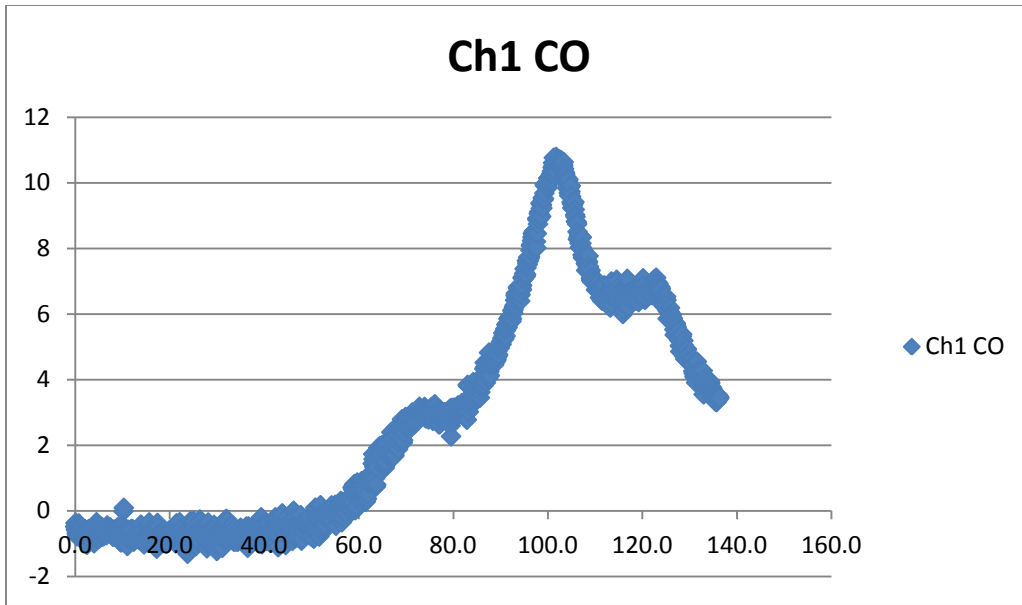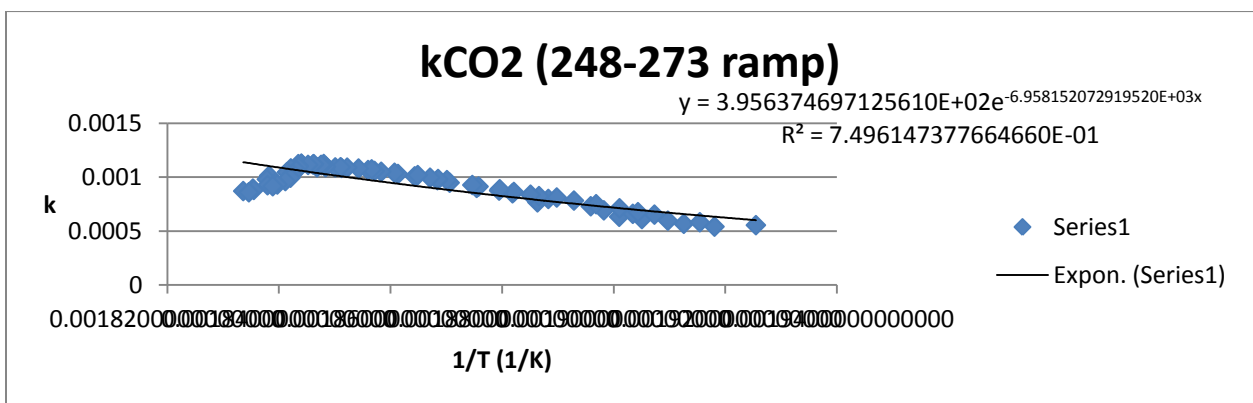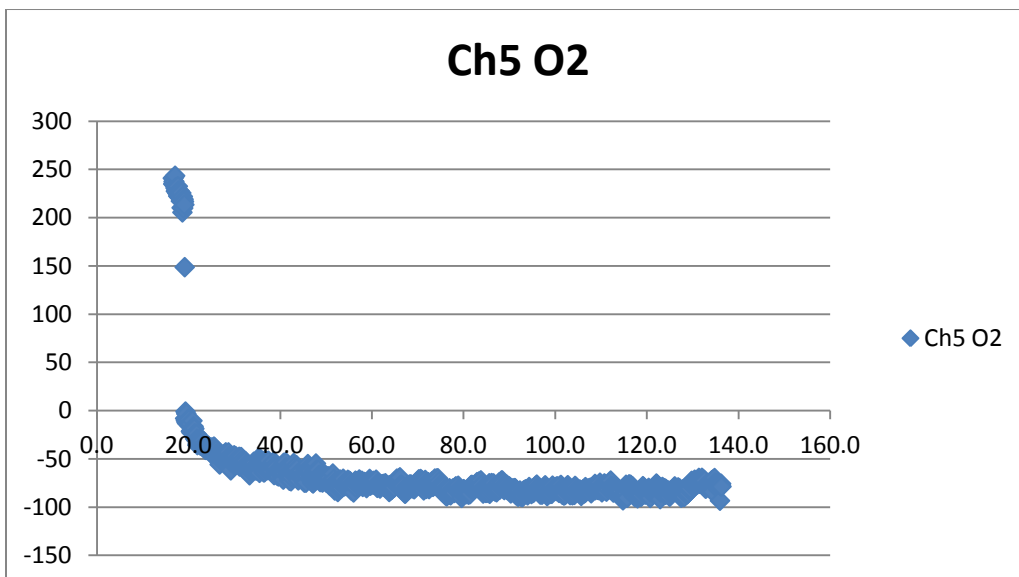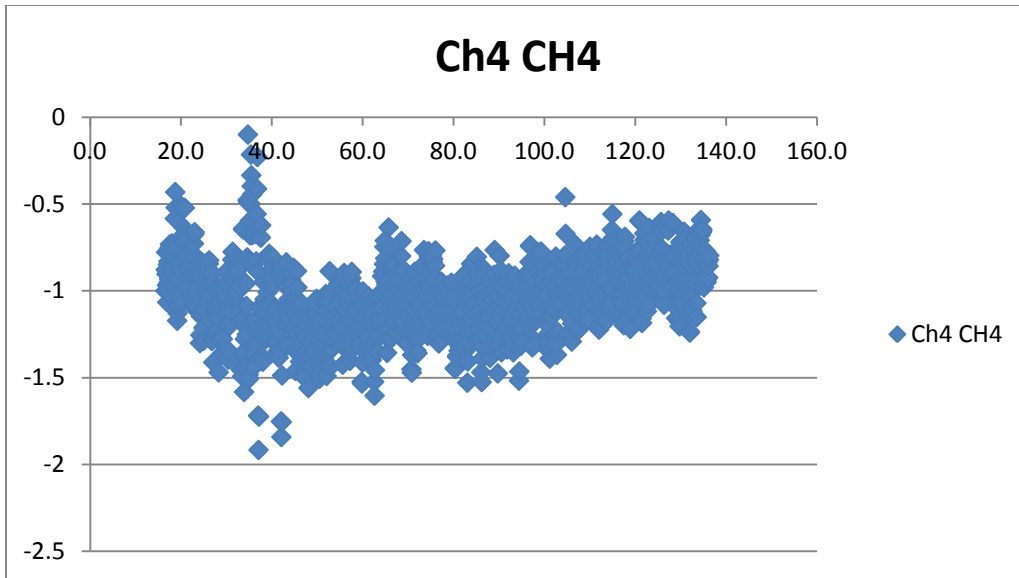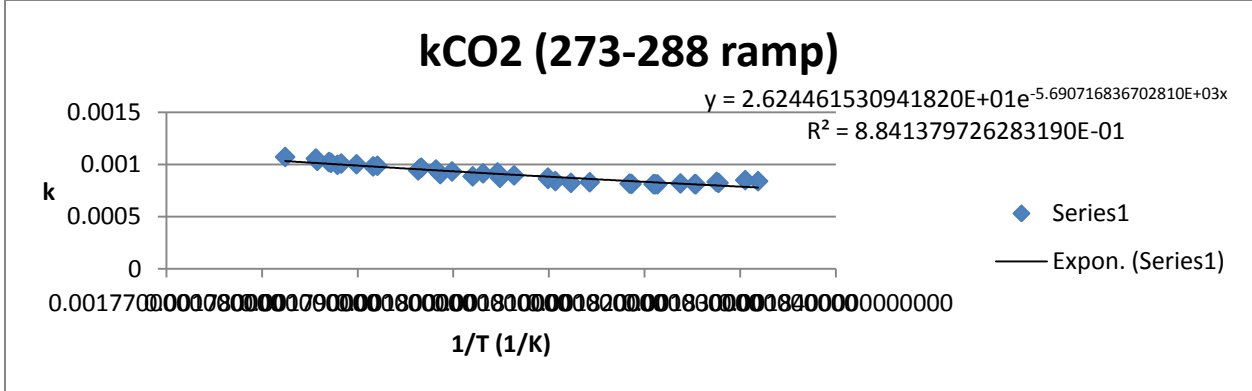
Appendix O

High Pressure Liquid Chromatography Procedure

After collection of the volatiles from the muffle furnace experiments, the volatiles were then analyzed and characterized using High Pressure Liquid Chromotography (HPLC). Small vial samples were created for analysis.The set up consisted of a series of various instruments (KNAUER Smartline Manager 5000, KNAUER Smartline Pump 1000, Spark Holland HPLC autosampler, Separations HPLC columen heater, Phenomenex Rezex Ion-Exclusion ROA-Organic Acid HPLC Column, KNAUER WellChrom UV Detector K-2600 (set to 210 nm wavelength), Shodex RI-101 Refractive Index Detector). For this, a diluted solution of sulfuric acid in water (0.005 N) was used as an elluent at 0.600 mL/min. A refractive index detector was used to characterize the sample after leaving the column. As this column was limited to separation of organic acids predominantly, and due to time constraints, not all components were characterized. Focus was given here to Lactic Acid, Formic Acid, Acetic Acid, and Methanol, as these are reported in literature to be the dominant volatiles for other biomass types, aside from water (Prins, Ptasinski, and Janssen 2006b; Bates and Ghoniem 2012; Shang et al. 2013). Lactic acid was not detected in the sample, and is thus not presented here. In addition, Furfural was detected, and this shall be discussed below. Water was assumed to comprise the remainder of all mass lost by the solid fraction, excluding the 5 other gas components produced (CO, CO_2, Formic acid, Acetic Acid, and Methanol).

First, ample elluent solution was prepared, using concentrated sulfuric acid, diluted to reach a concentration o 0.005 N (thus 0.0025 M H2SO4). The pump was set to operate at 6 mirco liters per minutes. In order to reach this flow, the flow was gradually increased in 1 uL/min increments to avoid pressure spikes in the HPLC column. Simultaneously, the HPLC column was heated to 60°C, as per instruction from the manufacturer. Both of these heating and pressure ramping processes were simultaneous to avoid over heating or over pressure in the HPLC column. After the pump, a mixer was also installed before the flow reached the HPLC autosampler

The autosampler was set to take samples of 30 microliters, with a wash of 20 microliters before the sample, to prime the sampling needle with the desired solution. A wash of the needle was programmed after every injection. Following a trial run, it was seen that all components left the HPLC column and were detected after 50 minutes. Thus, the autosampler was set to inject a new sample into the elluent flow every 50 minutes. Following the autosampler, the injected sample flowed through Organic Acid column, which separated the various components. Upon release from the column, the separated components (acids mostly) passed first through a UV Detector set to 210 nm, and subsequently a Refractive Index detector. As the UV detector was not able to detect Methanol at this wavelength, one of the three primary volatile components. Thus, RI data was used for characterization.

Standard vials with predetermined concentrations (3, 2, 1, 0.5 and 0.1 g/L) of the desired components (Lactic Acid, Formic Acid, Acetic Acid, and Methanol) were prepared. The samples of 0.5 and 0.1 g/L were made via dilution of the 1 g/L standard. These were characterized by the HPLC set up. The peaks measured were assigned to the 4 components according to previous knowledge of the order of the components leaving the column. The area under the peaks (in uV.min) was correlated with the concentration linearly. These data and correlations are shown below.

Table 32 - HPLC Standards Concentrations

Standard	Acetic Acid (mg)	Formic Acid (mg)	Lactic Acid (mg)	MeOH (mg)	Total Mass (mg)	Acetic Acid (g/L)	Formic Acid (g/L)	Lactic Acid (g/L)	MeOH (g/L)
3 g/L	35.4	29	38.9	31.1	10145.5	3.49	2.86	3.83	3.07
2 g/L	17.5	16.9	23.3	19.2	9938	1.76	1.70	2.34	1.93
1 g/L	10.1	11.5	12.7	8.9	10640.1	0.95	1.08	1.19	0.84

	Added Water (mg)	Added Solution (mg)	Acetic Acid (g/L)	Formic Acid (g/L)	Lactic Acid (g/L)	MeOH (g/L)
0.5 g/L	6245.5	6277.4	0.48	0.54	0.60	0.42
0.1 g/L	7737.4	1922.8	0.09	0.11	0.12	0.08

The graphs of the standards relations are shown below.
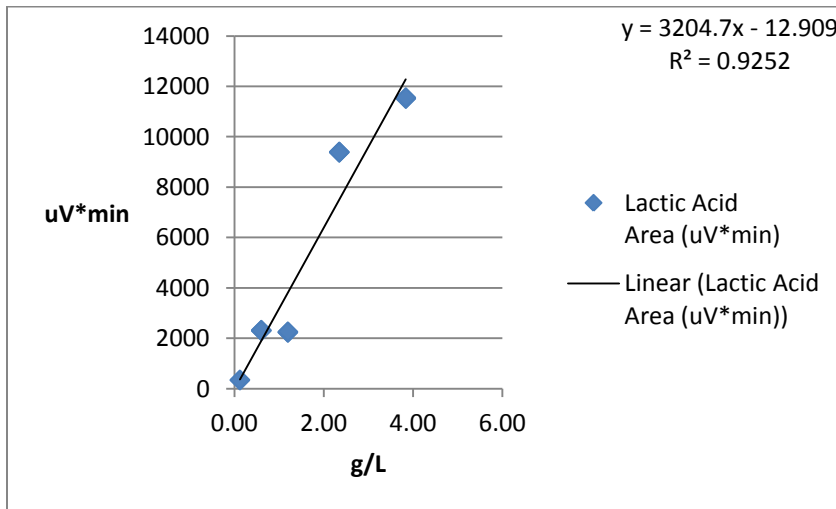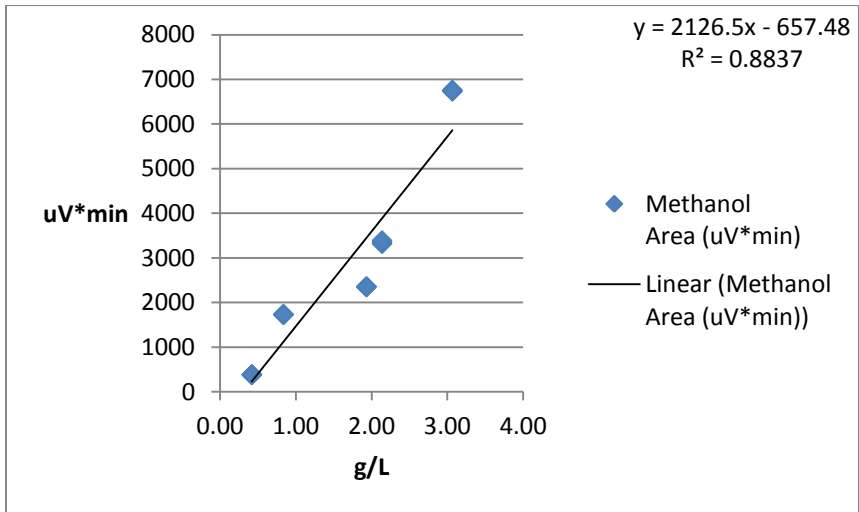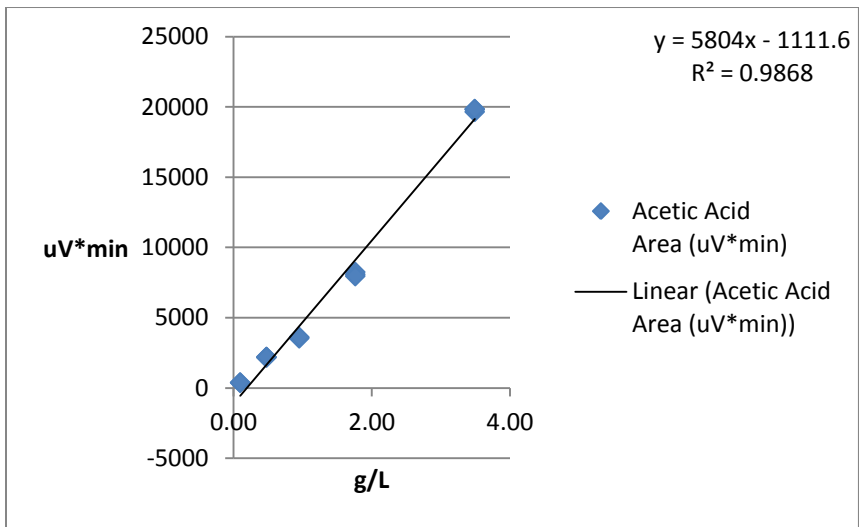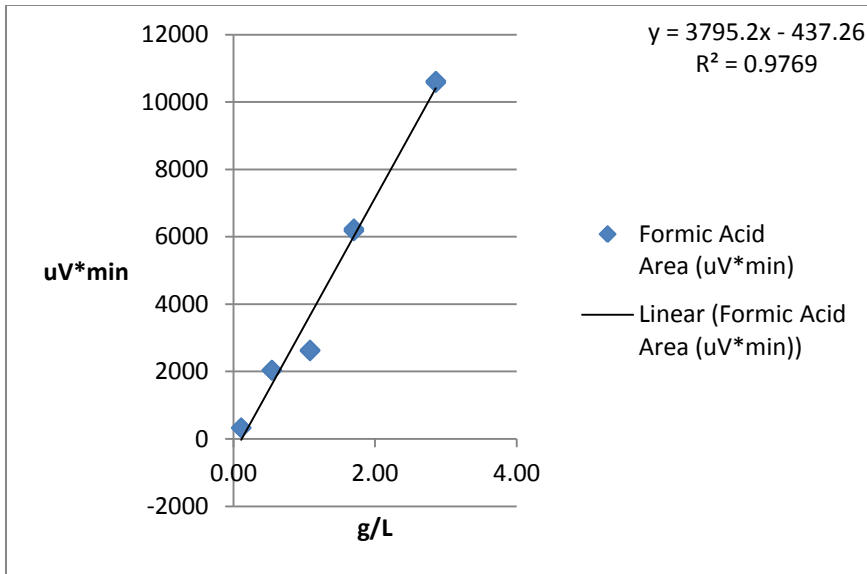
Following the development of these relations, the samples were characterized, applying the known times of exit from the column, and applying the relations of peak area (uV*min) vs. concentration (g/L). The results for the 5 samples (each of the 4 isothermal periods and the ramp period from 180-230°C) are shown below. As seen here, lactic acid was not measured, and is thus excluded from the kinetics relations.

Table 33 - Detected production of volatiles (per date of analysis)

		Lactic Acid (mg)	Formic Acid (mg)	Acetic Acid (mg)	Methanol (mg)
6/16/2015	230 begin	0.00	21.62	17.80	14.56
	230-45	0.00	23.46	29.45	21.80
	250-45	0.00	21.65	35.92	17.97
	270-45	0.00	22.17	53.30	20.16
	290-45	0.00	32.55	58.16	21.55
6/17/2015	230 begin	0.00	11.49	12.51	13.27
	230-45	0.00	25.78	32.96	23.08
	250-45	0.00	21.61	35.64	17.91
	270-45	0.00	27.81	60.25	24.94
	290-45	0.00	32.18	56.89	16.97

These data were then translated into kinetics coefficients, using the assumptions below. The mass loss valued were estimated from TGA data, while other parameters were measured. Thus, production was translated into g of volatile produced per g of pine needles per minute, assuming a constant temperature (and thus a constant value for k).

Table 34 - Muffle Furnace Assumptions

Experiment	Initial PN Mass (g)	Mass loss (g)	Average Torr Weight from TGA data (g)	Final Collection Volume (mL)	Residence Times (min)	Average Temp (deg C)
230-45	11	1.6	9.97	39	44	229.7
250-45	10.4	0.8	8.92	39.5	40	249.4
270-45	11.8	3.4	9.44	39	45	270.1
290-45	11.6	4	8.35	39	45	287.9

As discussed in Chapter 3, the values for ln(k) were plotted against 1/T to give Arrhenius type relations of kinetics for each of the 3 components. These are shown in Chapter 3.

Table 35 - HPLC Concentration and RI Data

Name	Conc (g/L)	Lactic Acid Conc (g/L)	Lactic Acid Height (uV)	Lactic Acid Area (uV*min)	Formic Acid Conc (g/L)	Formic Acid Height (uV)	Formic Acid Area (uV*min)	Acetic Acid Conc (g/L)	Acetic Acid Height (uV)	Acetic Acid Area (uV*min)	MeOH Conc (g/L)	Methanol Height (uV)	Meth Area (uV*r
Standard3.0-1	3	3.83	21803.7	11534.4	2.86	19815.8	10618.7	3.49	35732.6	19824.1	3.07	11676.2	67
Standard3.0-2	3	3.83	21755	11517.6	2.86	19747.1	10573.4	3.49	35627	19653.5	3.07	11647	(
Standard3.0-3	3	3.83	21796.7	11561.6	2.86	19787.1	10617.3	3.49	35676.1	19851.7	3.07	11639.9	67
Standard2.0-1	2	2.34	17757.1	9404	1.70	11818.4	6203.6	1.76	14804.4	8090.8	1.93	4190.6	
Standard2.0-2	2	2.34	17724	9394.8	1.70	11819.5	6240	1.76	14810.1	8251.6	1.93	4174.4	23
Standard2.0-3	2	2.34	17744.9	9384	1.70	11783.2	6170.3	1.76	14755.9	7963.2	1.93	4187.3	
Standard1.0-1	1	1.19	4325.2	2253.7	1.08	4889.8	2626.3	0.95	6482.1	3593.5	0.84	3061.8	17
Standard1.0-2	1	1.19	4308.1	2237.7	1.08	4864.7	2609.6	0.95	6452.1	3540.6	0.84	3044.8	17
Standard1.0-3	1	1.19	4354.1	2266.7	1.08	4916.9	2642.2	0.95	6521.4	3628.8	0.84	3059.7	17
Standard0.5-1	0.5	0.60	4390.5	2331.6	0.54	3808.4	2045.9	0.48	3999.6	2215.6	0.42	658.9	3
Standard0.5-2	0.5	0.60	4368.9	2303.2	0.54	3773.4	2031.4	0.48	3960.6	2175.1	0.42	658.9	3
Standard0.5-3	0.5	0.60	4383.2	2319.7	0.54	3780.1	2040	0.48	3978.4	2200.8	0.42	666.9	3
Standard0.1-1	0.1	0.12			0.11			0.09			0.08		
Standard0.1-2	0.1	0.12	743.9	350.1	0.11	655.7	332.7	0.09	744.9	391.7	0.08		
Standard0.1-3	0.1	0.12	736.7	353.9	0.11	659.2	325.8	0.09	731.9	383.8	0.08		

Appendix P

Full Reactor Model Code

Here the code for the reactor model is given below, first with the general code, and the ODE function is given after.

Overall Matlab Function

```matlab
% This script is meant to simulate the heat transfer
% characteristics of the torrefaction reactor designed
% and built by Vidyut Mohan and Ryan Helmer in Uttarakhand,
% India, at AVANI Bioenergy. This is part of the master's
% thesis project for Sustainable Energy Technology at the
% Delft University of Technology.
% Coded by Ryan Helmer

% This is based on conductive heat transfer primarily. Hot
% combustion gases at TinAir are taken through the inner
% chimney to heat the biomass packed around the chimney.
% The biomass used is pine needles according to the regional
% source of pine needles. A layer of fiberglass insulation is
% placed around the outer drum which houses the pine needles.
% The outer surface of the fiberglass is then exposed to air.
% Thin walls of metal (steel or aluminum) are ignored in the
% heat transfer model.

% In this code, it is assumed that there is unsteady heat
% transfer (varying in time), with variation in the radial
% and axial directions.



tic %Simulation timer begin

clear all

global UAInt UABioR UAInsR UABioZ UAInsZ1 UAInsZ2 torrTemp tlimit tDivisions
Vc dz zspan zDivisions rspan rDivisions massInitial TBio0 Tenv TenvK nuExt
PrExt g kExt BetaExt d1 d2 d3 L chimneyL kIns kBio aAir nuAir BetaAir PrAir
vFG ReInt rhoAir cpAir kAir TinAir rhoCpBio rhoIns cpIns

%Various Constants
TBio0=30; %C  - Initial Biomass Temp, assuming drying is already finished
Tenv=29.5; %C
TenvK=Tenv+273;
g=9.81; % m/s2

%Air Properties for Ambient Air
[aAir, rhoAir, muAir, nuAir, kAir, cpAir, PrAir]=airProp2(TenvK,{'alpha'
'rho' 'my' 'ny' 'k' 'cp' 'Pr'});
BetaAir=1/TenvK;
```

```matlab
%Reactor Dimensions - reactor in India
d1=.280; % m
d2=0.600; %m
d3=0.640; %m
L=0.850; %m
chimneyL= 2; %m, entire chimney from combustor to outlet

% Pine Needles Correlations from Anderson 1969
% Pine Needles values are from McAllister 2012
SAVRatio=4/0.00076; %For cylindrical geometry, assuming 0.76mm dia PN from
McAllister 2012
rhoPN = 567; %kg/m3 from Mcallister 2012
cpPN=(1.8e3); %J/kgK  from Mcallister 2012
rhoBed=10.5/((pi/4)*(d2^2-d1^2)*(L)); %actual measured in India
Va = (pi/4)*(d2^2-d1^2)*L;% Fuel Bed Volume
Vb = 10.5/rhoPN;% Fuel particles Volume
Vc=Va-Vb;% Gas phase volume
bedPorosity=(Vc)/(Va);
kBio=1.69e-1*(1-bedPorosity)+(bedPorosity*kAir); %W/mK
rhoCpBio=(1-bedPorosity)*(rhoPN*cpPN)+(bedPorosity)*(rhoAir*cpAir);

% Values for fiberglass - Insulation Numbers Paper
kIns=0.034; % W/mk
rhoIns=30; %kg/m3
cpIns=0.96e3; %J/kg K

% Radius vector
rDivisions=20; %Add 1!!
rspan=linspace(d1/2,d2/2,rDivisions+1); %This is for the Biomass only

% Height vector
zDivisions=4;
dz=L/zDivisions;
zspan=linspace(0,L,zDivisions+1);

%Time vector
tDivisions=50;
tlimit=9500;
tspan=linspace(0,tlimit,(tDivisions+1)); %5 hrs = 18000s, 3hrs = 10800s

% Vector of initial values
% This vector of initial values consists of a concatenation of three
% matrices: temperatures, solid mass, and vapor mass, arranged horizontally
% in that order. The temperature matrix is of size zdiv x (rdiv+3). The
% solid mass matrix is of size zdiv x (rdiv), as this only considers the
% section of the biomass. The vapor mass is of size zdiv x 6, with only the
% mass in each horizontal slice (zdiv) for each of the 6 components
% considered (CO, CO2, Acetic Acid, Formic Acid, Methanol, and Water).
Y0=zeros(1,zDivisions*((rDivisions+3)+(rDivisions)+6));
i=1;
while i<=zDivisions
    for j=1:((rDivisions+3)+(rDivisions)+6)
        if j<=rDivisions+3
            Y0(i+(j-1)*zDivisions)=TBio0+j*0.0001+i*0.01;
```

```matlab
        elseif (j>rDivisions+3) && (j<=(rDivisions+3)+(rDivisions))
            Y0(i+(j-1)*zDivisions)=1000*rhoBed*(pi*(rspan(j+1-
(rDivisions+3))^2-rspan(j-(rDivisions+3))^2)*dz); %in grams, not kg
        else
            Y0(i+(j-1)*zDivisions)=0;
        end
    end
    i=i+1;
end


%Matrix of the Initial mass loaded into the reactor, for mass yield
%calculations later
massInitial=zeros(zDivisions,rDivisions+1);
i=1;
while i<=zDivisions
    j=2;
    for j=2:rDivisions+1
        massInitial(i,j)=1000*rhoBed*(pi*((rspan(j))^2-(rspan(j-1))^2)*dz);
%in grams, not kg
        j=j+1;
    end
    i=i+1;
end
totalMassInitial=sum(sum(massInitial,1),2);



%ODE function
[t1,Y1]=ode45(@torrfun4_1_4,tspan,Y0);


runtime=toc %End simulation timer

%For the various graphs, matrices of temperature, mass, and gas components
%were recreated from the output of the ODE Y1, in order to make graphing
%more logical.

%Reconstruction of radial vector for plotting. This vector includes 2
%points for the chimney (to show a constant temperature across the
%chimney), the biomass, and the insulation.
r1=zeros(1,rDivisions+4);
j=1;
for j=1:(rDivisions+4)
    if j==1
        r1(1,j)=0;
    elseif j==2
        r1(1,j)=(d1/2)-0.002; %2 millimeters for the thickness of the metal
wall
    elseif (j>2) && (j<=(rDivisions+3))
        r1(1,j)=rspan(1,j-2);
    else
        r1(1,j)=(d3/2);
    end
end

%Reconstruction of radial vector for plotting, with only the biomass
%section
```

```matlab
r2=zeros(1,rDivisions);
j=1;
for j=1:(rDivisions)
        r2(1,j)=rspan(1,j);
end

%Reconstruction of axial vector for plotting
z=zeros(1,zDivisions);
i=1;
for i=1:(zDivisions)
    z(1,i)=zspan(1,i);
end

%Reconstruction of time vector into minutes for plotting
t2=zeros(1,tDivisions+1);
i=1;
for i=1:(tDivisions+1)
    t2(1,i)=t1(i,1)/60;
end


%Temperature Graphs

% The first temperature graph generates a short animation of the
% temperature values throughout the reactor, including the chimney, the
% biomass, and the insulation.

writerObjT= VideoWriter('ReactorTemp.avi');
open(writerObjT);

k=1;
figure
%Plotting the temperature matrix per time value
Temp=zeros(zDivisions,rDivisions+4); %Temperature  matrix
for k=1:(tDivisions+1)
    i=1;
        while i<=zDivisions
            j=1;
            while j<=rDivisions+4
                if j==1
                    Temp(i,j)=Y1(k,((j-1)*(zDivisions))+i);
                else
                    Temp(i,j)=Y1(k,((j-2)*(zDivisions))+i);
                end
                j=j+1;
            end
            i=i+1;
        end
        contourf(r1,z,Temp,20,'LineStyle','none')
%Additional lines inserted to mark the section of biomass
        line([(d1/2) (d1/2)],[0 L],'Color','k')
        line([(d2/2) (d2/2)],[0 L],'Color','w')
%Axes and Labels
        xlabel('r, [m]');
        ylabel('z, [m]');
```

```matlab
        caxis ([20 400]);
        cb = colorbar;
        ylabel(cb, 'Temperature, [C]');
%Insertion of a time counter on the graph
        currentTime = k*(tlimit/(tDivisions*60));
        mTimeCounter = uicontrol('style','text',...
            'String', char('time (min) =', num2str(currentTime,'%10.0f')),...
            'Position', [200, 50, 80, 30]);
        F(k)=getframe(gcf);
        writeVideo(writerObjT, F(k));
end
close(writerObjT);


%Repetition of the video plot
fig=figure;
movie(fig,F,3);


%Plotting the temperaure in time at various points: B for Bottom, T for
%top, I for inner, M for middle, O for outer. These correspond with the
%location of the thermocouples in the reactor tested in India. Bottom and
%Top are about 10 cm from the top of the reactor, Inner and Outer are 2 cm
%from the wall, and Middle is halfway between the inner and outer walls.

TempBI=zeros(1, tDivisions+1);
TempBM=zeros(1, tDivisions+1);
TempBO=zeros(1, tDivisions+1);
TempTI=zeros(1, tDivisions+1);
TempTM=zeros(1, tDivisions+1);
TempTO=zeros(1, tDivisions+1);
for k=1:(tDivisions+1)
    TempBI(1,k)=Y1(k,((2)*zDivisions+1));
    TempBM(1,k)=Y1(k,((11)*zDivisions+1));
    TempBO(1,k)=Y1(k,((20)*zDivisions+1));
    TempTI(1,k)=Y1(k,((2)*zDivisions+zDivisions));
    TempTM(1,k)=Y1(k,((11)*zDivisions+zDivisions));
    TempTO(1,k)=Y1(k,((20)*zDivisions+zDivisions));

end

%Plotting the temperatures within the bed
figure
plot(t2, TempBI,'m', t2, TempBM,'k', t2, TempBO, 'c', t2, TempTI, 'r', t2,
TempTM, 'g', t2, TempTO, 'b');
legend( 'Bottom Inner', 'Bottom Middle', 'Bottom Outer', 'Top Inner', 'Top
Middle', 'Top Outer');
ylabel('Temperature, [C]');
xlabel('t, [min]');

%Plotting the chimney inlet temperature, which was defined by a user set
%function to correspond with the chimney temperature in the tests in India.
%See torrfun for the actual function
figure
plot(t2, Y1(:,1))
xlabel('t, [min]');
ylabel('Chimney Inlet Temperature [C]');
```

```matlab
%Plotting the temperature gradient across the bottom of the reactor at the
%end of the process (before cooling began - thus at minute 151).
FinalBottomTemperatureGradient=zeros(1,rDivisions+4); %Temperature   matrix
        finalTimeIndex=floor((151*60)/(tlimit/tDivisions));
        j=1;
        while j<=rDivisions+4
            if j==1
                FinalBottomTemperatureGradient(i,j)=Y1(finalTimeIndex,((j-
1)*(zDivisions))+1);
            else
                FinalBottomTemperatureGradient(i,j)=Y1(finalTimeIndex,((j-
2)*(zDivisions))+1);
            end
            j=j+1;
        end

figure
plot(r1, FinalBottomTemperatureGradient)
xlabel('r, [m]');
ylabel('Final Temperature [C]');




%Mass Yield Graphs

% The first temperature graph generates a short animation of the
% temperature values throughout the reactor, including the chimney, the
% biomass, and the insulation.

writerObjM= VideoWriter('ReactorMass.avi');
open(writerObjM);
k=1;
figure
%Plotting the mass yield in the bed for each time value
massYield=zeros(zDivisions,rDivisions);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
        j=1;
        while j<=rDivisions
            massYield(i,j)=(Y1(k,((j-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3)))))/(massInitial(i,j+1))*100;
            j=j+1;
        end
        i=i+1;
    end
    contourf(r2,z,massYield,20,'LineStyle','none')
%Axes and Labels
    xlabel('r, [m]');
    ylabel('z, [m]');
    caxis ([0 100]);
    cb = colorbar;
    colormap(copper);
```

```matlab
    ylabel(cb, 'Mass Yield, [C]');
%Including a time counter on the graph
    currentTime = k*(tlimit/(tDivisions*60));
    mTimeCounter = uicontrol('style','text',...
        'String', char('time (min) = ',num2str(currentTime,'%10.0f')),...
        'Position', [200, 50, 80, 30]);
    F(k)=getframe(gcf);
    writeVideo(writerObjM, F(k));
end
close(writerObjM);


% %Repetition of the video plot
fig=figure;
movie(fig,F,10);


%Reconstruction of the mass yield graph for plotting separate from the
%animation
k=1;
massYield2=zeros((tDivisions+1), (zDivisions*rDivisions));
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
        j=1;
        while j<=rDivisions
            massYield2(k,(((j-1)*(zDivisions))+i))=(Y1(k,((j-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))))/(massInitial(i,j+1))*100;
            j=j+1;
        end
        i=i+1;
    end
end


%Plotting the mass yield for different points in the reactor: Bottom Inner,
%Bottom Middle, and Bottom Outer, in the same positions as the temperature
%values from above for BI, BM, and BO. The mass yield and temperature at
%these positions are here graphed together.
figure
[hAx, hLine1, hLine2]=plotyy(t2, massYield2(:,(2-1)*zDivisions+1),t2,
TempBI);
xlabel ('t, [min]');
ylabel (hAx(1), 'Mass Yield BI [%]');
ylabel (hAx(2), 'Temperature BI [C]');


figure
[hAx, hLine1, hLine2]=plotyy(t2, massYield2(:,(11-1)*zDivisions+1),t2,
TempBM);
xlabel ('t, [min]');
ylabel (hAx(1), 'Mass Yield BM [%]');
ylabel (hAx(2), 'Temperature BM [C]');


figure
[hAx, hLine1, hLine2]=plotyy(t2, massYield2(:,(20-1)*zDivisions+1),t2,
TempBO);
```

```matlab
xlabel ('t, [min]');
ylabel (hAx(1), 'Mass Yield BO [%]');
ylabel (hAx(2), 'Temperature BO [C]');

%Plotting mass yield at BI, BM, and BO together
figure
plot(t2, massYield2(:,(2-1)*zDivisions+1),'g', t2, massYield2(:,(11-
1)*zDivisions+1), 'c', t2, massYield2(:,(20-1)*zDivisions+1), 'r');
ylabel ('Mass Yield [%]');
xlabel ('t, [min]');
legend ('BI', 'BM', 'BO')


%Same as the mass yield, but not divided by the initial mass matrix, to
%allow for plotting of the total mass yield in time
mass=zeros((tDivisions+1), (zDivisions*rDivisions));
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
        j=1;
        while j<=rDivisions
            mass(k,(((j-1)*(zDivisions))+i))=(Y1(k,((j-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3)))));
            j=j+1;
        end
        i=i+1;
    end
end
totalMassYield=sum(mass,2)/totalMassInitial*100;

figure
plot(t2, totalMassYield.');
ylabel ('Overall Mass Yield [%]');
xlabel ('t, [min]');




%Gas Yield Graphs
%For each of the 6 gas components (CO, CO2, Formic Acid, Acetic Acid,
%Methanol, and Water), the following procedure was taken, in turn. First,
%the matrix of gas production per horizontal slice in time was constructed.
%ProdM refers to mass production, while Prodmol refers to molar production
COProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
        COProdM(i,k)=(Y1(k,((1-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
% Then, below the matrix construction loop, the production was summed to
%give the production in the whole reactor. In this model, this was assumed
%to be equal to the outflow of gas, due to the lack of pressure buildup in
%the reactor.
```

```matlab
sumCOProdM = sum(COProdM, 1);
%The cumulative production in time was then calculated.
cumCOProdM=cumsum(sumCOProdM);
%This was then converted into cumulative mass yield - compared with the
%intial mass loaded into the reactor
cumCOPercentYield=cumCOProdM/totalMassInitial*100;
%Then the production in terms of moles was found, dividing by molar mass
COProdmol=COProdM/28.01;
%This was likewise summed to give production in the whole reactor in time
sumCOProdmol=sum(COProdmol,1);


%The above process was repeated for the remaining 5 components
%CO
CO2ProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
            CO2ProdM(i,k)=(Y1(k,((2-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
sumCO2ProdM = sum(CO2ProdM, 1);
cumCO2ProdM=cumsum(sumCO2ProdM);
cumCO2PercentYield=cumCO2ProdM/totalMassInitial*100;
CO2Prodmol=CO2ProdM/44.01;
sumCO2Prodmol=sum(CO2Prodmol,1);


%Formic Acid
FormProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
            FormProdM(i,k)=(Y1(k,((3-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
sumFormProdM = sum(FormProdM, 1);
cumFormProdM=cumsum(sumFormProdM);
cumFormPercentYield=cumFormProdM/totalMassInitial*100;
FormProdmol=FormProdM/46.026;
sumFormProdmol=sum(FormProdmol,1);


%Acetic Acid
AcetProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
            AcetProdM(i,k)=(Y1(k,((4-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
sumAcetProdM = sum(AcetProdM, 1);
cumAcetProdM=cumsum(sumAcetProdM);
```

```matlab
cumAcetPercentYield=cumAcetProdM/totalMassInitial*100;
AcetProdmol=AcetProdM/60.053;
sumAcetProdmol=sum(AcetProdmol,1);


%Methanol
MethProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
            MethProdM(i,k)=(Y1(k,((5-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
sumMethProdM = sum(MethProdM, 1);
cumMethProdM=cumsum(sumMethProdM);
cumMethPercentYield=cumMethProdM/totalMassInitial*100;
MethProdmol=MethProdM/32.042;
sumMethProdmol=sum(MethProdmol,1);


%Water
WaterProdM=zeros(zDivisions,tDivisions+1);
for k=1:(tDivisions+1)
    i=1;
    while i<=zDivisions
            WaterProdM(i,k)=(Y1(k,((6-
1)*(zDivisions))+i+(zDivisions*(rDivisions+3))+(zDivisions*rDivisions)));
    i=i+1;
    end
end
sumWaterProdM = sum(WaterProdM, 1);
cumWaterProdM=cumsum(sumWaterProdM);
cumWaterPercentYield=cumWaterProdM/totalMassInitial*100;
WaterProdmol=WaterProdM/18.02;
sumWaterProdmol=sum(WaterProdmol,1);


%Then the total gas flow leaving the reactor, in g/min, was calculated
TotalGasFlow=sumCOProdM+sumCO2ProdM+sumFormProdM+sumAcetProdM+sumMethProdM+su
mWaterProdM+0.000000001;
%The molar production of gases, excluding water was found in time
sumTotalNonWaterGasProdmol=sumCOProdmol+sumCO2Prodmol+sumFormProdmol+sumAcetP
rodmol+sumMethProdmol;
%The water vapor produced was calculated in time, assuming 3% volume of the
%torr gas mixture was water vapor, according to the limit of saturated
%water vapor at 25C.
sumWaterVaporProdmol=(3/97)*sumTotalNonWaterGasProdmol;
%This was then converted into mass of water in the torr gas
sumWaterVaporProdM=18.02*sumWaterVaporProdmol;


%Plotting the gas production exit flow for each time value
figure
plot(t2, sumCOProdM);
ylabel('CO exit flow, [g/min]');
xlabel('t, [min]');

figure
```

```matlab
plot(t2, sumCO2ProdM);
ylabel('CO2 exit flow, [g/min]');
xlabel('t, [min]');

figure
plot(t2, sumFormProdM);
ylabel('Formic Acid exit flow, [g/min]');
xlabel('t, [min]');

figure
plot(t2, sumAcetProdM);
ylabel('Acetic Acid exit flow, [g/min]');
xlabel('t, [min]');

figure
plot(t2, sumMethProdM);
ylabel('Methanol exit flow, [g/min]');
xlabel('t, [min]');

figure
plot(t2, sumWaterProdM);
ylabel('Water exit flow, [g/min]');
xlabel('t, [min]');


%Volume Composition of Torr Gas exiting the reactor. First, the matrix for
%the volume fraction of each component was built.
COVolFraction=zeros(1,tDivisions+1);
CO2VolFraction=zeros(1,tDivisions+1);
FormVolFraction=zeros(1,tDivisions+1);
AcetVolFraction=zeros(1,tDivisions+1);
MethVolFraction=zeros(1,tDivisions+1);
WaterVolFraction=zeros(1,tDivisions+1);
totalGasProdmol=
sumCOProdmol+sumCO2Prodmol+sumFormProdmol+sumAcetProdmol+sumMethProdmol+sumWa
terVaporProdmol+0.0000001;
for k=1:(tDivisions+1)
    COVolFraction(1,k)=sumCOProdmol(1,k)/totalGasProdmol(1,k)*100;
    CO2VolFraction(1,k)=sumCO2Prodmol(1,k)/totalGasProdmol(1,k)*100;
    FormVolFraction(1,k)=sumFormProdmol(1,k)/totalGasProdmol(1,k)*100;
    AcetVolFraction(1,k)=sumAcetProdmol(1,k)/totalGasProdmol(1,k)*100;
    MethVolFraction(1,k)=sumMethProdmol(1,k)/totalGasProdmol(1,k)*100;
    WaterVolFraction(1,k)=sumWaterVaporProdmol(1,k)/totalGasProdmol(1,k)*100;
end
%Stacking and plotting the Volume Composition
stackedCO2VolFraction=COVolFraction+CO2VolFraction;
stackedFormVolFraction=FormVolFraction+stackedCO2VolFraction;
stackedAcetVolFraction=AcetVolFraction+stackedFormVolFraction;
stackedMethVolFraction=MethVolFraction+stackedAcetVolFraction;
stackedWaterVolFraction=WaterVolFraction+stackedMethVolFraction;
%Creating vectors for a filled plot of the stacked volume fractions
baseLine=zeros(1, tDivisions+1);
T2=[t2, fliplr(t2)];
Y1=[baseLine, fliplr(COVolFraction)];
Y2=[COVolFraction, fliplr(stackedCO2VolFraction)];
Y3=[stackedCO2VolFraction, fliplr(stackedFormVolFraction)];
```

```
Y4=[stackedFormVolFraction, fliplr(stackedAcetVolFraction)];
Y5=[stackedAcetVolFraction, fliplr(stackedMethVolFraction)];
Y6=[stackedMethVolFraction, fliplr(stackedWaterVolFraction)];
%Plotting of the stacked volume fractions
figure
plot(t2, COVolFraction,'m', t2, stackedCO2VolFraction,'c', t2,
stackedFormVolFraction, 'k', t2, stackedAcetVolFraction, 'r', t2,
stackedMethVolFraction, 'g', t2, stackedWaterVolFraction, 'b');
fill(T2,Y1, 'm', T2, Y2, 'c', T2, Y3, 'k', T2, Y4, 'r', T2, Y5, 'g',T2, Y6,
'b');
legend( 'CO', 'CO2', 'Formic Acid', 'Acetic Acid', 'Methanol', 'Water');
ylabel('Volume Fraction, [%]');
xlabel('t, [min]');




%Cumulative Mass Yield - Similar to the stacked volume fraction above, only
%here the cumulative mass yield of each component is found to show the
%closure of the mass balance
stackedCumCO2PercentYield=cumCOPercentYield+cumCO2PercentYield;
stackedCumFormPercentYield=stackedCumCO2PercentYield+cumFormPercentYield;
stackedCumAcetPercentYield=stackedCumFormPercentYield+cumAcetPercentYield;
stackedCumMethPercentYield=stackedCumAcetPercentYield+cumMethPercentYield;
stackedCumWaterPercentYield=stackedCumMethPercentYield+cumWaterPercentYield;
%Creating vectors to make a filled plot
Y1=[baseLine, fliplr(cumCOPercentYield)];
Y2=[cumCOPercentYield, fliplr(stackedCumCO2PercentYield)];
Y3=[stackedCumCO2PercentYield, fliplr(stackedCumFormPercentYield)];
Y4=[stackedCumFormPercentYield, fliplr(stackedCumAcetPercentYield)];
Y5=[stackedCumAcetPercentYield, fliplr(stackedCumMethPercentYield)];
Y6=[stackedCumMethPercentYield, fliplr(stackedCumWaterPercentYield)];
%Plotting the stacked cumulative yields
figure
plot(t2, cumCOPercentYield,'m', t2, stackedCumCO2PercentYield,'c', t2,
stackedCumFormPercentYield, 'k', t2, stackedCumAcetPercentYield, 'r', t2,
stackedCumMethPercentYield, 'g', t2, stackedCumWaterPercentYield, 'b');
fill(T2, Y1, 'm', T2, Y2, 'c', T2, Y3, 'k', T2, Y4, 'r', T2, Y5, 'g',T2, Y6,
'b');
legend( 'CO', 'CO2', 'Formic Acid', 'Acetic Acid', 'Methanol', 'Water');
ylabel('Cumulative mass yield, [%]');
xlabel('t, [min]');
%Plotting the stacked cumulative yields with the water yield removed to
%zoom in on the other components
figure
plot(t2, cumCOPercentYield,'m', t2, stackedCumCO2PercentYield,'c', t2,
stackedCumFormPercentYield, 'k', t2, stackedCumAcetPercentYield, 'r', t2,
stackedCumMethPercentYield, 'g');
fill(T2, Y1, 'm', T2, Y2, 'c', T2, Y3, 'k', T2, Y4, 'r', T2, Y5, 'g');
legend( 'CO', 'CO2', 'Formic Acid', 'Acetic Acid', 'Methanol');
ylabel('Cumulative mass yield, [%]');
xlabel('t, [min]');




%LHV of Output gas (kJ/g) - just exiting the bed at the top - 293 kj/mol CO,
%211.5 kj/mol Formic Acid, 814.6 kj/mol Acetic Acid, 638.2 kJ/mol Methanol.
%Both the wet and dry LHV values were calculated.
```

```
torrGasLHVwet=zeros(1,tDivisions+1);
for k=1:(tDivisions+1);
    torrGasLHVwet(1,k)=
((293/28.01)*sumCOProdM(1,k)+(211.5/46.026)*sumFormProdM(1,k)+(814.6/60.053)*
sumAcetProdM(1,k)+(638.2/32.042)*sumMethProdM(1,k))/(sumCOProdM(1,k)+sumCO2Pr
odM(1,k)+sumFormProdM(1,k)+sumAcetProdM(1,k)+sumMethProdM(1,k)+sumWaterVaporP
rodM(1,k)+0.000000001);
end

torrGasLHVdry=zeros(1,tDivisions+1);
for k=1:(tDivisions+1);
    torrGasLHVdry(1,k)=
((293/28.01)*sumCOProdM(1,k)+(211.5/46.026)*sumFormProdM(1,k)+(814.6/60.053)*
sumAcetProdM(1,k)+(638.2/32.042)*sumMethProdM(1,k))/(sumCOProdM(1,k)+sumCO2Pr
odM(1,k)+sumFormProdM(1,k)+sumAcetProdM(1,k)+sumMethProdM(1,k)+0.000001);
end
%Plotting the torrefaction gas LHV values, wet and dry, in time
figure
plot(t2, torrGasLHVwet);
ylabel('LHV wet, [MJ/kg]');
xlabel('t, [min]');

figure
plot(t2, torrGasLHVdry);
ylabel('LHV dry, [MJ/kg]');
xlabel('t, [min]');



% Plotting the Total Gas Flow vs. Total Mass Yield to further show the
% closure of the mass balance
figure
[hAx, hLine1, hLine2]=plotyy(t2,TotalGasFlow,t2, totalMassYield);
xlabel ('t, [min]');
set(hAx(2),'YLim',[0 100])
set(hAx(2),'YTick',[0:10:100])
ylabel (hAx(1), 'Overall Gas Outflow [g/min]');
ylabel (hAx(2), 'Overall Mass Yield [%]');

% Plotting the Total Gas Yield vs. Total Mass Yield
figure
[hAx, hLine1, hLine2]=plotyy(t2,stackedCumWaterPercentYield,t2,
totalMassYield);
xlabel ('t, [min]');
ylabel (hAx(1), 'Overall Gas Mass Yield [%]');
ylabel (hAx(2), 'Overall Solid Mass Yield [%]');
```

ODE function

```
function dYdt=torrfun4_1_4(t,Y)
```

```matlab
    global UAInt UABioR UAInsR UABioZ UAInsZ1 UAInsZ2 Vc torrTemp tlimit
tDivisions dz zspan zDivisions rspan rDivisions massInitial BetaExt Tenv
TenvK nuExt PrExt g kExt d1 d2 d3 L chimneyL kIns kBio aAir nuAir BetaAir
PrAir vFG ReInt cpAir rhoAir kAir TinAir rhoCpBio rhoIns cpIns

    t  %Display the time while executing

    %In order to make the formation of various equations easier, matrices
    %were build for various variables, such as temperature throughout the
    %reactor, mass in the biomass section, and gas component quantities,
    %all built from the Y matrix in the ODE.


    %Temperature  matrix
    Temp=zeros(zDivisions,rDivisions+3);
    j=1;
    while j<=rDivisions+3
        i=1;
        while i<=zDivisions
            Temp(i,j)=Y(i+(j-1)*zDivisions);
            i=i+1;
        end
        j=j+1;
    end

    %Mass matrix
    i=1;
    j=1;
    Mass=zeros(zDivisions, rDivisions+1); %in grams
    while i<=zDivisions
        for j=(1:rDivisions+1)
            if j==1
                Mass(i,j)=0;
            else
                Mass(i,j)=Y(i+(j-2)*zDivisions+(zDivisions*(rDivisions+3)));
            end
            j=j+1;
        end
        i=i+1;
    end

    %Gas quantity matrix - quantities at points in the reactor
    i=1;
    j=1;
    Gas=zeros(zDivisions, 6);
    while i<=zDivisions
        for j=(1:6)
            Gas(i,j)=Y(i+(j-
1)*zDivisions+(zDivisions*(rDivisions+3+rDivisions)));
            j=j+1;
        end
        i=i+1;
    end
```

```matlab
%   Chimney Inlet Temperature Model - see the report for a full
%   explanation, but this is based on the reactor tested in India.
    if (t>=0) && (t<(8*60))
        TinAir=50;
    elseif (t>=(8*60)) && (t<(16*60))
        TinAir=106.25*(t/60)-800+(152.75/2)*sin((t/60)*(2*pi)/7.33);
    elseif (t>=(16*60) && (t<(34*60)))
        TinAir=-22.22*(t/60)+1255.56+(152.75/2)*sin((t/60)*(2*pi)/7.33);
    elseif (t>=(34*30)) && (t<(151*60))
        TinAir=500+(152.75/2)*sin((t/60)*(2*pi)/7.33);
    elseif (t>=(151*60)) && (t<(158*60))
        TinAir=-64.29*(t/60)+10207.14+(152.75/2)*sin((t/60)*(2*pi)/7.33);
    else
        TinAir=50;
    end

    %Air Properties for the flue gas
    TinAirK=TinAir+273;
    [aAir, rhoAir, muAir, nuAir, kAir, cpAir,
PrAir]=airProp2(TinAirK,{'alpha' 'rho' 'my' 'ny' 'k' 'cp' 'Pr'});
    BetaAir=1/TinAirK;
    m=9.67; % kg Air/kg fuel - calculated from stoichiometric combustion of
pine wood

   %Air Properties for ambient air
    [PrExt, nuExt, kExt]=airProp2(TenvK,{'Pr' 'ny' 'k'});
    BetaExt=1/TenvK; %at 20C, 1/K

    % Chimney Flow Calculations - See section in the report on chimney
    % calculations
    vFG=0.65*(2*g*chimneyL*(TinAirK-TenvK)/TinAirK)^(1/2);
%http://www.arch.hku.hk/teaching/lectures/airvent/sect03.htm
    phiV=0.65*(pi/4)*d1^2*(2*g*chimneyL*(TinAirK-TenvK)/TinAirK)^(1/2);
    ReInt=vFG*d1/nuAir; % = 14.703e3

    %Penetration depth calculation
%     delta=(d2-d1)/2; %penetration depth
%     tPen=0.05*delta^2/aAir; % time to long term hearting
%     tLong=0.1*delta^2/aAir; % time to long term hearting


%   Radial Heat Transfer Coefficients

%   Radial Heat Transfer (External)
    GrExt=(g*BetaExt*(Y(rDivisions+3)-(Tenv-0.1))*L^3)/(nuExt^2);
    RaExt=GrExt*PrExt;
    NuExt=0.59*(RaExt)^(0.25); % Nusselt - free convection - vertical
cylinder
    hExtConv=NuExt*kExt/(L); %0.9513
    hExtRad=0.339; %Calculated from data from Perry - see spreadsheet
    UAExt1=((hExtConv)*pi*d3*dz); %W/K for comparison
    UAExt2=((hExtRad)*pi*d3*dz); %W/K for comparison
    UAExt=((hExtConv+hExtRad)*pi*d3*dz); %W/K

    %Radial Heat Trasnfer Coefficients (Internal, Biomass, Insulation)
```

```
    GrInt=(g*BetaAir*(TinAir-(Temp(1,2)))*chimneyL^3)/(nuAir^2); %for
verification
    ff=0.25*((1.82*log10(ReInt)-1.64)^(-2));
    NuInt=((ff/2)*(ReInt-1000)*PrAir)/(1+12.7*((ff/2)^(0.5))*(PrAir^(2/3)-
1))*(1+(d1/chimneyL)^(2/3))*(2.96/3.30)^(0.14); %for the transition region,
taken from Perry's
    hInt=NuInt*kAir/(L); %W/m2 K
    UAInt=((hInt*pi*d1*dz)); %W/K

    %Calculation of Biot number and UA for the biomass
    BiotNumber= hInt*((pi/4)*(d2^2-d1^2)*L)/((pi*d1*L)*kBio);
    UABioRTotal=(2*pi*kBio*L)/(log(d2/d1)); %W/K

    %Calculation of UA for each annular region of biomass
    j=1;
    UABioR=zeros(1,rDivisions);
    while j<=rDivisions
        UABioR(1,j)=(2*pi*kBio*dz)/(log(rspan(j+1)/rspan(j))); %Inner
Diameter
        j=j+1;
    end

    %UA for insulation
    UAInsR=(2*pi*kIns*dz)/(log(d3/d2));



    %Axial Heat Trasnfer Coefficients (Biomass, Insulation)
    %Axial heat transfer coefficient for each horizontal slice of biomass
    UABioZTotal=(kBio/L)*((pi/4)*(d2^2-d1^2)); %W/K
    i=1;
    UABioZ=zeros(1,rDivisions);
    while i<=rDivisions
        UABioZ(1,i)=(kBio/dz)*(pi*((rspan(1,i+1)^2) - (rspan(1,i)^2)));
%Inner Diameter
        i=i+1;
    end
    %Axial UA for the insulation
    UAInsZ1=(kIns/dz)*((pi/4)*(((d3+d2)/2)^2-(d2^2))); %Inner Diameter
    UAInsZ2=(kIns/dz)*((pi/4)*((d3^2)-((d3+d2)/2)^2)); %Inner Diameter

    %Building a matrix of Q=UA (delta T) for radial heat flow for all
    %points in the reactor
    i=1; % axial z counter
    j=1; % radial counter
    heatFlowR=zeros(zDivisions,rDivisions+3); %two extra having one for
internal (chimney), insulation, and external
    for i=1:(zDivisions)
        for j=1:(rDivisions+3)
            if j==1
                heatFlowR(i,j)=UAInt*(Temp(i,j)-Temp(i,j+1));%heatFlow is the
heat flowing out of the point, not out of
            elseif (j>1) && (j<=(rDivisions+1))
                heatFlowR(i,j)=UABioR(1,j-1)*(Temp(i,j)-Temp(i,j+1));
            elseif j==(rDivisions+2)
```

```matlab
                    heatFlowR(i,j)=UAInsR*(Temp(i,j)-Temp(i,j+1));
                else
                    heatFlowR(i,j)=UAExt*(Temp(i,j)-Tenv);
                end
                j=j+1;
            end
            i=i+1;
    end


    %Building a matrix of Q=UA (delta T) for axial heat flow for all points
    %in the reactor
    i=1;
    j=1;
    heatFlowZ=zeros(zDivisions-1,rDivisions+3); %one extra for top and bottom
surfaces
    for i=1:(zDivisions-1)
        for j=1:(rDivisions+3)
            if j==1
                heatFlowZ(i,j)=0;%heatFlow is the heat flowing out ofthe
point, not into
            elseif (j>1) && (j<=(rDivisions+1))
                heatFlowZ(i,j)=UABioZ(1,j-1)*(Temp(i,j)-Temp(i+1,j));
            elseif j==(rDivisions+2)
                heatFlowZ(i,j)=UAInsZ1*(Temp(i,j)-(Temp(i+1,j)));
            else
                heatFlowZ(i,j)=UAInsZ2*(Temp(i,j)-Temp(i+1,j));
            end
            j=j+1;
        end
        i=i+1;
    end


    %Differential matrix for the ODE
    i=1;
    j=1;
    dYdt=zeros((((rDivisions+3)+rDivisions+6)*(zDivisions)),1);


% dT Equations based on mass balances.
    for i=1:(zDivisions)
        %Bottom Layer of Reactor
        if i==1
            for j=1:(rDivisions+3)
                %Chimney
                if j==1
                    dYdt((i+((zDivisions)*(j-1))))=((vFG/dz)*(TinAir-
Temp(i,j)))+((-heatFlowR(i,j)/(rhoAir*cpAir*(pi/4)*d1^2*dz)));
                %Biomass Region
                elseif (j>1) && (j<=rDivisions+1)
                    dYdt((i+((zDivisions)*(j-1))))=(heatFlowR(i,j-1)-
heatFlowR(i,j)-heatFlowZ(i,j))/(rhoCpBio*pi*((rspan(j))^2-(rspan(j-
1))^2)*dz); %I am not sure the right grammar to call the r values
                %First layer of insulation
                elseif j==(rDivisions+2)
                    dYdt((i+((zDivisions)*(j-1))))= (heatFlowR(i,j-1)-
heatFlowR(i,j)-heatFlowZ(i,j))/(rhoIns*cpIns*pi*(((d3+d2)/4)^2-(d2/2)^2)*dz);
                %Outer layer of insulation
```

```matlab
            else
                dYdt((i+((zDivisions)*(j-1))))= (heatFlowR(i,j-1)-
heatFlowR(i,j)-heatFlowZ(i,j))/(rhoIns*cpIns*pi*((d3/2)^2-((d3+d2)/4)^2)*dz);
            end
            j=j+1;
        end
    %Middle Layers of Reactor
    elseif (i>1) && (i<zDivisions)
        for j=1:(rDivisions+3)
            %Chimney
            if j==1
                dYdt((i+((zDivisions)*(j-1))))=((vFG/dz)*(Temp(i-1,j)-
Temp(i,j)))+((-heatFlowR(i,j)/(rhoAir*cpAir*(pi/4)*d1^2*dz)));
            %Biomass Region
            elseif (j>1) && (j<=rDivisions+1)
                dYdt((i+((zDivisions)*(j-1))))=((heatFlowR(i,j-1)-
heatFlowR(i,j))+(heatFlowZ(i-1,j)-heatFlowZ(i,j)))/(rhoCpBio*pi*(rspan(j)^2-
rspan(j-1)^2)*dz); %I am not sure the right grammar to call the r values
            %First layer of insulation
            elseif j==(rDivisions+2)
                dYdt((i+((zDivisions)*(j-1))))= ((heatFlowR(i,j-1)-
heatFlowR(i,j)+(heatFlowZ(i-1,j)-
heatFlowZ(i,j)))/(rhoIns*cpIns*pi*(((d3+d2)/4)^2-(d2/2)^2)*dz));
            %Outer layer of insulation
            else
                dYdt((i+((zDivisions)*(j-1))))= ((heatFlowR(i,j-1)-
heatFlowR(i,j))+(heatFlowZ(i-1,j)-
heatFlowZ(i,j)))/(rhoIns*cpIns*pi*((d3/2)^2-((d3+d2)/4)^2)*dz);
            end
            j=j+1;
        end
    %Top Layer of Reactor
    else
        for j=1:(rDivisions+3)
            %Chimney
            if j==1
                dYdt((i+((zDivisions)*(j-1))))=((vFG/dz)*(Temp(i-1,j)-
Temp(i,j)))+((-heatFlowR(i,j)/(rhoAir*cpAir*(pi/4)*d1^2*dz)));
            %Biomass Region
            elseif (j>1) && (j<=rDivisions+1)
                dYdt((i+((zDivisions)*(j-1))))=((heatFlowR(i,j-1)-
heatFlowR(i,j))+(heatFlowZ(i-1,j)))/(rhoCpBio*pi*(rspan(j)^2-rspan(j-
1)^2)*dz); %I am not sure the right grammar to call the r values
            %First layer of insulation
            elseif j==(rDivisions+2)
                dYdt((i+((zDivisions)*(j-1))))= ((heatFlowR(i,j-1)-
heatFlowR(i,j)+(heatFlowZ(i-1,j)))/(rhoIns*cpIns*pi*(((d3+d2)/4)^2-
(d2/2)^2)*dz));
            %Outer layer of insulation
            else
                dYdt((i+((zDivisions)*(j-1))))= ((heatFlowR(i,j-1)-
heatFlowR(i,j))+(heatFlowZ(i-1,j)))/(rhoIns*cpIns*pi*((d3/2)^2-
((d3+d2)/4)^2)*dz);
            end
            j=j+1;
        end
    end
```

```matlab
            i=i+1;
        end

% dM Equations
% dYdt is for the actual ODE matrix, and thus should be negative, however
% the dMassLoss is used internally to calculate the water production, and
% thus should be positive
    dMassLoss=zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;

    %Constants from curve fit for a negative dM/dt - see the mass loss
    %model in the report
    A1=1.060157196106470E-10;
    B1=-9.416651575039170E-08;
    C1=2.842620902725070E-05;
    D1=-3.577882654575320E-03;
    E1=1.605497667363730E-01;


    A2=-6.774831817669070E-04;
    B2=1.682861057122920E-01;


    A3=1.363321014297400E-03;
    B3=-5.747339156383470E-01;


    A4=1.311122498070620E-10;
    B4=-2.642886132993150E-07;
    C4=1.983381490748260E-04;
    D4=-6.551707727055310E-02;
    E4=+7.999105610878530E00;


    %dYdt and MassLoss (the negative of each other)
    for i=1:(zDivisions)
        for j=(2):(rDivisions+1)
            %Temps 120 to 290
            if (Temp(i,j)>=120) && (Temp(i,j)<290)
                dYdt((i+((zDivisions)*(j-
2))+(zDivisions*(rDivisions+3))))=Mass(i,j)/60*(A1*(Temp(i,j)^4)+B1*(Temp(i,j
)^3)+C1*(Temp(i,j)^2)+D1*Temp(i,j)+E1);
                dMassLoss(i,j)=Mass(i,j)/60*-
(A1*(Temp(i,j)^4)+B1*(Temp(i,j)^3)+C1*(Temp(i,j)^2)+D1*Temp(i,j)+E1);
            %Temps 290 to 360
            elseif (Temp(i,j)>=290) && (Temp(i,j)<360)
                dYdt((i+((zDivisions)*(j-
2))+(zDivisions*(rDivisions+3))))=Mass(i,j)/60*(A2*(Temp(i,j))+B2);
                dMassLoss(i,j)=Mass(i,j)/60*-(A2*(Temp(i,j))+B2);
            %Temps 360 to 400
            elseif (Temp(i,j)>=360) && (Temp(i,j)<400)
                dYdt((i+((zDivisions)*(j-
2))+(zDivisions*(rDivisions+3))))=Mass(i,j)/60*(A3*(Temp(i,j))+B3);
                dMassLoss(i,j)=Mass(i,j)/60*-(A3*(Temp(i,j))+B3);
            %Temps 400 and above
            elseif (Temp(i,j)>=400)
                dYdt((i+((zDivisions)*(j-
2))+(zDivisions*(rDivisions+3))))=Mass(i,j)/60*(A4*(Temp(i,j)^4)+B4*(Temp(i,j
)^3)+C4*(Temp(i,j)^2)+D4*Temp(i,j)+E4);
```

```matlab
                    dMassLoss(i,j)=Mass(i,j)/60*-
(A4*(Temp(i,j)^4)+B4*(Temp(i,j)^3)+C4*(Temp(i,j)^2)+D4*Temp(i,j)+E4);
                %Temps below 120
                else
                    dYdt((i+((zDivisions)*(j-2))+(zDivisions*(rDivisions+3)))))=
0;
                    dMassLoss(i,j)=0;
                end
                j=j+1;
            end
            i=i+1;
    end
    cumMassLoss=sum(dMassLoss, 2); %cumulative mass loss for water
calculation


% dX Equations - the order of components, by column, is as follows: CO,
% CO2, Formic Acid, Acetic Acid, Methanol, and Water. The kinetics for CO
% and CO2 are distinct from the volatiles of Formic, Acetic, and Methanol.
% See the report for the differing approaching to modelling. Water merely
% comprises the remainder of the mass lost.

    %Permanent Gas Models
    COProd= zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;
    for i=1:(zDivisions)
        for j=2:(rDivisions+1)
            %For Temps from 180 to 215
            if (Temp(i,j)>=180) && (Temp(i,j)<215)
                COProd(i,j) = Mass(i,j)/60*4.291253644390620E+11*exp(-
1.852648795828730E+04/(Temp(i,j)+273.15));
            %Temps 315 to 248
            elseif (Temp(i,j)>=215) && (Temp(i,j)<248)
                COProd(i,j) = Mass(i,j)/60* 5.769720854250670E+05*exp(-
1.214549037799540E+04/(Temp(i,j)+273.15));
            %Temps 248 to 273
            elseif (Temp(i,j) >=248) && (Temp(i,j)<273)
                COProd(i,j) = Mass(i,j)/60*1.250205865052110E+07*exp(-
1.372205817964490E+04/(Temp(i,j)+273.15));
            %Temps 273 to 288
            elseif (Temp(i,j) >=273) && (Temp(i,j)<288)
                COProd(i,j) = Mass(i,j)/60*1.121309388162950E+02*exp(-
7.545719704344710E+03/(Temp(i,j)+273.15));
            %Temps 288 to 325
            elseif (Temp(i,j) >=288) && (Temp(i,j)<325)
                COProd(i,j) = Mass(i,j)/60*(5.48075036943674E-06*(Temp(i,j)-
288)+1.822399552895100E-04);
            %Temps 325 to 350
            elseif (Temp(i,j) >=325) && (Temp(i,j)<350)
                COProd(i,j) = Mass(i,j)/60*(-1.54011087583468E-05*(Temp(i,j)-
325)+3.850277189586690E-04);
            %All else beyond these regions
            else
                COProd(i,j)=0;
            end
```

```matlab
            j=j+1;
        end
        i=i+1;
    end
    cumCOProd = sum(COProd,2); %cumulative per row, not the whole reactor,
for the water calculations

    %Similar to CO, but with different kinetics constants
    CO2Prod= zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;
    for i=1:(zDivisions)
        for j=2:(rDivisions+1)
            if (Temp(i,j)>=180) && (Temp(i,j)<215)
                CO2Prod(i,j) = Mass(i,j)/60*4.482720921818850E+04*exp(-
9.457674776212580E+03/(Temp(i,j)+273.15));
            elseif (Temp(i,j)>=215) && (Temp(i,j)<248)
                CO2Prod(i,j) = Mass(i,j)/60*1.077385688185970E+02*exp(-
6.403231733858230E+03/(Temp(i,j)+273.15));
            elseif (Temp(i,j) >=248) && (Temp(i,j)<273)
                CO2Prod(i,j) = Mass(i,j)/60*3.956374697156560E+02*exp(-
6.958152072919520E+03/(Temp(i,j)+273.15));
            elseif (Temp(i,j) >=273) && (Temp(i,j)<288)
                CO2Prod(i,j) = Mass(i,j)/60*7.033174733294510E+01*exp(-
6.233769988459170E+03/(Temp(i,j)+273.15));
            elseif (Temp(i,j) >=288) && (Temp(i,j)<325)
                CO2Prod(i,j) = Mass(i,j)/60*(2.444173326065040E-
05*(Temp(i,j)-288)+1.150618933936710E-03);
            elseif (Temp(i,j) >=325) && (Temp(i,j)<350)
                CO2Prod(i,j) = Mass(i,j)/60*(-8.219852258323100E-
05*(Temp(i,j)-325)+2.054963064580770E-03);
            else
                CO2Prod(i,j)=0;
            end
            j=j+1;
        end
        i=i+1;
    end
    cumCO2Prod = sum(CO2Prod,2); %cumulative per row, not the whole reactor

    %Volatiles production models

    FormProd= zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;
    for i=1:(zDivisions)
        for j=2:(rDivisions+1)
            %Temp 182 to 228
            if (Temp(i,j)>=182) && (Temp(i,j)<228)
                FormProd(i,j) = (Mass(i,j)*4.683755827440820E-
07)/(60)*(Temp(i,j)-182);
            %Temps above 228
            elseif (Temp(i,j)>=228)
                FormProd(i,j) = Mass(i,j)/60*1.925824613964100E+01*exp(-
6.843190806752710E+03/(Temp(i,j)+273.15));
            %Temps below 182
```

```matlab
            else
                FormProd(i,j)=0;
            end
            j=j+1;
        end
        i=i+1;
    end
    cumFormProd = sum(FormProd,2); %cumulative per row, not the whole reactor


    %Acetic Acid follows the same structure as Formic
    AcetProd= zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;
    for i=1:(zDivisions)
        for j=2:(rDivisions+1)
            if (Temp(i,j)>=182) && (Temp(i,j)<228)
                AcetProd(i,j) = (Mass(i,j)*4.287173210214720E-
07)/(60)*(Temp(i,j)-182);
            elseif (Temp(i,j)>=228)
                AcetProd(i,j) = Mass(i,j)/60*3.556337665939760E+01*exp(-
6.827121246687870E+03/(Temp(i,j)+273.15));
            else
                AcetProd(i,j)=0;
            end
            j=j+1;
        end
        i=i+1;
    end
    cumAcetProd = sum(AcetProd,2); %cumulative per row, not the whole reactor


    %Methanol follows the same structure as Formic
    MethProd= zeros(zDivisions,rDivisions+1);
    i=1;
    j=2;
    for i=1:(zDivisions)
        for j=2:(rDivisions+1)
            if (Temp(i,j)>=182) && (Temp(i,j)<228)
                MethProd(i,j) = (Mass(i,j)*3.936970625337820E-
07)/(60)*(Temp(i,j)-182);
            elseif (Temp(i,j)>=228)
                MethProd(i,j) = Mass(i,j)/60*4.560621651060780E-01*exp(-
4.943411476739980E+03/(Temp(i,j)+273.15));
            else
                MethProd(i,j)=0;
            end
            j=j+1;
        end
        i=i+1;
    end
    cumMethProd = sum(MethProd,2); %cumulative per row, not the whole reactor


    %Calculation of water production to make up the remainder of the solid
    %mass loss.
    cumWaterProd= zeros(zDivisions,1);
    i=1;
```

```matlab
    for i=1:(zDivisions)
        cumWaterProd(i,1)=cumMassLoss(i,1)-
(cumCOProd(i,1)+cumCO2Prod(i,1)+cumFormProd(i,1)+cumAcetProd(i,1)+cumMethProd
(i,1));
        i=i+1;
    end

    %Concatenation of production of all gas components for easy building of
    %the dYdt matrix
    gasProd = horzcat(cumCOProd,cumCO2Prod,cumFormProd, cumAcetProd,
cumMethProd, cumWaterProd);

    %Building the dYdt matrix. Note that here is assumed that all gas
    %produced is expelled from the reactor immediately, as the pressure
    %does not build up in the reactor, and thus the amount of gas in the
    %reactor never increases. This also assumes that the concentration of
    %gas in the reactor doesn't change. This assumption can be accepted if
the
    %residence time of the gases in the reator is much smaller than the
    %time step in the model.
    i=1;
    j=1;
    for i=1:(zDivisions)
        for j=1:6 %(1:CO, 2: CO2, 3: Formic, 4: Acetic, 5: Methanol, 6:Water)
            dYdt(i+(j-1)*zDivisions+(rDivisions+3+rDivisions)*zDivisions) =
gasProd(i,j)-(Gas(i,j)/(tlimit/tDivisions));
        end
    end


    %Pause if needed for debugging
    % if t>=100
    %     keyboard
    % end


end
```

Appendix Q

Muffle Furnace Experimental Procedure

In order to gain empirical data for the basis of the modeling of the volatiles production (predominantly of organic acids), a new laboratory set up was constructed. A Nabertherm Controller B180 Muffle Furnace was used. Therein, a biomass chamber was placed, consisting of a sealed container of a cylindrical steel pipe of 2.5 cm diameter, holding 10g of powdered pine needles. Powdered pine needles were used in order to use a small bed that could fit inside the muffle furnace. A light nitrogen flow (1 L/min) was connected to the biomass container (fixed bed reactor) in order to push the volatiles from the reactor to the wash bottles. The muffle furnace was used to control the temperature of the air around the reactor, which drove the heat transfer to the reactor. Additional thermocouples were inserted into the biomass bed and the air in the around the bed to monitor and control the torrefaction process. Following the reactor, the gas flow went through two bubblers, containing 20 mL of demineralized water each, held in an ice bath to maintain the temperature close to 0 °C. The uncondensed gases were then directed to the exhaust. The temperature readings were recorded in LabView. A schematic of the setup is shown below.
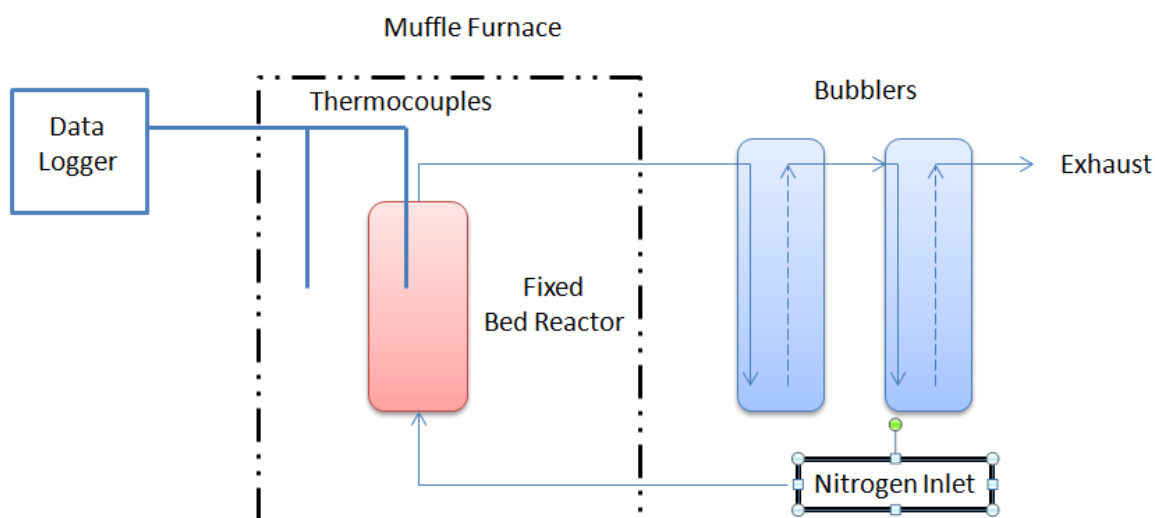

Figure 43 - Schematic of Muffle Furnace Setup

A photo of the arrangement of the reactor inside the furnace is shown in the figure below. Here the nitrogen enters from the lower tube, at the back of the furnace, travels through the reactor, and then leaves the muffle furnace via the opening at the top.

Figure 44 - Photo of Muffle Furnace Setup

A thermocouple was also inserted in the muffle furnace to measure the ambient air in the furnace. This was monintored during the entire experiment to control the heat transfer, as the temperature reading given by the furnace itself showed significant delay in adjusting to the actual air temperature in the oven. On the other hand, the temperature in the biomass responded very quickly to changes seen in the ambient air in the muffle furnace, measured by the extra thermocouple (not the furnace thermocouple). The temperature was driven primarily by the furnace, dependent on the furnace thermocouple, which often resulted in temperatures above the desired oven temperature, even up to 50°C more than desired. To control the temperature in the furnace, thus, the door of the furnace was propped open to varying degrees, thus allowing control of the biomass temperature. The muffle furnace was set to ramp to the desired temperature at a rate of around 5-8 °C/min, according to standard practice in torrefaction. Torrefaction was performed at temperatures of 230, 250, 270, and 290 °C.

As a cumulative measure of the gases only for the isothermal region was desired, the bubblers were not connected at the onset of the experiment. Rather, once the isothermal temperature was reached, the bubbler were then connected to the gas exhaust to only capture volatiles released during this period. After the full residence time of 45 minutes was reached, the bubblers were then disconnected, and the experiment was stopped. The muffle furnace was then set to 20°C to cool, and the door to the furnace was opened fully to cool the biomass quickly. Thus, the temperature of the furnace air dropped quickly

to ambient temperature. In addition, the nitrogen flow through the bed was increased to 2 L/min to increase the cooling rate.

This procedure was only modified for the experiment at 230°C. For this experiment, it was desired to gather some information regarding torrefaction gas production below 230°C, that is from 180°C to 230°C, as torrefaction gas production begins at this point. Thus, the bubblers (filled with 22 mL each of water) were connected when the biomass reached 180°C (182°C actually). When the biomass reached 228°C, the bubblers were quickly disconnected, and 2 mL were extracted from each bubbler with a syringe, and reserved for separate analysis. The bubblers were then reconnected, and the experiment resumed as with the others. The process of extraction took less than 4 minutes to achieve.

Graphs of the temperature profiles for each of the experiments are shown below.
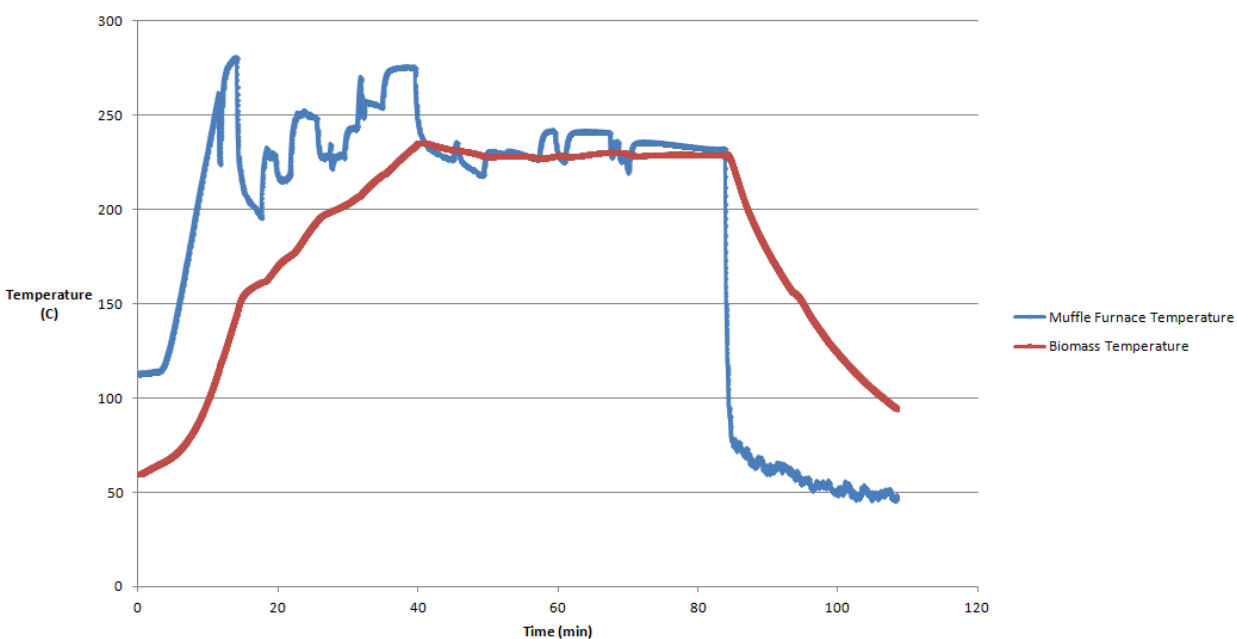

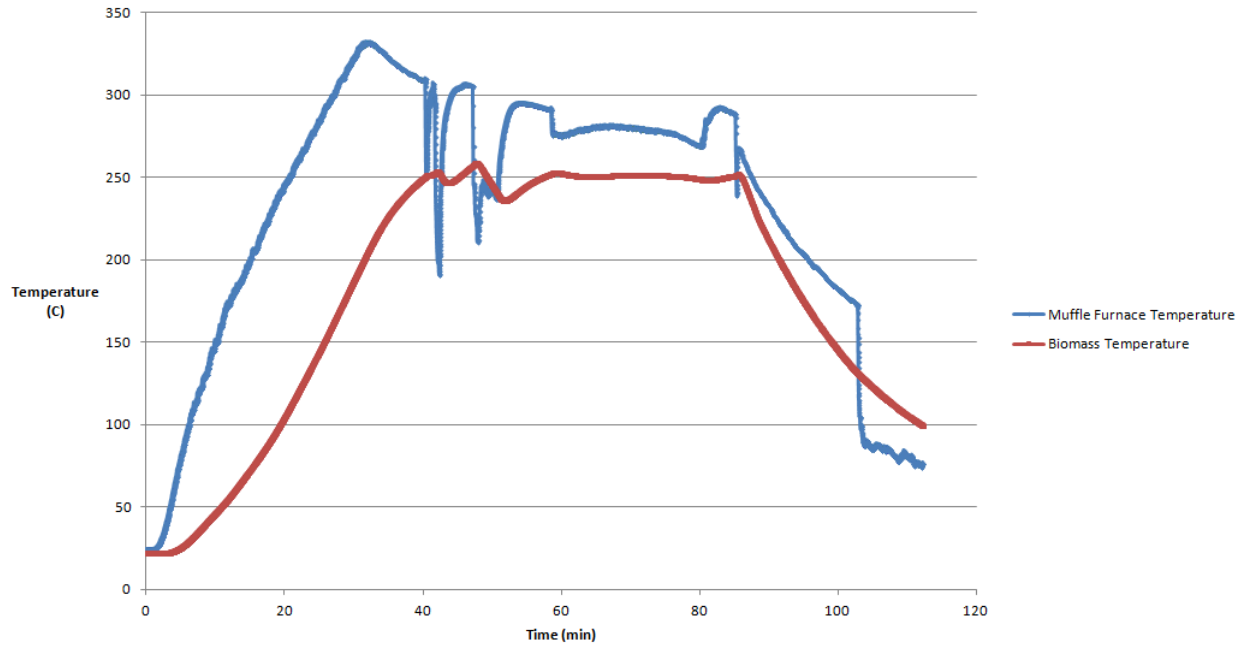**Figure 45 - Muffle Furnace Temperature Profiles (230°C and 45 min)**

Figure 46 - Muffle Furnace Temperature Profiles (250°C and 45 min)
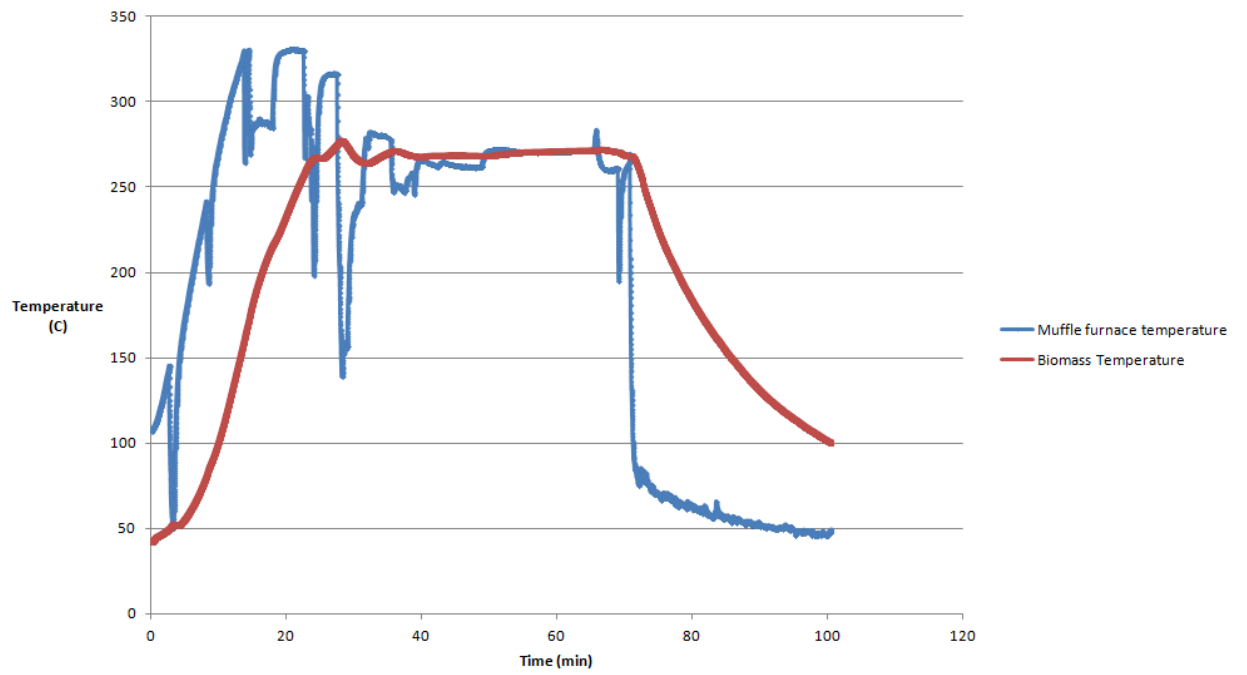

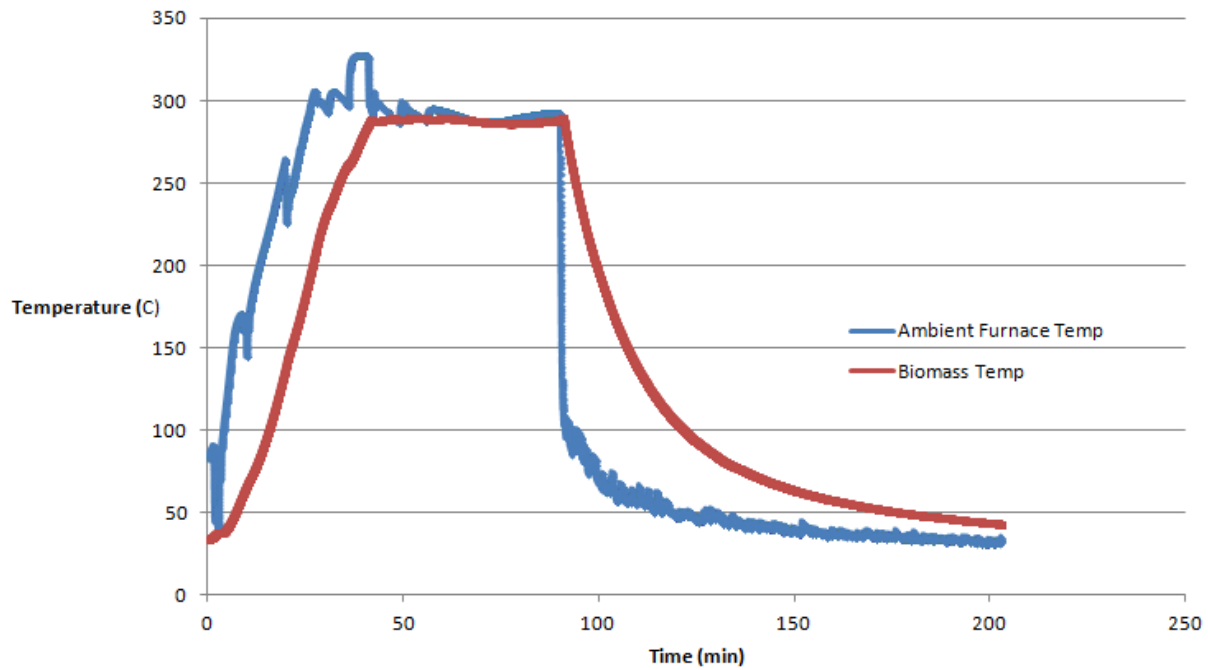**Figure 47 - Muffle Furnace Temperature Profiles (270°C and 45 min)**

Figure 48 - Muffle Furnace Temperature Profiles (290°C and 45 min)

Additional reactor photos are shown below.

Appendix R

Characterization of Volatile Production for 180°C to 230°C

For the characterization of the period in this temperature range, a simplistic approach was taken, due to the limited empirical data obtained (only having one data point for volatiles produced in this temperature range). It was assumed that no volatiles were produced at temperature lower than 180°C. Furthermore, it was assumed that the value of k, the reaction rate coefficient in g/g*min, would increase linearly over this range. Clearly, an Arrhenius relationship was not considered, in order to simplify the calculations. Thus,

$$\frac{dX}{dt} = k(T) * m_{PN}$$

where X is a given volatile component (formic acid, acetic acid, or methanol), k is the reaction rate, and m_{PN} is the mass of pine needles, assumed to approximately constant (an average value for the pine needle mass was estimated from TGA data). Also:

$$k(T) = m_1 * T + b_1$$

where m_1 and b_1 are constants and T is the biomass temperature in °C above 182. In this model, all values of temperature T and time t are taken relative to 182°C, or the time where the biomass temperature passes 182°C, in order to simplify the calculations. Thus, as k is assumed to be zero at 182°C, b_1 is thus set to zero. Furthermore, in order to relate. In order to solve for k, and use the data for volatiles collected, the differential equation was to be integrated vs. time. Thus, a dependency of k in time was needed. From experimental data from the muffle furnace experiments, the ramp of the biomass temperature was estimated for this range, according to the linear equation below:

$$T(t) = m_2 * t$$

With m_2 estimated to be 3.16151 °C/min (assuming a climb from 182 to 228 °C in the measured time of 14.55 minutes of the ramp in the muffle furnace experiment) and b_2 set to be 0, as T has been defined to be relative to 182°C. Time t was measured in minutes after reaching 182°C. Combining these three equations gives:

$$\frac{dX}{dt} = (m_1 * (m_2 * t)) * m_{PN}$$

Integrating with respect to time gives:

$$X = m_{PN} * \left(m_1 \left(\frac{m_2 * t^2}{2} \right) \right)$$

The only parameter to be solved for is m_1, which varies depending on the volatile component. Solving for m_1 at $t_f = 14.55\ min$ gives the following:

$$m_{1i} = \frac{X_{fi}}{m_{PN} * \left(m_1 \left(\frac{m_2 * t_f{}^2}{2} \right) \right)} \left[\frac{g}{g * min * °C} \right]$$

The assumptions for the parameters are shown in the table below, while X_{fi} is the measured quantity of volatile component i (formic acid, acetic acid, or methanol) collected over 182°C to 228°C.

Parameter	Assumed Value
X_0	0
k_0	0
m_{PN}	10.593 g
m_2	3.16151 °C/min
b_1 and b_2	0

The values for X_f and m_f are for each of the three volatile components are shown in the table below.

	Xf (g)	m1 (g/g*min*C)
Formic Acid	0.00166	4.683755827440820E-07
Acetic Acid	0.00152	4.287173210214720E-07
Methanol	0.001396	3.936970625337820E-07

These values were implemented in the Matlab simulation with the following formula, assuming only temperature and mass dependency of the reaction kinetics:

$$\frac{dX}{dt} = m_1 * (T_{real} - 182) * m_{PN}$$

Where T_{real} is the actual temperature in °C, not the temperature relative to 182°C.

Appendix S

Design Session Transcript and Artefact Examples

First, an example of a transcript produced by Vidyut Mohan for the Design Sessions is given below.

Chankana Scenarios Activity Session, 16/04/2015

Vidyut : Shall we start? I will give you different scenarious and you have to tell me what would be your reactions and what steps you will take to solve the problem.

Vidyut: Description of scenario 1 for women.

You are managing a sweet shop for one week, as the owner has left on holiday, and thus the sweet shop is in your care. One evening, several men walk in, sit down, and order halwa. After a few minutes, they order a bottle of whiskey. You tell them that the sweet shop does not serve alcohol, but they demand nonetheless, and begin to yell, until you give in, and decide to go to the nearby shop. You tell your male colleague to bring back a bottle of whiskey, which they proceed to drink within a few minutes. They quickly become drunk, and make comments at people walking by on the street. One of them gets into a fight with a taxi driver, breaking a table in the restaurant. Within minutes, the police arrive, and take the drunk men away. You regret ever buying the bottle of whiskey. Should you tell your boss when he returns? And how will you tell him if you do tell?

Girls sigh and hesitate o speak. Santoshi encourages them.

Vidyut: You can discuss amongst each other and also tell.

The to girls look towards to the older women to help them..

Deepa: We will tell sorry, today we made a mistake.

Vidyut: So you will tell the boss then?

Lalita: Yes. We will own up to our mistake and we will apologise. We shouldn't lie or hide it from him.

Vidyut: Now the 2nd scenario.

Again, you are managing a clothing shop for one week, as the owner is on holiday for a week for Holi. He purchased 2 full stocks of garments for the restaurant before leaving, which is usually enough for 1 week. However, the first day after he left, the shop had a large surge of customers unexpectedly, and made a lot of money. However, after that day, you have finished one entire stock, and are almost done with the second. You need to purchase more in order keep the shop open, but you have never made any large purchases for the shop, nothing above 1000 Rs. You have called your boss 10 times already, but he has turned his phone off, and is not answering. You can use restaurant's money to make the purchase,

but your employer has never let you purchase a stock in the past. Do you purchase them? Or close the restaurant until the owner returns?

Deepa: In my opinion a decision should be taken.

Vidyut: Why?

Girl: Because..then the shop will lose business in the remaining days of the two weeks that the garments were meant to last.

Vidyut: What about you Lalita?

Lalita answers to the other women in Kumaoni but Santoshi asks her to speak in Hindi to us.

Lalita: Whatever Deepa has said is correct.

Deepa: Don't know, I don't know…

There will be monetary loss, therefore I will take the decision to go and buy stocks. If he has given the responsibility, then I should fulfill it. Otherwise why would he have left me incharge?

Vidyut: The next scenario is this

You are the owner of the clothing now. You notice that your shop has been declining for the past 6 months, and it is predominantly due to the lack of enthusiasm and effort by your employees. They seem to be very tired, and they don't seem to care much about their work. Thus, you have noticed that the quality of customer is much worse, and you are having few customers than before. You need to improve things quickly if you want to keep your shop alive, and you know that the quality of the work of your employees is the problem. What do you do?

Deepa: By talking to them!

Vidyut: Like how? How will you talk with them?

Santoshi: Talk.. Talk..

Lalita: There are working there, so they must also be having some problems and there will be reasons for that. We need to understand that first.

Deepa: We need to tell them that if the business doesn't grow, your salary will also become less. That's why you should pay more attention. It will be beneficial for you and us.

Lalita: We should speak to them, know their problem and find a solution for this.

Vidyut: So you will keep a meeting and speak to everyone regarding this and find a solution together?

Girls: Yes

Vidyut: Ok… so the next scenario is..

You are an employee in a Saree shop and one day an old couple comes in and the wife is looking for a saree. They have travelled very far, all the way, for this. They like a saree, which is the last piece and are about to buy it , when all of a sudden, the owner of the shop walks in with one of her young friends and likes the same saree and decides to buy it. The old couple had been waiting patiently all this while for this piece. How would you feel? What do you do? What do you say to your boss?

Lalita: Those people who have come from far, you have to give the saree to them.

Deepa: You can give the same saree sometime again to your friends.

Vidyut: How will you explain this to the owner of the shop?

Deepa: I will say that you can give the saree to your friend later, these people have come from far and it is very unlikely that they will come back again. Hence, they should take the saree.

Vidyut: Will take the step to tell your boss that this is not right?

Deepa: In my opinion, one should raise this with the owner.

Vidyut: Anything else?

Vidyut: So the next scenario is:

You are an employee of a weaving center. One morning, you show up to work, and the woman in charge does not arrive, but rather, a man you have never seen before walks in and says that he is now managing things. He informs you that the manager had an emergency family situation to take care of, and will be gone for two weeks, and she has left him in charge of the weaving center until she comes back. He says that it will be his personal mission to make the center twice as efficient as it is now, with no one wasting time while at work, and they everyone will have to work hard to make sure that happens before the owner comes back. How would you react? What would you think? What would you feel?

Geeta: This is a very interesting point…

Deepa: In one way he is our supervisor and we should listen to him to whatever extent possible.

Deepa and Lalita: Whatever is within our capacity we will do, and if we need to do something more we won't be able to do. We have never even seen him before. It will take time to understand him as well. If he explains what to do in a polite manner, we will also feel nice. If he is not polite or scolds a lot, then work will not happen properly. Whatever that can be done within our capacity, we will do it.

Vidyut: Ok, theek hai. Thank you. Do you want to say anything else? No? Ok!

Vidyut: Now I just wanted to ask something small. Did you work somewhere else before or have yoy been just working here?

Girls: Just here.

Vidyut: Then you must have been working here for months?

Deepa: Not months, years..

Vidyut: Can you talk about some good and bad memories/experiences during your time here? What events/memories come to your mind that you would like to share?

Santoshi, Lalita to Deepa: Tell, you have been working here for 10 years..

Deepa to Lalita: You tell, you have also been working here for 3 years…

Some whispering between the two girls..

Lalita: Some friends who used to work with us, they got married and have gone away, but their memories are still with us. We used to have lots of fun together, sometimes too much joking around. We used to fight a lot as well, so those are some of the bad memories that we had.

Vidyut: Any bad memory worth sharing?

Deepa: It is always nice to keep bad memories hidden.

Vidyut: Any not that bad memory that you would like to share? You can also share good memories….

Santoshi: Don't tell bad memories then, tell good ones….

Deepa: I have told, these are the ones…

Vidyut: Or you can talk about some memories where someone has praised your work or said something critical about it? Or you got a scolding from a supervisor…

Deepa: Yes, I have such memories…and I have been scolded by a supervisor as well…

Lalita: One thing bad is that we work late at night here as well. We even forget about food and stay here late at night.

Deepa: No, these are memories, good memories….

Vidyut: So use to work late at night a lot?

Deepa: Yes, we used to do that a lot during the time of orders.. These are good memories, I liked them a lot. We got to sleep here as well. Because of this we stayed together..

Vidyut: Is there anytime when you felt that that the work that you were doing could have been done in a better way?

Deepa: No… there is nothing like that..

Vidyut: Or did anyone give you praise for your work?

Deepa: No, I remember, there was training going on and I got the first prize for my work…

Lalita: compared to other centers, work in our center is going well…The waevers here are doing well.

Deepa and Lalita: There was a weaving fair as well, where people really liked and appreciated our work. The Village people also appreciated our work and said that they brought a good name to the village. Our name came in the newspaper as well, with our parents and supervisors. It felt nice. Whoever worked with us, their name also came. The most vivid memory is this till now. Don't know about the future.

Vidyut: Anything else?

Lalita: Bad memory….hmmm…fights!!

Vidyut: Between yourselves? Is this a friendly fight?

Deepa: When you are working with your colleagues for a long time at the same place, there can be times that you end up confronting each other.

Lalita: There is an element of fun in that too.

Deepa: This keeps on going on…

Vidyut: Ok

Vidyut: Have you ever been scolded before?

Deepa: We also get scolded now and then.

Lalita: Not big scoldings, small ones…

Vidyut: Any examples that come to your mind?

Deepa: When we were trainees, we would be scolded now and then…

Vidyut: On what issue were you scolded?

Deepa: On weaving.. "There is an order, weave well, weave fast..".

Vidyut: You were trained here as well?

Deepa: First the center was somewhere else in chankana and it was on rent. This was built later.

Vidyut: Ok.. theek hai..if you have anything more to share you can do so..otherwise we are done…
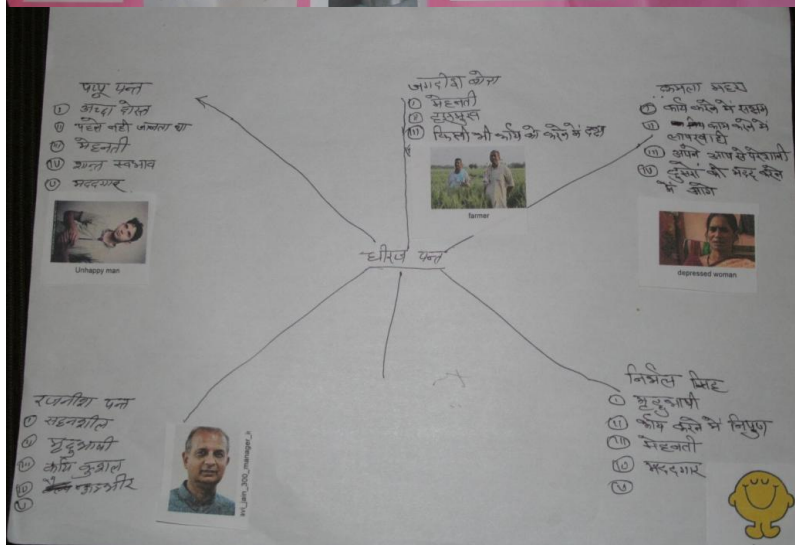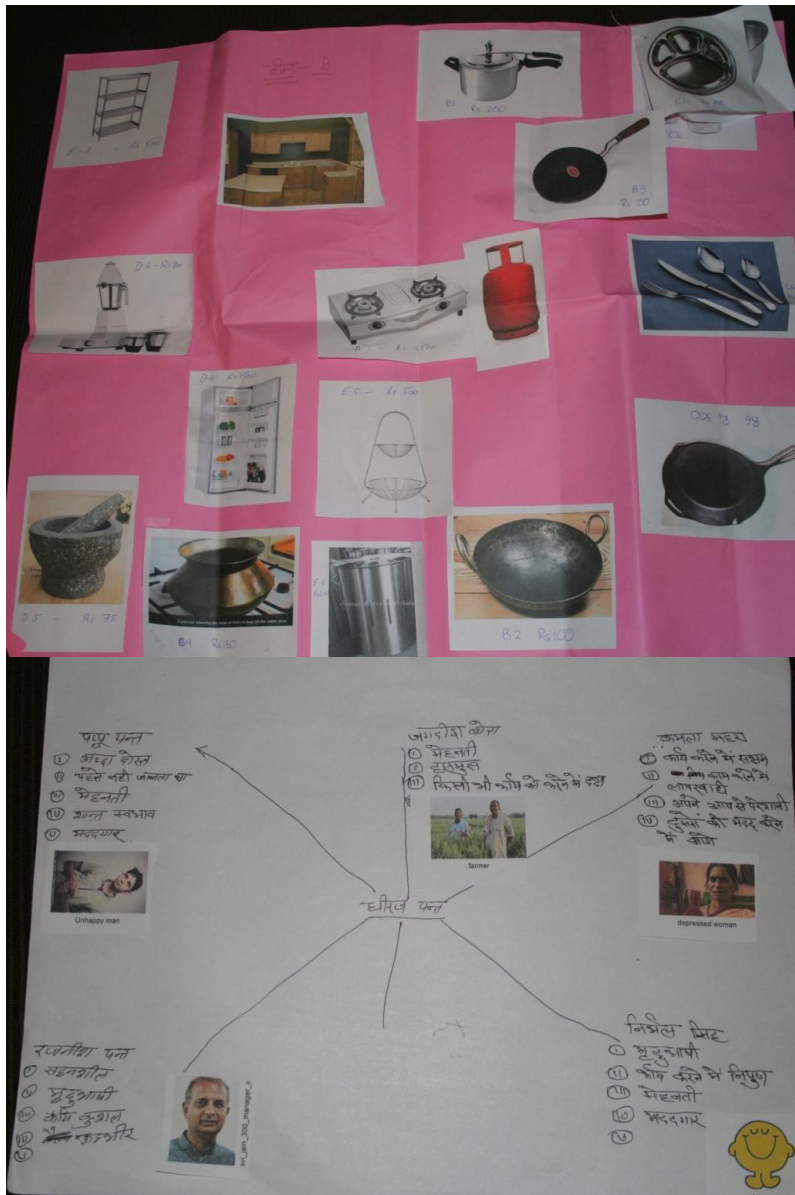
Deepa: And..where are you from?

Vidyut: From Delhi (and explained our research)

Geeta: So you go to Chachret and make the women collect pine needles?

Vidyut: Explained the design sessions carried out with pine needle collectors there.

Sample Artefacts

The sample artefacts, produced from various design sessions, are shown below, including collages and other artefacts.

Appendix T

Gas Model Production Outflow Graphs

The following graphs depicts the outflow of the 6 gas components from the reactor as given by the model.
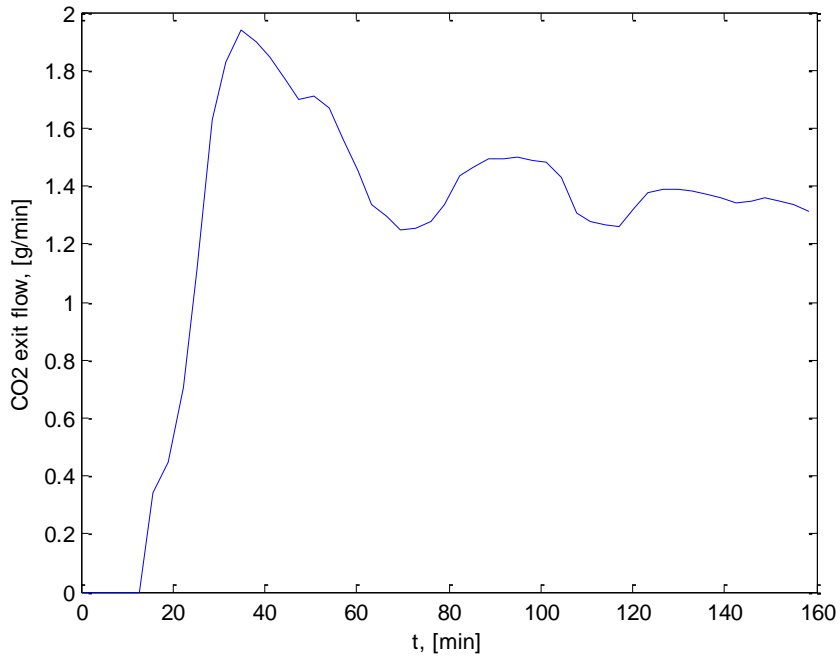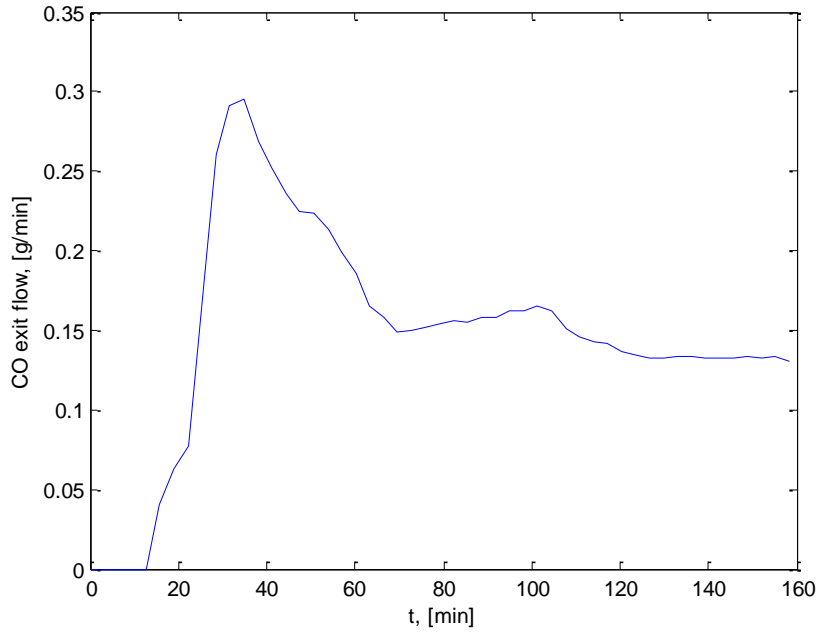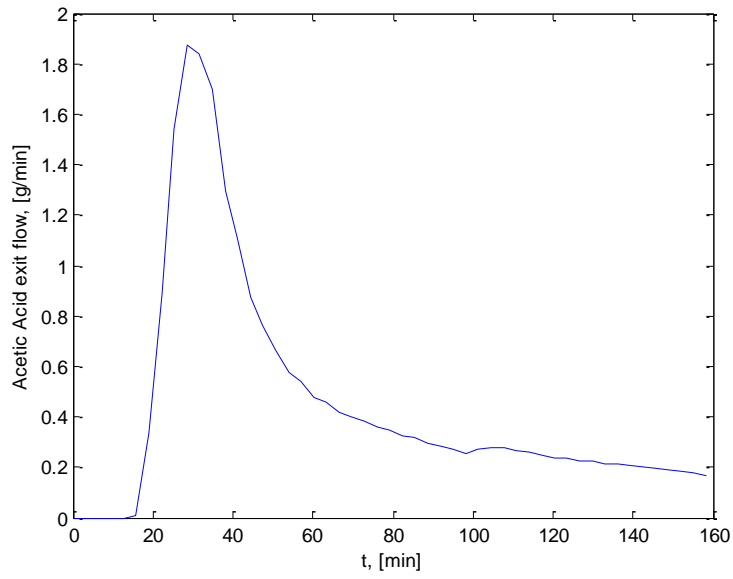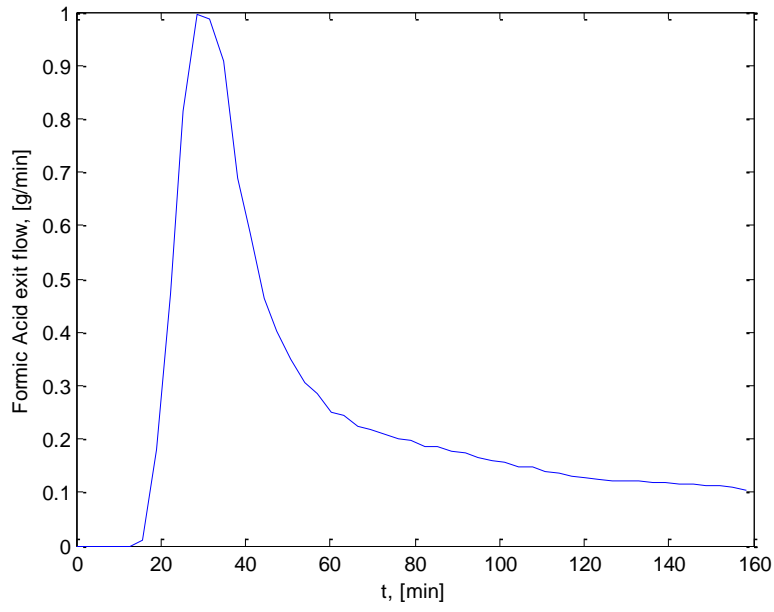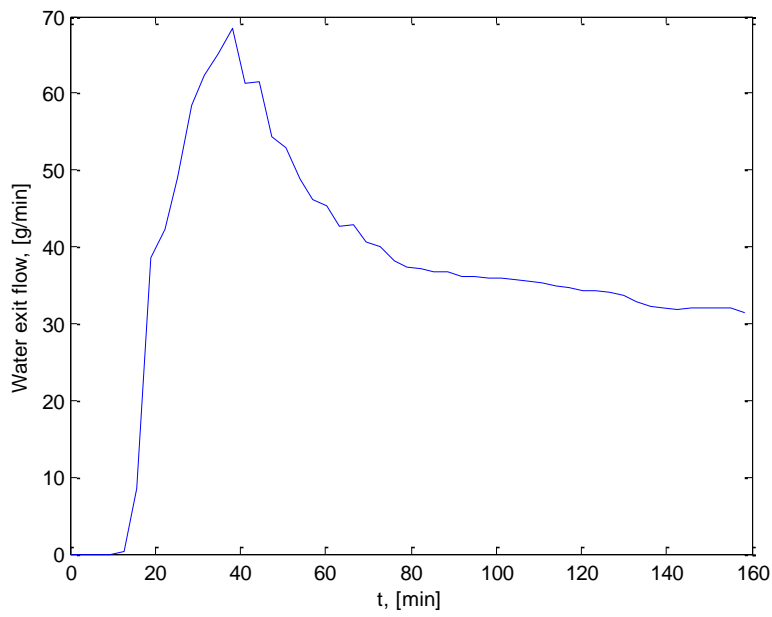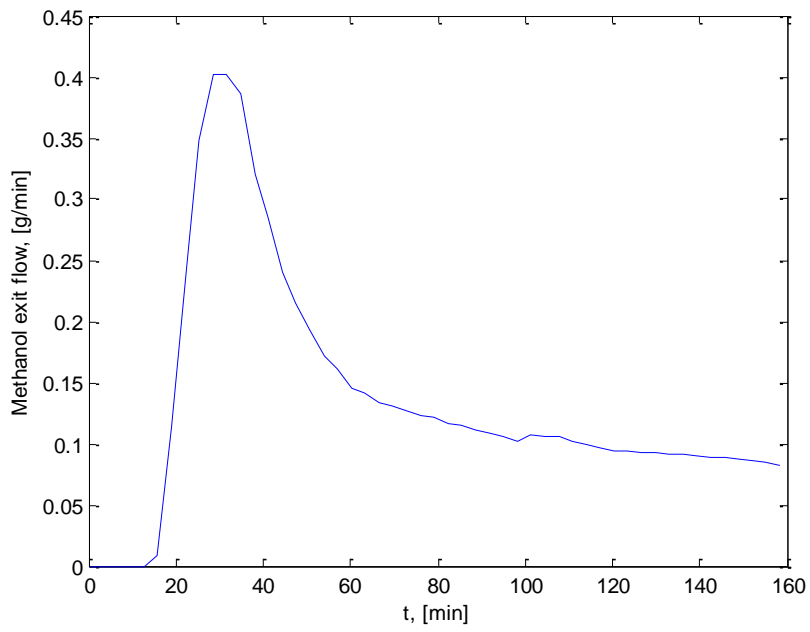
Appendix U

Business Model Schematics

Here the Business Model Canvas for the business system is shown.
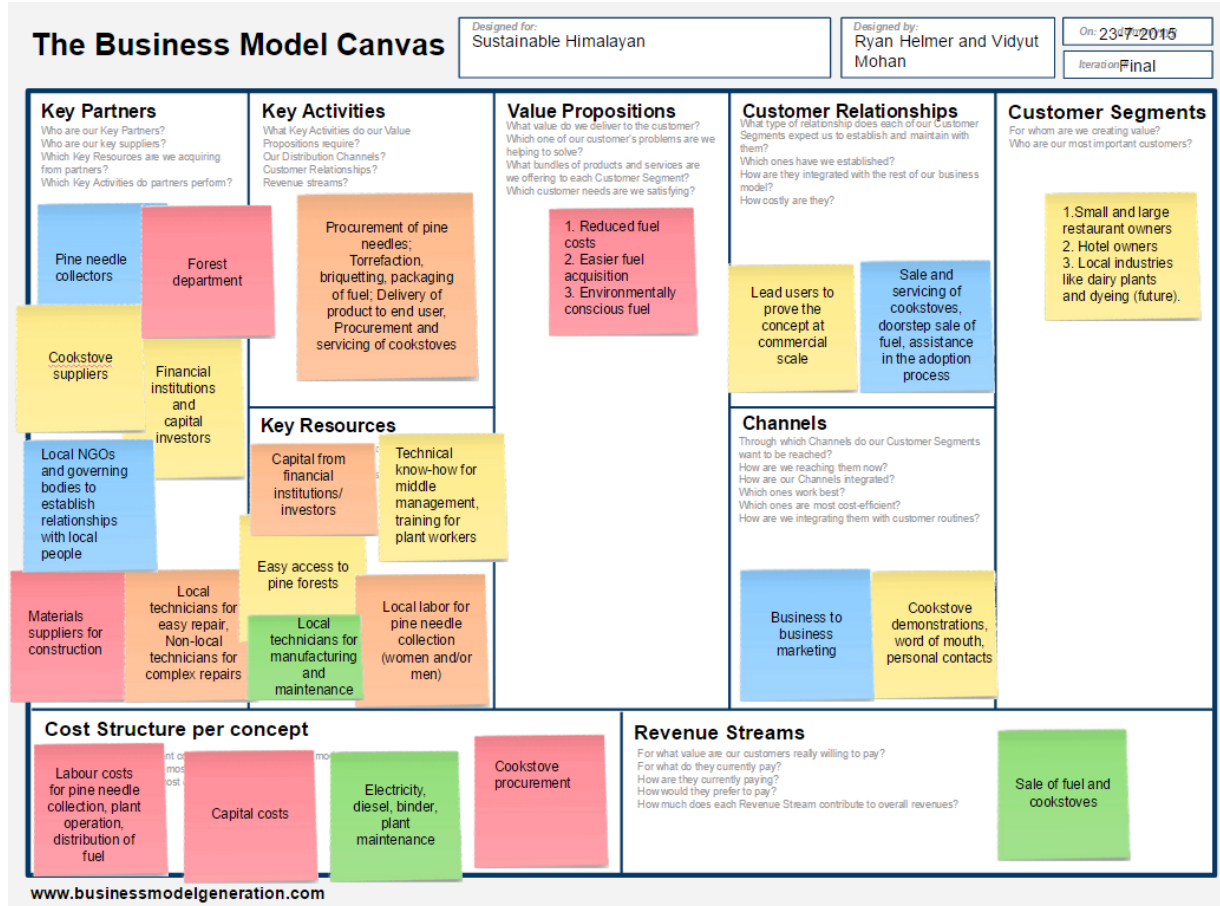
Here the System Map for the service system is shown. More information is given in Mohan's report.
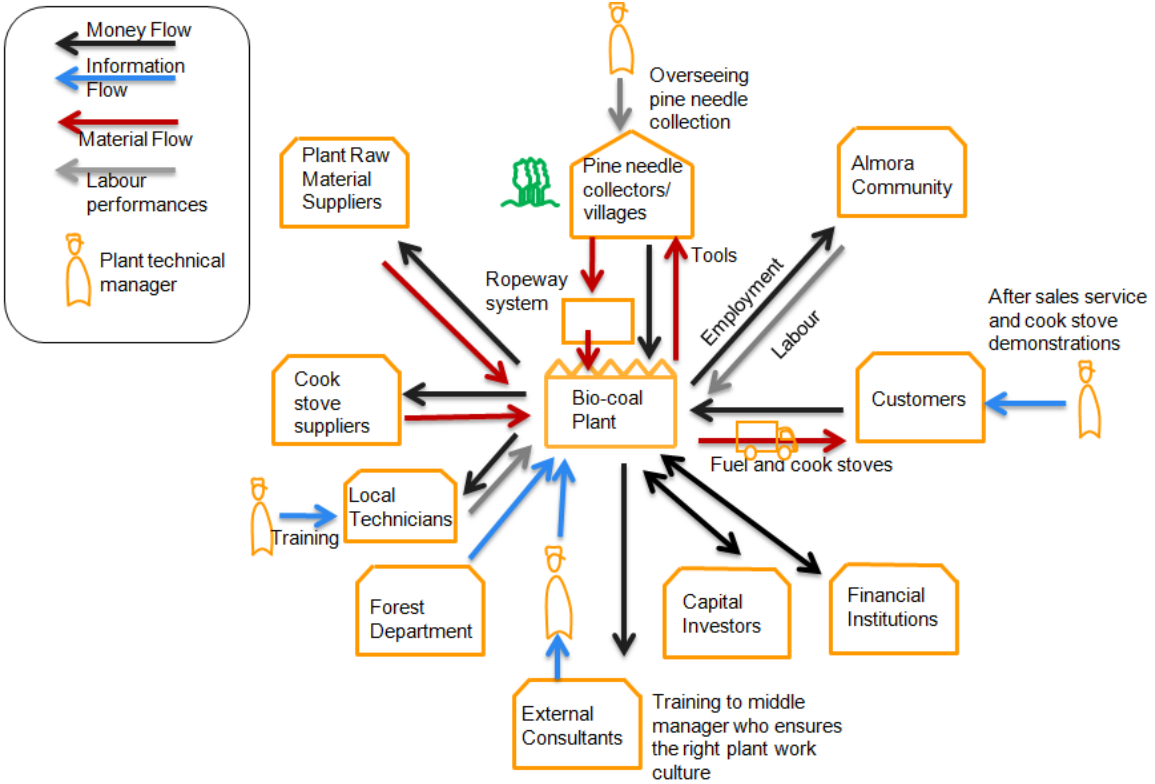
Appendix V

Revenues and Overall Financial Results

The assumptions for the calculation of revenues for the business are shown below.

Selling Price Charcoal (Rs per ton)	Selling Price Charcoal (Rs per kg)	
15000	15	
Output per steel drum reactor (kg bio coal)	Size of steel drum reactor (m3)	Total process time (hr)
3.9486825	0.064	3.5

| Cookstove Costs (Rs/kg fuel)	(Rs/m3 reactor/yr)		
0.3875	6926.941332		
Operational Weeks/yr	Work Day (hours/day)	Operational Time (hr/yr)	Output (kg/yr/m3 reactor)
12	14	1008	17875.97763

The revenue versus reactor size (cumulative) is shown below:

Cumulative Reactor Size (m3)	Revenue (Rs/yr)
0	0.000
1	261212.723
2	522425.446
3	783638.169
4	1044850.893
5	1306063.616
6	1567276.339
7	1828489.062
8	2089701.785
9	2350914.508

10	2612127.231
11	2873339.954
12	3134552.678
13	3395765.401
14	3656978.124
15	3918190.847
16	4179403.570
17	4440616.293
18	4701829.016
19	4963041.739
20	5224254.463
21	5485467.186

The Revenue, Costs, and Profit for the chosen service system (centralized, cable car collection, proprietary vehicle distribution) are shown below, per cumulative reactor size.

Cumulative Reactor Size (m3)	Revenue (Rs/yr)	Total Costs (Rs/yr)	Specific costs (Rs/kg)	Profit (Rs/yr)
0	0.000	675628.901		-675628.901
1	261182.459	909631.691	50.892	-648449.232
2	522364.917	1132462.481	31.679	-610097.563
3	783547.376	1355293.270	25.275	-571745.894
4	1044729.835	1578124.060	22.073	-533394.226
5	1305912.293	1800954.850	20.152	-495042.557
6	1567094.752	2023785.640	18.871	-456690.888
7	1828277.211	2246616.429	17.956	-418339.219
8	2089459.669	2469447.219	17.270	-379987.550
9	2350642.128	2692278.009	16.736	-341635.881
10	2611824.586	2915108.799	16.309	-303284.212
11	2873007.045	3137939.589	15.960	-264932.543
12	3134189.504	3360770.378	15.669	-226580.875
13	3395371.962	3583601.168	15.423	-188229.206
14	3656554.421	3806431.958	15.211	-149877.537
15	3917736.880	4029262.748	15.028	-111525.868
16	4178919.338	4252093.537	14.868	-73174.199
17	4440101.797	4474924.327	14.727	-34822.530
18	4701284.256	4697755.117	14.602	3529.139
19	4962466.714	4920585.907	14.489	41880.807
20	5223649.173	5154588.697	14.419	69060.476

21	5484831.632	5377419.486	14.326	107412.145

The same data, for the same service system, only now after year 6 when the majority of capital costs have been written off, is shown below.

Cumulative Reactor Size (m3)	Revenue (Rs/yr)	Total Costs (Rs/yr)	Specific costs (Rs/kg)	Profit (Rs/yr)
0	0.000	0.000	0.000	0.000
1	261212.723	195705.754	10.948	65506.969
2	522425.446	380239.508	10.635	142185.939
3	783638.169	564773.261	10.531	218864.908
4	1044850.893	749307.015	10.479	295543.877
5	1306063.616	933840.769	10.448	372222.846
6	1567276.339	1118374.523	10.427	448901.816
7	1828489.062	1302908.277	10.412	525580.785
8	2089701.785	1487442.031	10.401	602259.754
9	2350914.508	1671975.784	10.392	678938.724
10	2612127.231	1856509.538	10.385	755617.693
11	2873339.954	2041043.292	10.380	832296.662
12	3134552.678	2225577.046	10.375	908975.632
13	3395765.401	2410110.800	10.371	985654.601
14	3656978.124	2594644.554	10.368	1062333.570
15	3918190.847	2779178.307	10.365	1139012.539
16	4179403.570	2963712.061	10.362	1215691.509
17	4440616.293	3148245.815	10.360	1292370.478
18	4701829.016	3332779.569	10.358	1369049.447
19	4963041.739	3528485.323	10.389	1434556.417
20	5224254.463	3713019.077	10.385	1511235.386
21	5485467.186	3897552.830	10.383	1587914.355

The same data is also shown for the centralized system without the use of a cable (this system was not chosen finally).

Cumulative Reactor Size (m3)	Revenue (Rs/yr)	Total Costs (Rs/yr)	Specific Costs (Rs/kg)	Profit (Rs/yr)
0	0.000	277782.682	-	-277782.682
1	261182.459	783279.585	43.823	-522097.127
2	522364.9173	1017779.488	28.471	-495414.571

3	783547.3759	1252280.391	23.354	-468733.015
4	1044729.835	1486780.294	20.795	-442050.460
5	1305912.293	1721281.197	19.260	-415368.904
6	1567094.752	2319039.100	18.535	-751944.348
7	1828277.211	2541289.003	17.772	-713011.793
8	2089459.669	2763539.906	17.179	-674080.237
9	2350642.128	2990409.809	16.731	-639767.681
10	2611824.586	3212659.712	16.340	-600835.125
11	2873007.045	3434910.615	16.015	-561903.570
12	3134189.504	3657160.518	15.739	-522971.014
13	3395371.962	3879411.421	15.503	-484039.458
14	3656554.421	4101661.324	15.299	-445106.903
15	3917736.880	4323911.227	15.119	-406174.347
16	4178919.338	4546162.130	14.962	-367242.791
17	4440101.797	4773020.032	14.835	-332918.235
18	4701284.256	4995270.935	14.709	-293986.680
19	4962466.714	5217520.838	14.595	-255054.124
20	5223649.173	5439770.741	14.492	-216121.568
21	5484831.632	5662021.644	14.399	-177190.013

Also, the data is shown for the decentralized system (also not chosen finally).

Cumulative Reactor Size (m3)	Revenue (Rs/yr)	Total Costs (Rs/yr)	Specific production costs (Rs/kg)	Profit (Rs/yr)
0	0.000	0.000	0.000	0.000
1	261182.459	2844236.819	159.128	-2583054.360
2	522364.917	3057319.896	85.525	-2534954.978
3	783547.376	3270402.972	60.990	-2486855.596
4	1044729.835	3483486.049	48.723	-2438756.214
5	1305912.293	3696569.126	41.363	-2390656.832
6	1567094.752	3909652.202	36.456	-2342557.450
7	1828277.211	4122735.279	32.951	-2294458.068
8	2089459.669	4335818.356	30.322	-2246358.686
9	2350642.128	4548901.432	28.278	-2198259.305
10	2611824.586	4761984.509	26.642	-2150159.923
11	2873007.045	4975067.586	25.304	-2102060.541
12	3134189.504	5188150.662	24.189	-2053961.159
13	3395371.962	5401233.739	23.245	-2005861.777
14	3656554.421	5614316.816	22.436	-1957762.395
15	3917736.880	5827399.892	21.735	-1909663.013

16	4178919.338	6040482.969		21.122	-1861563.631
17	4440101.797	6253566.046		20.581	-1813464.249
18	4701284.256	6466649.122		20.100	-1765364.867
19	4962466.714	6679732.199		19.669	-1717265.485
20	5223649.173	6892815.276		19.282	-1669166.103
21	5484831.632	7105898.352		18.931	-1621066.721

Appendix W

List of Interviews

Domestic End Users	Institutions
Villagers	Schools
Peri- urban residents	University campus and its dormitory
Migrant workers	Military campus
Small Businesses	*Small Industries*
Small eating joint (*dhabas*) owners	Workers at Avani's gasification plant
Restaurant owners	Iron smiths
Hotel/resort owners	Biscuit factory
	Dairy Plant
Fuel Outlets	*Financial Institutions*
LPG warehouses	State Bank of India regional office, Almora
Kerosene/LPG ration shops	Uttarakhand Grameen Bank, Pithoragarh
Government Officials	*Non- Governmental Organizations (NGOs) in Kumaon*
Divisional Forest Officer (DFO) and Forest Ranger, Almora	Various managers and workers at Avani Kumaon, Tripuradevi
District Magistrate of Almora	Founders of Himalprakriti, Munsiyari
Van panchayat (village forest council) sarpanch (head) of Bhandari Village	Founder of Aarohi, Sitoli village
Gram Pradhan (village council head) of Belada Agar Village	Other social activists and people knowledgeable about the local context

Appendix X

Energy Comparison of Reactor Energy Sources (Convective vs. Electric)

Here, the convective reactor is compared with the electrically heated reactor. The energy input for the convective reactor is taken directly from experimental data, based on the pine wood fuel for combustion. The assumptions for this energy input calculation are shown below. A total of 112 MJ in pine wood or torrefaction pellets would be required for each batch, which only produces 84 MJ of energy in torrefied pine needles. As deforestation for the process is not a sustainable option in such a region, torrefied pellets would need to be used as fuel. Clearly, as the input to the process in terms of fuel is higher than the output, the process cannot be sustained (all of the torrefied pine needles from one batch, plus extra fuel, would be needed for the next batch, leaving none for sale). The overall energy efficiency, calculated by including the initial energy value of the pine needles, the fuel input, and the final energy value of the torrefied pine needles, is shown below, coming to 36%.

Reactor Volume (m3)	Mass Input (kg)	Packing Density (kg/m3)	Reacor Output (kg)
0.064	6.1	95.9	3.9486825
Energy Input (kg wood)	Energy Content Wood (MJ/kg)	Energy Input (MJ)	
7.65	14.7	112.455	

Yields (250-15) dry basis			
Mass Yield	Energy Yield	Cal Value	PN Initial Energy
0.8631	0.907	21.15	122.305
Energy Output (MJ)			
83.51463488			
Efficiency			
0.36			

For the electrically heated process, the amount of energy required is based on various measured and assumed parameters, including the reactor size, the packing density, the mositure content of the pine needles, and the temperature of the torrefaction process. The specific heat of increasing the bed to 250°C (based on considerations discussed in Mohan's report) and the latent heat of vaporization for the moisture in the biomass. Furthermore, a heat loss of 20% during the process was assumed. The other assumptions are given in the table below.

Reactor Volume (m3)	Mass Input (kg)	Packing Density (kg/m3)	Reactor Output (kg)
0.064	6.1	95.9	3.948225
Rho Cp (kJ/m3 K)	Energy Input (kJ)	Energy Input (MJ)	
173.1	7175.152348	7.175	

The energy input is calculated according to the equation below.

$$Q = V\rho c_{p-bed}\Delta T + V\rho_{packing}Y_{moisture}h_{fusion}$$

The required energy input was calculated to be 7.2 MJ, much more efficient than the convective reactor. The overall process efficiency, calculated with the initial and final energy values of the pine needles, and the electrical input was calculated, shown below to be 64%. This is a drastic improvement over the convective reactor, which apparently is highly inefficient.

Yields (250-15) dry basis			
Mass Yield	Energy Yield	Cal Value	PN Initial Energy
0.863	0.907	21.15	122.305
Energy Output (MJ)			
83.50495875			
Efficiency			
0.64			