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Opportunities and Challenges in using SOFCs in Waste to Energy Systems

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A summary of research activities and on-going multiple projects at Delft University of Technology aimed at the development of Solid Oxide Fuel Cells (SOFCs) integrated waste to energy systems are presented in this paper. A wide range of studies ranging from pattern cell impedance analysis to integrated system development is also presented. Cleaning the gas to match constraints of SOFCs requires complex approaches. A brief discussion on the achievable system efficiencies with SOFC integrated waste to energy systems is presented and novel concepts such as gasifier- Reversible SOFC integrated power production cum energy storage systems are discussed. Additionally, an overview of a wide range of national, European and international projects that helped or currently helping us to carry out the above mentioned research activities are presented.

Introduction

Biomass is expected to contribute significantly to the production of electricity and heat in the future. However, the high price of biomass often makes several attempts to produce electricity from biomass economically unattractive [1]. On the other hand, effective waste management is considered a challenge in many countries and bio-waste, in many cases, is available for a negative price [2]. This makes it attractive to develop technologies for electricity and heat production from such waste streams. However, highly efficient and inexpensive power plants are required to make these projects economically attractive. This brings in an opportunity to evaluate Solid Oxide Fuel Cells (SOFCs) as efficient energy conversion devices for such plants.

This paper presents a review of the ongoing research activities at the Delft University of Technology, The Netherlands, aiming at the development of waste to energy systems involving SOFCs. Activities at Delft span from studies at electrode level to understand the influence of contaminants on electrochemical fuel oxidation at anodes to complete system design and integration.

Waste Streams (bio), Composition, and Contaminants

A wide variety of waste streams are available at different places and their compositions vary significantly. Some of the major waste streams we consider for energy production are:

Municipal Solid Waste (MSW). The amount of MSW generated globally is approximately 1.3 billion tons. This value is expected to increase and reach the 2.2 billion tons per year by 2025 [3]. It is also worth noting that the composition of MSW changes both qualitatively and quantitatively along the different regions of the world. The regions with low-income countries having the highest fraction of organic waste while in high-income countries MSW mostly contains paper, plastic and other inorganic materials.

Agricultural Waste. The potential of the agricultural waste is hard to estimate due to a wide variety of resources. The availability and the type of residues change significantly from country to country. It is estimated that about 3.7e6 tons per year dry basis of residue is produced globally with a theoretical energy production capacity of 65 EJ per year, mainly from barley, maize, rice, soybean, sugar cane and wheat [4]. The reported total energy production capacity in 2050 often varies widely due to variations in calculation approaches [4].

Human Waste. Besides MSW, humans living in cities produce large amounts of wastewater. The amount and composition of this waste are highly dependent on location, and collection and treatment methods applied. The volume of wastewater globally produced accounts to approximately 330 km^3/year [5]. A minor portion of the wastewater generated is treated and an even smaller fraction is safely reused. The term wastewater usually indicates the water used in houses, offices but also industries and agriculture. It is, therefore, useful to distinguish the wastewater based on its origin into urban, industrial or agricultural wastewater. The wastewater collected in a municipal sewerage, called sewage, after being treated in plants to remove suspended solids and convert soluble organic substances becomes sludge. In 1992, the amount of sludge generated in the USA only was equal to 7 million tonnes per year dry basis [6] and in 2008 the amount of sludge was roughly 6.5 million tonnes dry base [7]. In China, the sludge produced in 2008 was 2,966,000 while in the Netherlands 1,500,000 tonnes dry base [7].

Table 1. Proximate and ultimate analysis of (bio) waste streams

		MSW			Barley straw			Corn cob			Sugar cane bagasse			Sewage sludge 1			Sewage Sludge 2		
		As received	Dry	Dry ash free	As received	Dry	Dry ash free	As received	Dry	Dry ash free	As received	Dry	Dry ash free	As received	Dry	Dry ash free	As received	Dry	Dry ash free
Proximate Analysis																			
Moisture content	wt%	7.0			11.5			7.0			5.8			9.9			73.2		
Ash content	wt%	2.9	3.1		5.2	5.9		2.9	3.1		3.5	3.7		31.5	35.0		12.8	47.8	
Volatile matter	wt%	72.7	78.2	80.7	67.3	76.1	80.9	72.7	78.2	80.7	73.4	77.9	80.9	48.2	53.5	82.3	13.4	50.0	95.7
Fixed carbon*	wt%	17.4	18.7	19.3	15.9	18.0	19.2	17.4	18.7	19.3	17.3	18.4	19.1	10.4	11.5	17.7	0.6	2.2	4.3
Ultimate Analysis																			
Carbon+	wt%	43.2	46.5	48.0	40.9	46.2	49.1	43.2	46.5	48.0	45.0	47.7	49.5	30.6	34.0	52.3	7.2	27.0	51.7
Hydrogen+	wt%	5.3	5.7	5.9	5.0	5.7	6.1	5.3	5.7	5.9	5.7	6.0	6.2	4.4	4.9	7.5	1.0	3.8	7.2
Nitrogen+	wt%	1.7	1.8	2.2	0.5	0.6	0.6	0.4	0.5	0.5	0.5	0.5	0.5	4.2	4.7	7.2	0.9	3.2	6.2
Sulphur+	wt%	0.2	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.2	0.2	1.2	1.3	2.0	0.3	0.9	1.8
Oxygen*	wt%	41.0	44.1	45.6	36.8	41.5	44.1	41.0	44.1	45.6	39.5	41.9	43.6	18.0	20.0	30.8	4.6	17.2	32.9
Total(with halides)*	wt%	100.0	100.0	100.0	100.2	100.3	100.3	100.0	100.0	100.0	100.3	100.3	100.3	100.0	100.0	100.0	100.0	100.0	99.9
Calorific Values																			
Net calorific value (LHV)	MJ/kg	17.4	18.7	22.5	15.1	17.4	18.5	15.1	16.4	16.9	15.6	16.8	17.4	12.4	14.0	21.6	0.9	10.1	19.4
Gross calorific value (HHV)	MJ/kg	16.4	17.6	18.2	16.5	18.7	19.9	16.4	17.6	18.2	17.0	18.1	18.8	13.6	15.1	23.2	2.9	11.0	21.0

+ Measured *Calculated

Table 1 shows the results from proximate and ultimate analysis available on ECN online database Phyllis 2 [8] (MSW #2920 [9], Barley straw #3169 [10], Corn cob #2791 [11], Sugar cane bagasse #3170 [10], Sewage 1 #658, sewage 2 #2810 [12]). The moisture content of the sewage 2 is higher, and this might be due to a different treatment method employed: sedimentation, de-watering and drying are used to lower the moisture content of the sludge. The ash content is found to be higher in sewage waste compared to MSW and agricultural waste as received and it is about tenfold on a dry basis. The volatile matters and fixed carbon are higher in MSW and agricultural waste indicating that they contain a larger amount of gaseous fuel and further helping in an easier ignition [13]. The oxygen content in MSW and agricultural waste is more compared to sewage sludge. The low carbon content in the sewage sludge 2 might be related to the high moisture content.

Unprocessed biomass waste streams like cellulosic food, paper, cotton clothing, and human/animal feces can contain high amounts of moisture (up to or more than 40-50% vol). In order to produce useful energy from such wet biomass waste streams using gasification/combustion, it is important to carry out appropriate pre-treatment steps. Pre-treating wet biomass wastes prior to gasification/combustion lead to a higher conversion temperature, improved gasification/combustion and a lower requirement for excess combustion air; thereby leading to higher net plant efficiencies [14]. Torrefaction is one of the thermochemical pretreatment technologies useful to upgrade lingo-cellulosic biomass to a higher quality fuel (increased LHV and grindability). The process involves heating wet biomass slowly to a temperature of 200-300°C in a non-oxidizing atmosphere [15, 16]. This causes the biomass to become brittle and hydrophobic with a decrease in the O/C and H/C ratios. The resulting "coal-like" fuel with an increased LHV could be utilised as a solid fuel for energy production. Modelling studies carried out within our research group indicate that large-scale SOFC integrated IGCC power plants using high amounts of torrefied biomass as feedstock could produce power with net electrical efficiencies up to 50% (LHV based) [17]. Literature indicates that torrefaction of biomass wastes like human feces and other waste streams can be a good option for water production and as a space fuel [18].

Waste to Energy Research Projects at Delft

Flexifuel-SOFC Project

Flexifuel-SOFC is an industry lead European project aimed at developing an innovative, low-cost, highly efficient and fuel-flexible micro-scale biomass combined heat and power technology comprising a small-scale fixed-bed updraft gasifier, a gas cleaning system, and an SOFC stack [19]. The system is designed and developed for a capacity range of 25 to 150 kW (fuel feed) and is applicable to a wide range of agricultural fuels (wood pellets and wood chips and additionally agricultural waste with various sizes and moisture contents), with high gross electric (40%) and overall (85-90%) efficiencies as well as almost zero emissions.

The project is divided into a technology development part (based on modeling and simulations, test plant construction, performance and evaluation of test runs, risk and safety analysis) as well as a technology assessment part covering risk, techno-economic, environmental and overall impact assessments, market studies etc. as well as dissemination activities. In order to achieve these ambitious goals a multidisciplinary consortium consisting of a biomass conversion technology provider (WindHager Zentralheizung Technik GmbH), an engineering company specialized in the development of energetic biomass conversion systems (BIOENERGIESYSTEME), specialists regarding gas cleaning (TU Delft, HyGear) and fuel cell technologies (IKTS, AVL) as well as partners experienced in market studies and techno-economic assessments (Wuppertal Institut für Klima, Universiteit Utrecht) has been formed.

The team at Delft is involved in assessing the contaminant tolerance limits for SOFCs, and in developing a gas cleaning/processing concept for the integrated plant. HyGear is designing and building the gas processing unit based on the concepts developed at Delft

Development of Advanced Toilet Systems based on Microwave Assisted Plasma Gasifiers and Solid Oxide Fuel Cells

The Bill & Melinda Gates Foundation has awarded Delft University of Technology (TU Delft, the Netherlands) a grant to develop a radically new toilet concept [20]. The system is being developed in order to be able to operate without connections to water, energy, or sewer lines. Costs are expected to be affordable to the poor in developing countries.

Researchers from the Industrial Engineering faculty at TU Delft have developed a water diverting toilet, and the process and energy department is focussing on the development of a plasma gasifier-SOFC system for human waste processing. Microwave technology is applied to produce plasma and the plasma is used to produce syngas from human waste. Syngas is then cleaned and fed to the SOFC to produce power, and a part of the power produced is used for generating the microwaves.

Ming Liu *et al.* have presented a basic system concept indicating how the system can be energy neutral [21]. Power is produced using syngas and the heat from the SOFC is used to dry the human waste. The syngas is cleaned using a gas cleaning system with both high temperature and low-temperature components.

In the initial stages of the project, the entire chain consisting a microwave assisted gasifier, gas cleaning system and an SOFC (single cell) was integrated in the laboratory. Gasifier was operated with solid biomass as fuel [22] and power was produced using the fuel cell. In parallel, an integrated large-scale system was developed. The system included an SOFC system with ~4 kW electric power production capacity (Figure 1) and a large scale gas cleaning unit that was capable of cleaning the gas required for the SOFC plant. The syngas specific SOFC plant was developed jointly by TU Delft and Sunfire GmbH. The next planned step in the development effort is integrated operation of the gasifier and the large scale SOFC system.

Recalde *et al.* [23] with the help of detailed thermodynamic calculations have presented how in future it might be possible to improve this concept. With improved thermal integration, it was shown that it is possible to achieve electrical efficiencies around 40-50% using a similar plant based on microwave assisted plasma gasifier and SOFCs.

Figure 1. 4 kW SOFC power plant designed for gasifier integration at TU Delft.

SCWG-SOFC Project

Supercritical water gasification (SCWG) is a promising technology for treating very wet waste biomass. SOFCs, on the other hand, combine high energy conversion efficiency at high temperature with fuel flexibility. Thus, the combined SCWG-SOFC system is a sustainable solution to reach high thermal and electrical efficiencies. TU Delft, together with a start-up company (Gensos B.V.) is trying to demonstrate the integration of SCWG-SOFC system, using a large scale SCWG pilot plant and SOFC single cells/stack. To reach this stage, the SCWG principle was previously experimentally proven in a small-scale prototype by Gensos [24]. The methane-rich gas obtained by the system can be efficiently converted to green electricity in an SOFC or gas turbine (GT). The contaminants present in the gas are currently being measured at the SCWG pilot plant. On the other hand, TU Delft fuel cell group is developing the gas cleaning unit (GCU) for the SCWG-SOFC integrated testing and for further future applications. Additionally, experiments are being planned for studying the SOFC performance with the cleaned syngas from the gasifier.

In addition to the experiments, thermodynamic modelling of the integrated system concepts is being carried out, and futuristic system concepts are being developed. The joint research efforts are expected to lead to the demonstration of SCWG – SOFC systems and the development of integrated systems at a commercial level.

The LOTUS Project and Biogas-SOFC System Development

A considerable amount of methane emissions is attributed to the uncontrolled natural release from landfills, wastewater treatment plants (WWTPs), and farms. Anaerobic digestion is an efficient technique in order to produce and collect biogas from organic sources. Biogas production is becoming increasingly popular in Europe [25]. By the end of 2014, a total number of 17,240 biogas plants were installed in Europe, (8,300 MW). Generally, biogas from anaerobic digestion consists of methane (60%), carbon dioxide (35%), nitrogen, water vapour and based on the waste sources, minor traces of contaminant gases such as hydrogen sulphide (H_2S), ammonia (NH_3), siloxanes ($SiO\text{-}R_2$) and halogens (HCl).

In conventional WWTPs the biogas produced is flared in order to suppress methane emission. Biogas can be used for power production in commercially available energy conversion devices such as gas engines and gas turbines. When sufficiently cleaned, biogas also can be used as a fuel for SOFCs. The LOTUS project aims at the development of the advanced waste water treatment technologies at a selected location in New Delhi, India (Barapulla drain). Delft University of Technology and Indian Institute of Technology are jointly leading the project. Biogas production is planned and an SOFC based power plant is proposed to produce electric power and heat using the biogas generated.

Wastewater-Ammonia-SOFC Project [26]

This is a project initiated and lead by DHV (presently Royal Haskoning DHV). While there were several partners, TU Delft took care of the SOFC part. The project focussed on energy efficiency improvement in waste water treatment systems. Waste water treatment facilities are used to treat large volumes of waste water and the removal of nitrogen and phosphate from the wastewater is important. This is an energy consuming process step. To eliminate this energy consuming step and to replace it with a potentially energy producing step, a new concept is proposed. It involves the addition of magnesium hydroxide to the wastewater. When appropriate process conditions are provided, $MgNH_4HPO_4$ crystals (struvite) are produced. Ammonia is released upon heating struvite and this ammonia can be used as a fuel for SOFCs. Electric power can then be produced. Nitrogen is thus removed from the waste water stream using electricity producing process step which replaces and electricity consuming traditional process route. When ammonia is removed from struvite, magnesium hydrogen phosphate is produced and this can be used in the phosphate processing industry as an environmentally friendly alternative to mined phosphate ore or as fertilizer. During the project period, an SOFC was operated in the laboratory, producing electric power with ammonia produced from the waste water treatment plant used as the fuel. In 2010, the project won the "De Vernufteling Award", from the Royal Institute of Engineers in the Netherlands for the most innovative project from engineering companies in The Netherlands.

Related Research

Development of SOFC systems based on waste derived fuels requires a clear understanding of chemistry and electrochemistry of fuel oxidation and influence of contaminants on the cell performance. Fuel oxidation electrochemistry and influence of contaminants on electrochemical reactions is studied within our group using pattern electrodes, porous symmetric electrodes, complete cells and stacks.

The electrochemical reactions take place at the triple-phase boundary (TPB), where the gaseous, ionic, and the electronic phases meet. Pattern anodes are usually chosen for studying electrochemistry due to their advantages of easily quantifiable TPB length and the simplified 2D structure. The 2D structure of patterns eliminate the structural and even the gas phase effects which exist in the cermet anodes and can help in understanding the effect of fuel contaminants on the electrochemical reactions kinetics [27, 28, 29, 30, 31].

Experiments are then carried out porous symmetric cells and complete cells with anode and cathode to study these effects further [32, 33]. Studies on complete cells include often reforming studies and the results from these studies are necessary for developing efficient biogas SOFC systems. Detailed understanding of reforming kinetics and its effects on safe and efficient cell performance is aimed at and experiments are complemented with detailed computational fluid dynamic studies [34, 35, 36, 37]. A special focus is on internal dry reforming. While biogas as a methane-rich gas fuel can be used in the SOFC systems, methane needs to be reformed to produce hydrogen and carbon monoxide in order to electrochemically oxidize the fuel. CO_2 presence in biogas is an advantage then and it can be used to dry-reform methane inside the SOFC. On the other hand, high concentrations of carbon in the fuel gas stream increases the chance of carbon deposition in the stack. Dry reforming studies are carried out with the objective of developing safe and efficient biogas-fueled SOFC systems.

Fuel streams coming from waste processing facilities contain contaminants that must be removed to meet the process requirements and the pollution control regulations. Detailed understanding of the influence of contaminants on cell performance helps to design and develop appropriate gas cleaning systems. These impurities such as sulphur compounds, alkali metals, halides, tar and particulates etc may cause fouling, slagging, corrosion and catalyst poisoning in the downstream equipment including fuel cells. Particulates in the fuel gas at SOFC operating temperature are likely to block the microporous anode, hindering the gas diffusion into the pores. Halides and sulphur contaminants at high concentrations can irreversibly damage the anode of the SOFC and seriously affect its lifespan. Therefore, novel integrated systems for gas cleaning have been developed combining different steps including particle filtration, H_2S and HCl removal as well as tar cracking [20, 38].

While developing the complete units integrating waste processing units, gas cleaning units, fuel cell stack and other Balance of Plant components, high efficiencies need to be targeted. Thermodynamic modelling and exergy analysis help with this. Exergy analysis is carried out in our team using tools such as Cycle Tempo and ASPEN. Cycle Tempo is a software tool developed in-house at Delft. Using Exergy analysis, it has been shown how to achieve electrical efficiencies close 50% in waste to energy systems [21, 23]

Summary and Future Work

Research efforts at TU Delft resulted in the following i.e., 1) There is significant potential for high efficiency power production from waste streams when SOFCs are integrated with appropriate waste processing systems, 2) Laboratory scale "proof of the concept" trials were conducted at least in two cases, plasma gasifier-SOFC systems and waste water- ammonia- SOFC systems resulting in electrochemical power production from the proposed process chains. Development efforts have progressed since then resulting in the development of power plant components for large scale system in case of the plasma gasifier-SOFC system. However large scale integrated experiments are yet to be carried out.

In the future, we plan to continue to develop a detailed understanding of the fuel oxidation electrochemistry and the influence of contaminants on SOFCs and use the knowledge thus developed for coming up with large scale, efficient, fully integrated systems.

While power production from waste streams using solid oxide fuel cells is appealing, the potential that SOFCs could be operated in reverse mode producing fuels might make such systems even more attractive. This is an ongoing activity in our group and we are studying the thermodynamic and technical potential for such systems with the EU funded BALANCE project

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