Natural ventilation based bioclimatic redevelopment
Building transformation and improvement into an integrated energy efficient multifunctional design

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Abstract – Natural ventilation and bioclimatic design in general, have the potential to considerably improve the energy efficiency of a building by saving on fan electrical energy, cooling and heating. It is however not commonly applied due to higher investment costs in the construction phase, a lack of knowledge or of access to information in the architectural design phase and a minimal integration of climate design and architectural design disciplines starting from the first stages of the design process. This paper is intended to give an understanding of the possibilities of natural ventilation combined with other bioclimatic design solutions, while focussing on the application in the redesign of a mechanically climate controlled vacant office building without any energy saving solutions. A literature review study has led to the identification of eight main typologies of natural ventilation of which the driving forces and design considerations have been explained. Case studies to advanced naturally ventilated buildings and full scale test objects have provided additional solutions for combination systems and insights to other considerations and possible complications. These studies combined with design by research methods and climate and context related input, directed the focus of further research to buoyancy-driven ventilation systems for the selected design project. A simple calculation tool was created that can help integrate and dimension buoyancy-driven ventilation systems into the preliminary design of a building. The effectiveness of natural ventilation systems depends highly on the early integration of climate design and architectural design. Air refreshment through natural ventilation is more easily achieved, but a more complex combined system of the different ventilation typologies and other bioclimatic design solutions can further improve the energy efficiency and comfort of the building. To achieve the highest efficiency of the passive climate control system, the possibilities and requirements have to be taken into account immediately at the start of the design phase and the review of knowledge within this paper can be beneficial in this process.

Keywords – architectural engineering, natural ventilation, stack effect, thermal buoyancy, bioclimatic design, energy efficiency, office building transformation

1 Introduction
Energy efficiency is an important consideration in architectural design nowadays. One of the elements of a building that can still be greatly improved on this issue is the climate control system. In a standard office the mechanical air conditioning, heating and cooling can cover thirty percent of the total energy use. In several western countries it can even be approximately half of the energy consumption of the building (Larsen, 2008). Therefore the use of natural ventilation is certainly an advantage regarding the costs and environmental impact of high energy use. In combination with other passive climatic solutions it can increase the energy efficiency even further.

The consideration of local climate influences on the building has been a part of architectural design for a long time. But with the industrial revolution and correlated developments in building technologies, climate design became a separated engineering discipline. Nowadays the mechanical climate control systems are mostly added to the design in the final stages of the project and are unintegrated in the architecture.

It will be up to the architect to design a building including the necessary bioclimatic solutions. However, the architect is usually not the one with sufficient knowledge about the details of climate design, let alone a more delicate system like natural ventilation. While the engineer who does know, has no opportunities or comprehension to include it in an architectural design. Therefore an integrated design approach of architecture and climate design is necessary to ensure the most profitable solution of climate responsive architecture. The future climate control of a building will recall the history of designing in conjunction with the local climate, but using the technological advancements of recent years to comply with today’s higher living standard.

This paper is a review of the existing knowledge of natural ventilation, with the objective to classify the possibilities and their implications, requirements and disadvantages, while aiming for a renewed relation between architectural design and climate engineering. The presented information is collected through four research methods. The main source of information is literature review of the existing knowledge. These findings will form the largest content of the paper, starting with a brief definition of ventilation in general in the next chapter. Followed by the classification of driving forces, the principles and techniques of natural ventilation from chapter 3 through 5. The next chapter will explore some additional bioclimatic solutions that can be combined with natural ventilation. Another used research method are case studies of built systems in buildings and in full scale test objects. Chapter 7 will provide the additional information gained through these. Research by design methods were used to investigate the application of the techniques in settings of architecture and building functionality, from which the conclusions are given in chapter 8. Finally, calculation methods have been used to create a better understanding of the actual driving forces of the processes, described in chapter 9. Ultimately, this paper may lead to a better understanding of natural ventilation and its potentials in creating sustainable, environmentally friendly, climate responsive architecture.
2 General definitions
Ventilation is the process by which fresh air is intentionally provided to an indoor space and stale air is removed. In which fresh air is normally outside air containing necessary oxygen to breathe, and stale air is the inside air containing pollutants, such as CO2, micro-organisms, smells and particles from textiles, carpets, cooking, etcetera. In addition it can also be used to remove excessive heat from a space and thus improve the thermal comfort in summer. Usually when ventilation is used as a cooling mechanism, the required airflow through the space is greater.

With natural ventilation the necessary airflows are generated purely with ‘free energy’ from the local climate. The main drawback is the difficulty of winter heat recovery from the warm exfiltration air, but an advantage is that high ventilation rates for cooling can be achieved using summer solar heat gain without any electrical energy need (Schulze, 2013). Natural ventilation may not only benefit the energy use of the building, but can also affect the users themselves. It is possible that the air will be healthier due to less issues with ducts, filters and air-treatments, but this is on-going research at this time (Bokel, 2011; Riba, 2011). Although there does seem to be a positive psychological effect of natural ventilation on the users of the building, essentially deciding on intuition that natural systems are better (idem).

The use of natural energy sources from the local climate is the foundation of bioclimatic design. Climate responsive architecture focusses mainly on the architectural integration of systems for daylight, passive heating, natural ventilation and cooling, based on the following three motivations according to Hamzah & Yeang (1994), well-known bioclimatic architects:
- Ecological: reducing energy use and increasing the sustainability of buildings;
- Social: expanding human awareness;
- Cultural: continuing the historical human learning process of adapting buildings to the local climate.

3 Driving forces
The main mechanism behind natural ventilation is natural or free convection. This principle in air and fluid movement relies on pressure differences as a result of a temperature gradient. The driving force of the movement is buoyancy (Wikipedia, 2013b), where the differences in density of the air will result in a vertical distribution. Air that is heated becomes less dense and therefore rises. It is then replaced by cooler surrounding air, which is subsequently also heated and will rise as well. While this process goes on, a continuous flow of air is created. This mechanism produces the two driving forces for natural ventilation on a building scale, which are wind-driven and buoyancy-driven ventilation.

3.1 Wind-driven
Free convection occurs cyclic in the atmosphere. The heated risen air will cool down in higher altitudes and fall back down to replace the newly heated air there. This pressure difference based mass air movement is an important cause of wind, flowing from high to low pressure areas. The wind forces generated in the atmosphere are a driving force of its own on a building scale and can be used as an external source for natural ventilation.

Wind can be used for natural ventilation in different ways. Wind-driven systems either rely on forced displacement or on pressure differences due to the effects of the wind on the building’s or object’s shape. Furthermore, the wind can be of assistance in a combined system with thermal buoyancy, where it is often an important actor in removing exfiltration air and therewith ease the outflow of air. Due to the dependence of buoyancy-driven techniques on temperature differences, wind assistance can make the difference for a working ventilation system on some summer days.

Wind flows are hard to predict and highly influenced by the surrounding environment, which makes it difficult to solely use complicated wind-driven techniques for ventilation. However, the estimated main wind directions based on derived averages from weather data, must be considered in the design of any ventilation system, also if it’s buoyancy-driven.

3.2 Buoyancy-driven or the stack effect
The stack effect is the movement of air into and out of a building (or other vertically oriented structures, such as a chimney) as a result of thermal buoyancy. It is in principle indoor free convection on a building scale and thus the mechanism is similar. Due to a temperature difference of the indoor and outdoor climate and a temperature gradient within the building itself, a difference in pressure occurs. This causes the air to rise and exfiltrate in the top while being replaced by infiltrating air in the bottom. There is only a stack effect when the inside temperature is greater than the outside temperature, which is usually the case in well insulated buildings. (Baker, 2013; Klote, 1991; Wikipedia, 2013c)

1.1.1 Neutral pressure plane
As a result of the differences in density and the resulting air flow, the top of the building is under relative positive pressure compared to the outside air and the bottom is under relative negative pressure (Fig. 3.1). The transition between these, where the inside and outside pressures are equal, is called the neutral pressure plane, or simply neutral plane. Exfiltration takes place above this fictional plane and infiltration below. The further away the opening is located from this plane, the greater the pressure difference and thus the greater the potential airflow.

![Fig. 3.1. Stack effect principle](image)

This naturally occurring phenomenon in buildings can be used as a driving force for natural ventilation with techniques and systems that enhance the stack effect. The aim is to increase the height of the neutral plane as far as possible to ensure access to fresh inlet air for a larger area below. There are several ways in which the stack effect can
be used and enhanced, which will be explained in the next chapter. However, there are a few common considerations for all these solutions that will first be mentioned.

1.1.2 Openings
As explained above and illustrated in Fig. 3.1, the pressure difference is greater further away from the neutral plane. With an even distribution of spaces as displayed in the diagram, it would mean that for example openings on the lowest floor would have a greater inflow of air than openings on higher floors (Holford, 2003). Therefore, when a building has multiple similar spaces that depend on the same buoyancy-driven system, the design of air intakes and outlets is important to consider and adjust to the requirements. Self-regulating vents adjusted to the calculated necessary airflows can be a solution in the right positions, as long as they don’t disrupt the airflow too much.

1.1.3 Great height differences
In high rise buildings the height difference and resulting pressure differences can be great enough to cause difficulties in opening doors on the top levels and noise problems from air flowing through cracks (Jo, 2007). However, in purposely designed stack effect systems this pressure difference is used through a controlled and directed airflow and all interfering flows, such as mentioned through cracks, should be anticipated.

1.1.4 Fire areas
The vertical spaces necessary for the stack effect can cause significant problems in the fire safety engineering of the building, mainly because smoke will travel through the system similarly to the regular ventilation air. However, there can also be a benefit, because in these high spaces, the ground floor will stay clear of smoke for a longer period of time, while the top of the space is filled up with smoke.

1.1.5 Reverse stack effect
The stack effect occurs when the indoor temperature is higher than the outdoor temperature. Due to the heat gain through solar radiation and the use of the building, this temperature difference is positive most of the time in insulated buildings. However, if spaces are cooled in summer, the temperature difference may become negative, which can undesirably reverse the stack effect. This negative temperature difference may off course also be generated purposefully to create a downward airflow in a natural ventilation system.

1.1.6 Wind effects
The difference in wind pressures on the façades and the resulting infiltration in ventilation inlets have an effect on the airflow in the system and on the neutral plane. Abstractly explained, it will cause the plane to tilt, disrupting the regular airflow through the building. On the windward side, more infiltration will occur and due to this pressure difference the plane will move upwards. While on the leeward side the opposite happens and the plane moves downwards.

The same wind induced pressure differences around the building are a very important design consideration in centralised systems with a single inlet or outlet. Depending on the design of the building and of the systems, the wind pressure can have a positive or negative effect. Air will escape easier through an area of lower pressure, for example on the leeward side of the building. And vice versa for inlet air an over pressure is beneficial.

4 Wind-driven techniques
4.1 Cross ventilation

Cross ventilation is the simplest form of wind induced forced displacement of indoor air. Essentially it can be seen as a controlled draft of wind through the space. It is based on the overpressure on the windward façade and the under pressure on the leeward façade, which will cause the air to flow from one side to the other. To accommodate this airflow every space needs to have an opening on both sides, which can be a window or a regulated grille. Adjacent spaces can cause difficulties for an unobstructed airflow or for the air quality of the exfiltration air from one space to another. This may be solved by adding a bypass to the system, either under the floor, as in figure 4.1, or above a lowered ceiling.

4.2 Single-sided ventilation

Single-sided ventilation is affected both by the stack effect and by wind. The stack effect occurs in any height difference where partly a heat gain in the air occurs. Which means that even on a small scale within a single room, an airflow can occur when there are two openings on different heights. Concerning effectiveness when purposefully
applying this, the two openings should be as far apart as possible, preferably just above the floor and below the ceiling. The same idea applies to cross ventilation within a room with a height difference between openings. Because the height difference and resulting pressure difference is not that large, the airflow will not be great either. However, width a working depth of 2.5 meters a single room can be locally ventilated this way.

Wind flows have a greater influence on single-sided ventilation. The openings should not only be divided vertically, but should also have a wide spatial division to make use of the differing in wind pressures on the façade. The pressure distribution by the wind is never even, which will cause an indoor airflow between two openings that are under a different pressure. The efficiency can be increased by building the façade as a wing wall (Fig. 4.4) (Mak, 2007).

By adding an element to the façade that separates openings and redirects the wind, a higher and lower pressure area are created on the windward and leeward side of the element, thus ensuring an easier airflow.

Even when the wind direction is perpendicular to the façade a small amount of ventilation occurs. The façade causes turbulence in the wind, which produces fluctuations in wind speeds that will create a sort of pumping action (Khan, 2008). Small inflows of air will be followed by outflows via a single opening. However, single opening single-sided ventilation cannot ventilate a deep room, because the fresh air will not reach far.

### 4.3 Wind catcher or wind tower

Originating from hot arid climates this tower is used to draw fresh air from passing winds into the building and through another shaft in the same tower or another tower connected to the building, the air flows back outside (Fig. 4.5). The tower has multiple openings to account for different wind directions and possibly multiple shafts. The thick walls keep the interior of the tower cool and when air flows into the opening it is cooled and increases in density, which helps the inward airflow into the building. It is essentially a combination of overpressure by wind force with additional help from the reversed stack effect. Night ventilation cools the mass in the tower and building to ensure the effectiveness of the wind catcher on the next day. This principle works well in the hot climates where it is applied now, but in a humid, temperate climate such as the Netherlands, the tower will essentially become a buoyancy-driven ventilation chimney as will be described in chapter 5.

### 4.4 Venturi roof

The Venturi roof uses the Venturi effect as a driving force for a central ventilation extract system. The principle normally applies to closed flow systems of fluids, but has been proven to also occur in open systems of wind flows, given the right circumstances and design (Blocken, 2011).

According to the laws of fluid dynamics, the velocity of a fluid increases when it passes through a contraction while the pressure will decrease. In a closed system, the fluid has no other option than to flow through the contraction, but in an open air system, if the obstruction is too large, the air will more easily flow around it. Fig. 4.7 shows a computer model of a Venturi roof for computational fluid dynamics (CFD) analyses from the research of Bronsema (2013). A physical model with the same dimensions was tested in a wind tunnel. These tests showed that the effect is greatest when the narrowing in the centre is a third from the height of the outer spacing of the roof (van Hooff, 2011), and as little as possible construction elements obstruct the wind flow path through the roof.

The pressure decrease in the air at the narrow part of the roof will result in a negative pressure difference with the inside, which will cause air to exfiltrate and withdraw along with the passing wind flow.

### Exhaust cowls

Typically every chimney or air exhaust is covered with a cowl to prevent wind blowing the exhaust air (or smoke) back in, down draughts, rain or insects entering the building. Some types of cowls can also benefit the ventilation system, because they are designed to create negative pressure when they are continuously being rotated by the wind, and thus support the air flow outside. Other cowls serve the ventilation system in a more passive
way with the use of a vane that directs the outlet opening away from the wind. This settles the outlet always on the leeward side, where the air can exfiltrate without being forced back in by wind flows, and in some cases a negative pressure is formed that can even reinforce the exfiltration.

5 Buoyancy-driven techniques

5.1 Atrium

An atrium can make use of the thermal buoyancy for natural ventilation (Fig. 5.1). Warm air from the adjacent rooms escapes to the high atrium space where the stack effect occurs and the continuous airflow is generated. The infiltration takes place locally in the façades of the rooms. The effect can be enhanced with heat gain from solar radiation by making an atrium with a glass façade or an extended glass cover on the roof. (Holford & Hunt, 2003).

5.2 Ventilation chimneys

Plain chimneys for ventilation have been used in English school buildings quite a few times (e.g. Queens Building in chapter 7.2). These types of buildings are characterized by lots of large chimneys extending high above the roof, which are mostly providing for just one large room in the building. The thermal buoyancy in this system only originates from the heat gain from the use of the building itself and is not enhanced by external factors. Therefore a large number of stacks is necessary to ensure enough ventilation with the lower airflow speeds. The heights of the chimneys, extending far beyond the roof, are necessary to raise the height of the neutral plane and thus ensure a sufficient intake of fresh air. A further benefit of this height is the easier access to wind flows that remove the exfiltration air and help the overall airflow of the system.

5.3 Solar chimney

The solar chimney is specifically developed to enhance the stack effect by adding heat from solar radiation. The solar chimney is therefore preferably directed towards the sun, to enable it to admit and absorb as much radiation energy as possible. The ventilation chimney is an old system that has recently been rediscovered and developed further with modern technologies. In principle it is the same chimney as has been discussed in the preceding subchapter. If the solid walls of such a chimney are not too thick, the solar radiation will heat the wall enough for the inner surfaces to start radiating heat to the air and therewith enhance the thermal buoyancy. Through an outlet in the top this heated air will escape and through an opening in the bottom air will be sucked into the chimney and out of the room. This composition of thin concrete or masonry walls is not very efficient for admitting solar radiation, and the large dimensions of the cavity relate to a relatively large amount of air that should be heated as well. A more optimal chimney composition is thus a narrow cavity with a south facing transparent surface. Efficiency can be increased further by insulating the cavity and therefore retaining the heat inside, and by choosing the right materials for the interior of the cavity. In principle the solar chimney can be subdivided into a fast and slow responding type, depending on the type of material used. Fast responding types use an interior cladding that conducts heat easily and heats up quickly (Fig. 5.4). Slow responding types use heat storage in mass to ensure a more equalised cavity heating and therefore a more constant airflow, but they will take a period of time to start working properly.
5.3.1 Air cavity
Different researches prove that the air cavity width is an important factor in the solar chimney (Gan, 1998; Harris, 2007). The flow rate will be decreased when the cavity is either too narrow, and it is difficult for air to flow through due to a lot of friction, or if the cavity is too wide (larger than 50 cm), which will create a downward flow in the centre of the cavity (where the air is not heated by the surfaces and is therefore colder and denser).

5.3.2 Tilt/position
The inclination of a solar chimney affects the amount of solar radiation that passes into the air cavity. The best direction of the chimney for the highest heat gain would be a glass surface perpendicular to the sun, because in this case the least amount of radiation will be reflected by the glass surface. However, the tilt will also affect the ease of airflow through the cavity. A vertical cavity is best suited for an efficient airflow, because it will cause the least amount of resistance by the interior surfaces. Harris & Helwig (2007) found that in the Scottish climate the optimal inclination angle would be 67.5° from horizontal. On this tilt, the balance of heat gain and ease of airflow would get the best results. However, this was tested on small scale chimneys for single houses (similar to tilted photovoltaic or solar panels on roofs). In a higher building where a solar chimney spans multiple levels and serves multiple spaces, an inclined chimney is hard to achieve and may not be as efficient.

5.3.3 Glass
The glass surface for a solar chimney needs to have two important properties that are often contradictory in regular glazing. Firstly, it should have a high insulating value to enclose the heat in the chimney. Regular high insulating glass types normally have another property that is undesirable though, which is a low solar transmittance to prevent overheating. In the chimney this heat is actually very important. With a special anti-reflective (AR) coating, well insulating glass can allow more solar radiation to infiltrate. (Deubener, 2009; Gan & Riffat, 1998; Lee, 2009)

5.3.4 Absorber
When an absorber plate is used in the solar chimney, the material for this plate should have a high thermal conductivty value to ensure that the plate heats up easily and evenly and that it radiates this heat to the surrounding air. Considering the costs, aluminium would be the optimal absorber plate material.

When mass is used as an absorber, a lot of heat is first stored in the walls, but eventually the same airflow rate will be achieved and maintained for a longer period after sunset. Normally a thickness of 6 cm is used to calculate stored heat in mass at regular temperatures in a room. However, the temperature inside a solar chimney is much higher and so is the working thickness of mass. Afonso (2000) calculated that in a chimney a thickness of 10 cm can be used as thermal storage.

5.4 Top down ventilation
This technique is mainly based on the reverse stack effect, but is in most cases in principle an enhanced wind tower. As can be seen in the diagram in Fig. 5.6, a tower extends above the building to catch wind. However, the important difference with a regular wind tower is that once the wind is in the confined space of the shaft it will pass some means of cooling. A heat exchange principle of for example water filled tubes or a cold water shower will cool the air and hence create more density, which sets the reverse stack effect in motion. Consequently, this technique will create inlet air that can be used very well as a cooling medium. Therefore the downdraft tower is often also called a cooling tower. More on a version of this type of technique can be found in the Earth, Wind & Fire case study in chapter 7.5. The passive way of cooling, where air is exposed to water is evaporative cooling. This has been used in versions of wind towers in hot arid regions for a long time. The water is evaporated by the hot air, but in this process a significant amount of heat is retracted from the air, while the relative humidity increases. The traditional methods of evaporative cooling include porous water jugs suspended in the wind catcher shaft, moist matting or wet charcoal. However, as said the relative humidity of the air increase, but in an already humid climate, such as in the Netherlands, not much water vapour can be added to the air and therefore the system is not very efficient most of the time.
6 Heating and cooling

The problem with natural ventilation is that the thermal comfort is harder to maintain without losing much on energy efficiency. This is because airflow paths with natural ventilation should be as unobstructed as possible to prevent a lot of air drag that reduces the overall airflow speed. In mechanical ventilation this is solved with more fan power, however, in natural ventilation the driving force is limited to a certain amount and this has to be used optimally most of the time to maintain a working system. This means that interferences in the airflow like filters and standard means of heat recovery are difficult to incorporate. Thus, while the naturally ventilated air will freely exfiltrate the building, it will also remove the heat in winter, or infiltration air in summer will bring the heat inside. This may eventually mean that the energy efficiency is not increased much, because what energy is gained through the natural ventilation system is lost through the heating and cooling systems. It is therefore necessary to combine the ventilation system thoughtfully with other bioclimatic techniques for heating and cooling. There are different possibilities and this chapter will explain some examples, starting with cooling principles, followed by combined systems for heat exchange and concluded with systems purely for heat recovery and heating.

6.1 Lowering heat gains

The first step in cooling in bioclimatic design is preventing the building from heating up too much in the first place. Daylight is important in climate responsive architecture. However, heat gain from solar radiation should be prevented as much as possible. There is always an alignment to be made between sun shading solutions and the amount of daylight access (i.e. for example tiny windows will prevent a lot of heat gain, but will create an uncomfortable dark space). For the remaining heat gain a passive solution can then be designed.

6.2 Night-time ventilation

One ventilation specific cooling solution is night-time ventilation (Fig. 6.1). This is more of a strategy than a ventilation technique. The mass of the building is used for storing heat during the day to prevent overheating. This heat is then removed during the night, when the spaces are not used, by greatly increasing the airflow rate of cooler night-time air through the building. Due to the stack effect, and the heat gain of the night-time air from heat exchange with the storage in mass, a high airflow rate can be achieved. This approach basically lowers the peaks of heat gains on warm summer days.

6.3 Heat exchange

Natural ventilation air through the techniques described in chapter 4 and 5 is usually not treated within these systems. However, while the indoor thermal comfort will be maintained with other systems of heating and cooling, the ventilation air may disrupt this comfort, due to the differences in temperature between the indoor space and the fresh inlet air. Therefore it will often be important to consider combining system of ventilation and heat exchange to treat the air beforehand and prevent uncomfortable airflows.

6.4 Ground-coupled heat exchange

A ventilation system based on heat exchange is the earth tube or earth field for treating inlet air. The air is run through a tube or series of tubes buried at a certain depth under the ground before entering the building (Fig. 6.2). Below one meter the ground temperature is quite constant throughout the year and therefore in wintertime infiltration air will be preheated and in summer time cooled passively. The downside of this system is that it requires a lot of space, and is often only possible in smaller scale buildings with a certain open surrounding area to allow for the inlets.

6.5 Trombe wall, Solar Accoustic Ventilation windows and double-skin façade

These systems are all similar in operation. They are based on an air cavity behind glass with a means of gathering solar radiation. Depending on a winter or summer situation this heat will then either be used for preheating infiltration air or it will be removed by directly ventilating the cavity to the outside.
A Trombe wall is based on storage in mass, where the interior separation is solid and the exterior most often glass. This is practically the same configuration as a solar chimney, with the important difference in the winter situation, when heat is collected and used indoors. The SAV window has glass on both sides and metal fins in between that heat up more quickly and it can therefore be faster used in a ventilation system if necessary. The double-skin façade is quite the same in composition, but it often stretches over multiple stories and therefore can also be used as a less efficient solar chimney principle.

6.6 FiWiHEx

FiWiHEx is an abbreviation for Fine Wire Heat Exchanger, which is a very efficient air to water heat exchanger with minimal airflow resistance. The successful heat exchange of this system is based on the great contact surface area of the air with a weave of very thin copper wires around thin water containing pipes. With this system heat exchange already starts occurring at a temperature difference of air and water of 2 degrees and from a temperature difference of 5 degrees, economic efficiency is achieved (Van Andel, 2006). Because of this great efficiency and the minimal airflow resistance, this is an ideal system for heat exchange in natural ventilation.

Due to its simple design it can also be adapted quite easily to the performance of the natural ventilation system. In places where the airflow is strong and more resistance is permitted, more layers of FiWiHEx weaves can be added to increase the gain in heat recovery. Furthermore, in combination with ground heat storage, the efficiency can be increased further.

Thermal buoyancy-driven systems are more powerful in summer due to the greater heat gain from solar radiation. When the possible more powerful airflow is not fully used for cooling ventilation, this greater airflow can be used to recover a larger amount of heat to be stored in the ground for later use in winter. This can increase the efficiency of the full bioclimatic system throughout the year, while heat losses in winter may become less significant when this heat is generated freely in summer. For example in the study of Bronsema (2013), the use of a solar chimney is not very beneficial to the ventilation system, but is used primarily to generate heat that is stored in the underground storage.

7 Case studies

The research to finished projects, tested prototypes and completed designs can help in comprehending how the theory is applied in practice. Some of the more important case studies have been summarised in this chapter and were selected on their explicit application of a natural ventilation technique, their combination with other bioclimatic solutions, or their unique alternative of a technique.

7.1 BedZED

The Beddington Zero Energy Development (BedZED) near London is a housing development with a zero energy and overall sustainable concept. One of the measurements taken to achieve a minimal energy use is passive ventilation with heat recovery. The roofs of the houses are characterized by large colourful wind cowls, shown in Fig. 7.1. The specifically designed cowl is a wind-driven system for both the inlet and outlet air flows. (See Fig. 7.2 for an exploded view for reference.) A vane directs the rotatable top into the wind direction, with the air inlet towards the windward side, using the overpressure for easier inflow (blue arrow). This places the outlet on the leeward side in the lower pressure zone (red arrow), where it is instantly removed by the passing wind. The two airflows pass each other inside the cowl where heat exchange takes place in a low pressure drop plate heat exchanger (orange section). About 70% of the heat from the exfiltration air is recovered this way (Lazarus, 2003).
7.2 Queens building

The Queen’s building in Leicester makes use of a set of different techniques of which the tall ventilation chimneys are most noticeable (Fig. 7.3). Because it is a school building, there are a lot of different large spaces, such as lecture rooms, class rooms and a machine room for the mechanical engineering department. These larger spaces each have their own stack ventilation system (Fig. 7.4), which explains the lay-out of a variety of chimneys and vents on the roof. Narrow side wings of the building with smaller spaces make use of cross ventilation. The lecture rooms have the most noteworthy overall system, which was particularly innovative at the time of construction in 1993. The fresh inlet air flows in through a plenum below the seats and is preheated in winter to a minimum of 12°C by finned tubes behind the supply grilles (EEBPP, 1997). The extraction then takes place through the 13 meter high chimneys and is monitored and operated with input from carbon dioxide sensors. The airflow is controlled by motorised dampers on top of the chimneys and is backed up when necessary by fans under the plenum. Other sensors prevent the dampers from opening more than 50% when there is a risk of rain entering due to winds.

Construction of the building was completed in 1993 and as one of the precursors in the application of more advanced natural ventilation, it had a few problems that were discovered in post-occupancy analyses (Bunn, 2006). Although the use of thermal mass and the natural ventilation system seemed effective, the users were dissatisfied with high temperatures in summertime, especially on the top floor. Furthermore, there were issues with noise, due to the use of a lot of open-plan areas.

7.3 Tax office in Enschede

This office wing uses the stack effect of a narrow atrium for ventilation (Fig. 7.5), assisted with six large wind cowls on the roof of the atrium. There are two pressure independent trickle vents (small ventilation grates) just under the ceiling above each window of an office. This high position is purposefully chosen to make use of the Coandă effect, which is the tendency of fluids to be attracted to a nearby surface (Wikipedia, 2013a). Due to this effect, the airflow reaches further into the space and the distribution is more even. One small vent is enough for air refreshment of the adjacent office with 100 m³/h on average. A second vent is used in summer for night ventilation with an increased air change rate of 4 ACH. Because the airflow is generated by the atrium and its wind cowls, the trickle vents are not normative and there is the possibility of opening a window without disrupting the overall airflow.

The system is effective for most of the time, but there are fans in the atrium to extract air for exceptional weather conditions of high outdoor temperatures and no wind (Boonstra, 1996).

As mentioned, night ventilation is used as a passive cooling strategy. Furthermore, measures are taken to limit solar heat gain but maintain a large amount of natural daylight to save on electrical lighting energy. Fig. 7.6 shows a section of the office spaces in which a lightshelf is indicated with number 3. This aluminium shelf reflects daylight to the white glossy ceiling, which creates a diffuse distribution of light and decreases the need for artificial lighting. The bottom part of the section displays the airflow through the office and to the atrium.

7.4 Some other atria in brief
1.1.7 Keelung Terminal design by Architeken Cie

This design for a cruise terminal and office building in Keelung City, Taiwan, depends on a system of connected atria for air extraction (Fig. 7.7). Fresh air flows in through a centralised downdraft shaft, which is cooled using a sea water heat exchanger. Due to the high temperatures in Taiwan, a lot of passive measures were taken to prevent heat gain and therewith lower the energy demand. These include sun shading with overhangs and selective sun protection glazing. The atria are also an important part in this, as they act as buffer zones between the cooled office spaces and high temperature moist outdoor climate.

1.1.8 Commerzbank

The Commerzbank Tower in Frankfurt, is a stack effect driven ventilated high rise office building. Connected atria on different levels are used for natural ventilation and also function as winter gardens for the office personnel. Next to that, a double-skin exterior façade ventilates the offices that are not adjacent to an atrium. The building also has mechanical systems in place, that take over with outdoor temperatures above 25°C and below 2°C, but the natural ventilation is suitable for two-thirds of the year (Dalrymple, 2004).

A noteworthy element in the tower’s climate control is the Building Monitor System (BMS), which checks the weather parameters and indoor requirements, and automatically adapts the system accordingly. For example, when an employee opens a window, this will turn off the heating or cooling system in that particular space. Or on a larger scale, depending on the outdoor climate conditions, the system decides if full operation of the natural ventilation system is allowed. It will notify the building’s users of the current settings by different led lights on the control panels for lighting, sun-shading and windows in every room.

7.5 Earth, Wind & Fire

Earth, wind & fire is the dissertation of Ben Bronsema about a concept for natural air-conditioning. The complete system is shown in the diagram in Fig. 7.9, and the Ventec roof and solar chimney were already referred to in chapters 4.4 and 5.2. The third important element of this concept is the climate cascade on the left, which is essentially a large heat exchanger. This downdraft tower is different from earlier described cooling towers in that it is not based on evaporative cooling. Instead the driving forces are heat exchange, hydraulic pressure and aerodynamic pressure. In the top of the shaft, nozzles continuously spray a fine mist of 13°C water during both summer and winter. Heat exchange takes places between the air and the small water droplets, causing the air to either be preheated in winter or cooled in summer. The droplets not only exchange heat with the air, but also their impulse force, causing the air flow to increase slightly. Additionally, due to the fine spread of air droplets, the tower also works hydraulically, pushing the air downwards. Due to the high heat transfer coefficient of water and the large working surface of all the small droplets, the climate cascade heat exchange is very efficient and can function at a small temperature difference (Bronsema, 2013). An example of the competence of the cascade is shown in Fig. 7.10 where 28°C hot summer air is cooled down to 18.3°C.

An additional benefit of the system is the treatment of the inlet air. That is, not only is the air heated or cooled, but also humidified or dehumidified. The second ability seems peculiar, but it relies on the water being cooler than the
air, which causes condensation of the water vapour in the air on the surface of the colder water droplets.

Among other topics within the system are the heat exchange pump and ground heat storage on which the water circulation of the climate cascade is connected to ensure an overall energy efficient system. Also the risk of bacteria, specifically legionella, were investigated, but the cascade turned out to be perfectly safe, due to the low temperatures of the water (Bronsema, 2013).

8 Research by design
As a supportive method of exploring applications of natural ventilation techniques in buildings, design research has been performed through architectural references, case studies and sketching. These were used to try and define other than the technical characteristics of the ventilation techniques to position them in a more architectural rating. Although this has led to some conclusions with the preconditions from this particular project, the range of criteria is greater in reality and more research by design can be done with the knowledge from the previous chapters. However, the conclusions from this particular investigation have led to a focus in further research and are considered important to mention briefly.

8.1 Context
The natural ventilation and bioclimatic design research presented in this paper is part of a redevelopment design project of a vacant office building. Office vacancy is a problem nowadays with over 7.7 million square meters (or 15.7%) of unused office space in the Netherlands (DTZ Zadelhoff, 2014). And with the structural vacancy there has been an active discourse on the transformation to other, actually needed functions, such as housing. The study case of the design project is the area of Amsterdam Sloterdijk, which additionally to a vacancy rate of 18%, also has an issue with mono-functionality of large scale office buildings (Karsing, 2012). This has led to the design task of transforming one of the vacant offices into a combination of housing with public functions on the ground level.

In the research by design process the natural ventilation techniques were tested in the three different fields following from this, which are: program, context (urban space) and form (of the building).

8.2 Conclusions
Searching for relevant reference projects and trying implementations of the techniques into a building has introduced a categorisation within the eight identified natural ventilation techniques (Fig. 8.1).

On the vertical axis, the scale of the systems are indicated and on the horizontal axis the impact they will have on the design of a building. Depending on the amount and types of different applications, this can be wide spread, meaning it can have both small and large implications. Additionally some of the techniques can be subdivided in terms of possibilities in architecture, meaning:
- Visually appreciable: top down ventilation using water;
- Usable space: atria;
- Purely technical efficiency: solar chimney, Venturi roof.

Further important conclusions from this research phase were that some of the techniques are not very suitable for housing developments. These are atria as a collectively usable space, which are not used much, and solar chimneys, because their efficient operating time mostly coincides with office hours during which most dwellings are unused. Ultimately, the research by design has in part directed the concept design of the building to be based primarily on buoyancy-driven techniques.

9 Calculation
A simple Excel tool was devised that can help during the design process to quickly assess certain decisions on their viability (Fig. 9.2). While the tool at the moment is only a combination of existing equations, it is sufficient to test sketch designs, and can be developed simultaneously with the design itself to enable more precise calculations in later stages. The tool focuses only on buoyancy-driven airflows, which are easier to predict and are most important in this design project.

9.1 Equations
(Estimated) Ventilation airflow rate in m³/s:

\[ Q = C_d \cdot A_e \cdot \sqrt{\frac{2 \cdot g \cdot h \cdot (\Delta T / T_c)}{7}} \]

\( C_d = \) discharge coefficient for opening [0,8]
\( A_e = \) equivalent area of ventilation opening [m²]
\( g = \) gravitational acceleration [9.81 m/s²]
\( h = \) height difference of openings midpoints [m]
\( \Delta T = \) temperature difference indoor-outdoor [°C]
\( T_c = \) outdoor temperature [°K]

Equivalent area of ventilation opening:

\[ \frac{1}{A_e^2} = \frac{1}{A_{in}^2} + \frac{1}{A_{out}^2} \]

\( A_{in} = \) area of inlet opening [m²]
\( A_{out} = \) area of outlet opening [m²]

if \( A_{in} = A_{out} \) then \( A_e = A_{in} / \sqrt{2} \)

Temperature difference of inlet and outlet air:

\[ \Delta T = \frac{\frac{1}{A_{out}^2} - \frac{1}{A_{in}^2}}{(2g'h)^{\frac{1}{2}}(\rho_{air} c_{p} A_d)^{\frac{1}{2}}} \]
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\[
\Delta T = 0.0279 \cdot \left( \frac{\Delta W}{h \cdot A_f^2} \right)^{\frac{1}{3}}
\]

\[\Delta W = \text{net heat gain} = W_{\text{sun}} + W_{\text{inter}} - W_{\text{trans}}\]

\[W_{\text{sun}} = \text{heat gain through solar radiation (e.g. Fig. 9.1)}\]

\[W_{\text{inter}} = \text{internal heat production}\]

\[W_{\text{trans}} = \text{heat loss through façades}\]

Fig. 9.1. Clear day solar radiation loads on a south facing vertical surface

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10 Conclusions

There are several typologies of natural ventilation that can be applied in a building. Each of these techniques can be subdivided into different systems and different ways of utilization within a building. The highest efficiency can be achieved with a combination of different systems, because none of these can ensure full natural ventilation on their own. Due to the dependency on local climate influences, all systems will have a certain percentage of downtime, which can be resolved by a smart combination with other techniques. Additionally a mechanical back-up should always be in place for the occasional moderately warm wind still day on which the natural driving forces are unavailable.

A combination with passive heating and cooling systems can further increase the energy efficiency. This can be optimally increased by starting climate design engineering simultaneously with architectural designing, securing the possibility of both disciplines to adapt to each other.

The neutral plane in buoyancy-driven ventilation is an important characteristic to consider in building designs. The objective is to increase it as high as possible, but the architectural design will most likely limit this to a certain height. Additionally on days of less beneficial climate conditions, the system may not be strong enough to ensure the desired neutral plane height. To prevent backflow of stale ventilation air, the top floors of the building should be designed with a separate approach for natural ventilation. Another important consideration within the same setting is the position of a potential centralised inlet, which should be below the line as well. Additionally centralised inlets should regard the difference in wind directions, ensuring that it is positioned in a relatively high pressure zone.

The Excel calculation tool that was created is sufficient for the simplest of buoyancy-driven airflow calculations. It is useful in the early sketch phases of a design project to prevent lengthy manual calculations for each change of parameters, but cannot be used as of now as a tool to validate a final design.

11 Recommendations

Firstly the improvement and further development of the Excel tool is favourable. It should include more parameters, including the heating and cooling systems and possibly more detailed equations. The quality and level of detail of the calculation tool can increase the advantage of using it during a design process and can ensure the quality of the designed ventilation system. It may also be interesting to incorporate a section for a comparison with the existing mechanical systems, which can quantify the increase in energy efficiency.

The descriptions of the techniques and systems in this paper were very brief. Each of these can be extended a lot with more detailed information. However, it is more efficient to select a suitable set of systems for a particular building design and then look into the additional information concerning these, which can mostly be found within the same literature study as the summaries.

The research by design in this case was specifically focussed on preconditions from one particular context and design project. For more generic conclusions a very broad design research could be done with an extended set of different criteria, contexts or subjective influences.

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Images
Fig. 4.2: *Duct or underfloor supply (s.d.) viewed on 17 June 2013 via: http://elizabethgatlin.com/tips-and-tricks/natural-ventilation-tricks-to-cool-off-your-summer/*

Fig. 4.4: (Mak, 2007:996)

Fig. 4.7: <cropped> (Bronsema, 2013:78)

Fig. 5.5: (Bronsema, 2013:243)

Fig. 6.1, Fig. 6.2, Fig. 6.3: *CLARK, G.R. (1986) Understanding passive cooling systems [illustrations], viewed 06 January 2014 via: www.cd5wd.com/cd5wd_40/vita/coolingp/en/cooling.htm*

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Fig. 7.1: *CHANCE, T (2007) Wind cowl chatter, Flickr, viewed 13 January 2014 via: www.flickr.com/photos/tomchance/1008213510/

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Fig. 7.4: *Ventilation section (s.d.) viewed on 28 March 2013, via: www.ecosensual.net/drm/ecco/ecodiavent1.html*

Fig. 7.5: *Boonstra & Vollebregt, 1996:36*

Fig. 7.6: *Boonstra & Vollebregt, 1996:35*

Fig. 7.7: *DE ARCHITECTEN CIE. (2012) 12313_Keelung_0018, viewed 04 May 2013 via: www.cie.nl/projects/67#*

Fig. 7.8: *Dalrymple, 2004*

Fig. 7.9: *Bronsema, 2013:4*

Fig. 7.10: *Bronsema, 2013:138*

Fig. 9.1: *Van der Linden, 2005:10*

Literature


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