Natural and hybrid ventilation principles based on buoyancy, sun and wind

Peter van den Engel
Delft University of Technology and
Deerns consulting engineers
p.vd.engel@deerns.nl

Remco Kemperman
Delft University of Technology and
Deerns consulting engineers

Heleen Doolaard
Delft University of Technology and
Deerns consulting engineers

Abstract

An outline is given of basic design principles or natural and hybrid ventilation related to a moderate climate such as in the Netherlands. Experiences from the past should be used to improve the design of naturally and hybrid ventilated buildings in order to improve the confidence in these systems. However, with a better use of buoyancy, wind and sun, the combined pressure-differences can be increased, which will result in a more robust system. The potential improvements of these natural forces are explored with CFD- and mass-flow-simulations. The simulation results of an advanced designed naturally ventilated building are discussed. The results show that the reduction of fan-energy can be substantial which could be applied on low-pressure mechanical ventilated buildings as well. The results of the research can be applied on new as well as on existing, to refurbish buildings.

This research is inspired by and based on the research project "Earth, Wind & Fire – Air-conditioning powered by Nature" (Bronsema 2010).

Introduction

General

Natural and hybrid ventilation systems have many advantages and, used in an advanced way, will lead to:

- more satisfied occupants;
- better air quality;
- less energy consumption.

Many studies show that more or less advanced natural of hybrid ventilated buildings have a higher occupant satisfaction than mechanical ventilated buildings. Another advantage is reduced energy consumption (Bordass, 2001, Hellwig, 2006, Brager, 2008). However, it is not always clear yet what the key success-factors are, because there are hybrid or natural ventilated buildings that have been adapted only due to a poor climate control (draught, too hot, poor air quality). It should also be noted that many fully air-conditioned buildings have comfort-problems as well. Consequently, for natural and hybrid ventilation systems more insight in effective design principles, better calculation models and a more robust control strategy are essential.

More satisfied occupants

Advanced designed natural or hybrid ventilated buildings have the potential of a high appreciation by the occupants. Especially operable windows are essential, not only for physical but also for psychological reasons. The direct supply of outdoor air can lead to the following improvements:

- Improving air quality, depending on the local environment of the building.
- Cooling of the building, by using the outdoor temperature.
- Increasing the local and average air velocity, when the indoor temperature is high (comfort cooling).

Occupant satisfaction is one of the starting points of the design of buildings with second skin façades. In building certification systems like BREEAM and LEEDS operable windows will receive special credits. In the program of requirements of the Dutch Government Buildings Agency operable windows are already design-standard for years.

Better air quality

Air quality can be measured by assessing the CO_2-levels, but there are other important physical and subjective elements as well, such as the scent of a tree or the experience of nature. Much of it is difficult if not impossible to measure.

Less energy consumption

Fan-energy contributes, together with energy of appliances and lighting, for a major part to the energy-demand of a building. A well isolated and solar protected building with efficient energy generation neither need much heating nor cooling energy.

Fan energy can be reduced by:

- Reduction of the resistance of all the components of a ventilation system. An air velocity of 1–2 m/s is recommended (Gräslund, 2011).[1]
- Natural ventilation during only a part of the day or the year when the outdoor circumstances are favorable.[2]
- The design of buildings with natural air supply, exhaust or both.
- Making use of natural elements like internal or external thermal pressure differences (buoyancy), sun and wind.

The ultimate goal is a building that is, as far as possible, completely naturally ventilated with a minimum use of heating and cooling energy. This is possible by:

- Air flow control of the inlet and outlet, after measurement of the CO_2-levels, and ventilation only during working hours.
- Increase of ventilation only when the outdoor temperatures are not too high or too low.
- Heat recovery with a low air resistance, if necessary connected with a heat pump (Christensen, 2010). When the temperature-differences (between extracted and supplied heat) are low, the efficiency of the heat pump will be high.

Economy

For a cost-benefit analysis several parameters are important.

Costs will increase due to the following factors:

- Natural or hybrid ventilated buildings have very low energy consumption only if the air flows are effectively controlled. A control system is expensive.
- The size of ducts is generally larger in case of natural ventilation.
- Hybrid systems incorporate a mechanical back-up system.
- A façade with operable windows is more expensive than without. The opening of a window during a hot and humid summer day will lead to the increase of the cooling capacity of a central air handling unit. An option is a window that can be closed either automatically or by the occupant as a result of a warning signal.

Benefits are:

- Natural ventilation and operable windows will contribute to the productivity of occupants and reduce sick-leave.
- Fan and cooling energy will be reduced.
- The total length of ductwork can be reduced (depending on the design-principle).

To a new type of risk assessment

Naturally ventilated buildings are more vulnerable to air flow disturbances and draught than mechanical ventilated buildings, however, it should be noted that this is also a matter of assessment, which is often too general. Consequently, naturally ventilated buildings need a special type of risk assessment, which is not available yet. For instance, the kind of turbulence produced by a window is different from cooled mechanical supplied air. Air supplied via a window has another size and frequency distribution of eddies, which requires another kind of draught-evaluation. Moreover, the comfort-expectation of the occupants can be different.

Points of attention

General points of attention are:

- In a completely naturally ventilated building a single operable window may disturb the whole ventilation system due to the large air flows when the pressure-differences are high. However, when the air quality of a building compartment as a whole remains well, a different air flow pattern will not always be a problem.
- Mechanical systems are often able to solve air pressures due to open windows, but it is not always clear enough what the real limitations are. What are acceptable pressure differences?
- In natural ventilated buildings an operable window will not interfere with other fresh-air flows when a building compartment or space has its own air inlet and exhaust (Short, 2004).

---

[1] For natural systems a velocity 0.5 m/s is most adequate for the primarily design stage (Lomas, 2007). Critical elements are filters, sound-absorbing air ducts and heat-recovery systems. However, these elements can be integrated in natural systems as well.

[2] This is the common occupant behavior with operable window, but windows are not always intelligent designed for both large and minimum air flows.

- In office landscapes not all persons are equally sensitive to draught by operable windows, so when occupants can choose their working place in accordance with their sensibility to draught there is less risk.
- Cold supplied outdoor air may produce draught. Depending on the amount of supplied air, inlet temperature and mixing qualities there may be draught or not.
- An inlet can become an outlet at the top of the building; however, a separate exhaust-system can prevent this.
- The air-tightness of the façade needs enough attention, which is often overlooked.

Natural ventilation principles

Hybrid ventilated buildings are difficult to compare. Air supplies or exhausts may be centralized or decentralized. Apart from the chosen system there is a varied use of natural forces, like buoyancy, wind and sun.

The most important different types of ventilation are: (1) decentralized supply and central exhaust, (2) central supply and decentralized exhaust and (3) central supply and central exhaust.

Additionally, there are all kinds of combinations possible with mechanical ventilation and cooling. Moreover, the way of local ventilation may vary as well, with mixing or displacement ventilation as the most obvious differences. When displacement ventilation is applied it will always be necessary to warm the air to near room-temperature. In the long run economical and practical issues will determine as well which system will be applied.

Physical principles

General

Buoyancy or the stack-effect is the most important driving force of natural ventilation being to a large extend sufficient to ventilate a building. Interesting is the self-regulating effect of buoyancy: the higher the heat load of the building, the larger will be the air flow and cooling effect of natural supplied and exhausted air. Recently several buildings have been designed that make use of this principle (Lomas, 2007), but even those buildings make use of positive wind-pressures in the inlet-plenum.

In a hot and moderate climate extra heating of the chimney or cooling is necessary during some periods of the year.

However, for a moderate climate with a modest internal and external heat load the use of other natural forces like sun and wind may be required as well in order to create higher pressure differences in certain periods of the year. For instance, when the desired low indoor temperatures in summer are achieved, the stack-effect will be reduced. Buildings with natural air supply via the façade can suffer from high negative pressures on the façade, which differ from systems with natural air supply via a central atrium. Heat recovery in the exhaust may be required in order to minimize heating and cooling energy, but this depends on effectiveness of the airflow-control strategy as well.

Buoyancy

Buildings that are ventilated via atria and shafts have more options to use wind-pressure in a positive way. Buoyancy is effective when the inside temperature is higher than the outside temperature. Cool outdoor air with a higher density will replace hotter air with a lower density. In principle, internal heat sources are sufficient to ventilate a building. However, in the cooling season with lower pressure differences, there is in an increased risk of a return flow of air. Buoyancy can be increased by the height of a shaft, the temperature in the shaft or a lower pressure in the shaft due to wind. Another option is a building-design where return-flows are just another way of ventilation.

Wind

Wind is almost always available, but an effective usage is often misunderstood. Coastal areas have more wind. The wind-pressure depends on the height of the building related to the surrounding buildings. The under-pressure is generally the lowest above the roof of a building. This can be increased by the shape of building and exhausts. Options are a venturi-shaped outlet or a cowl-system (Khan, 2008, Blocken, 2011). The under-pressure above a roof should always be lower than the pressure on the inlets.

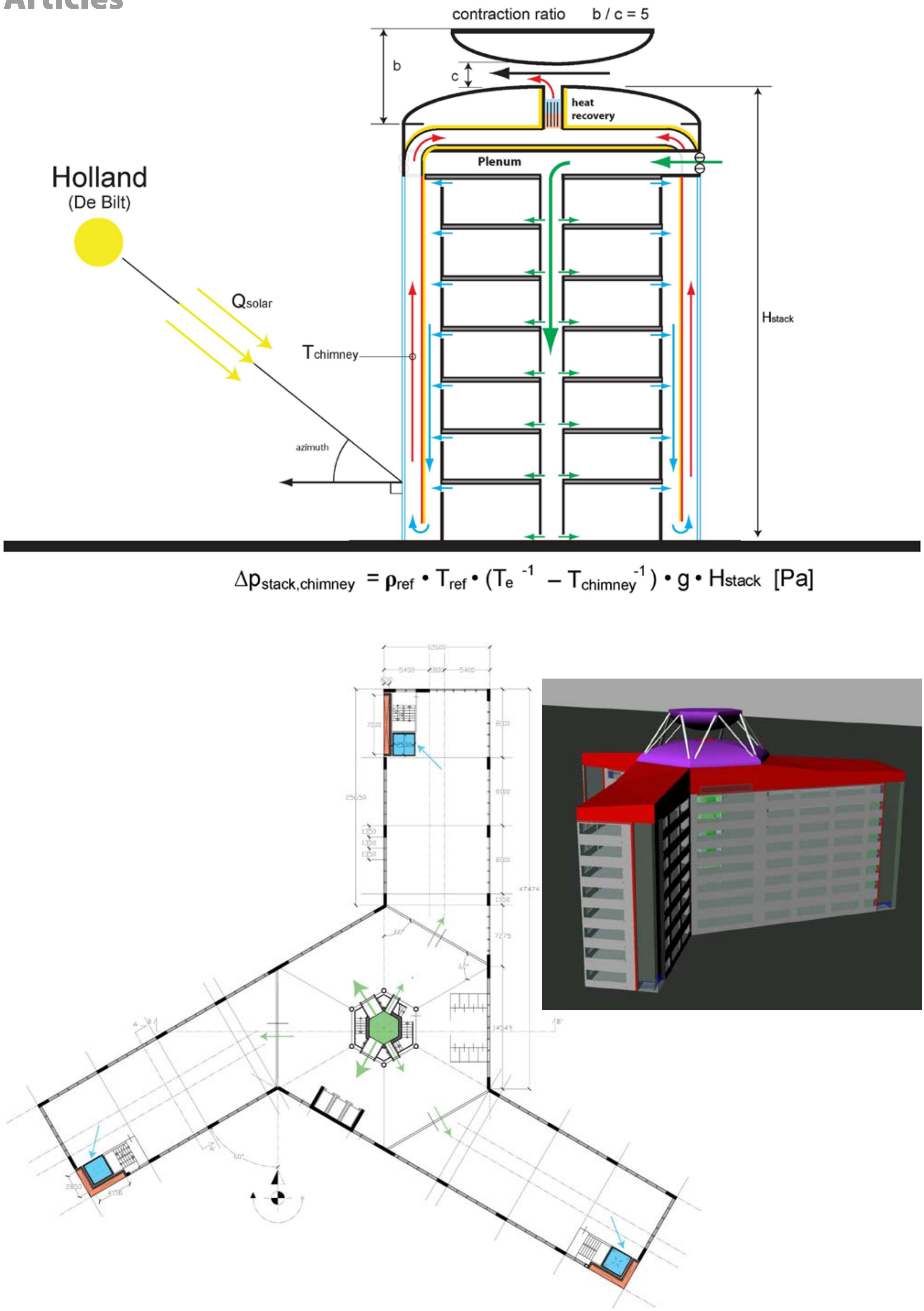
Sun

High outdoor temperatures go always together with much sunshine. In periods with a low buoyancy force, the sun can overtake the role of buoyancy and can heat the exhaust-duct or transfers its power to a fan via a PV-system.

Simulations

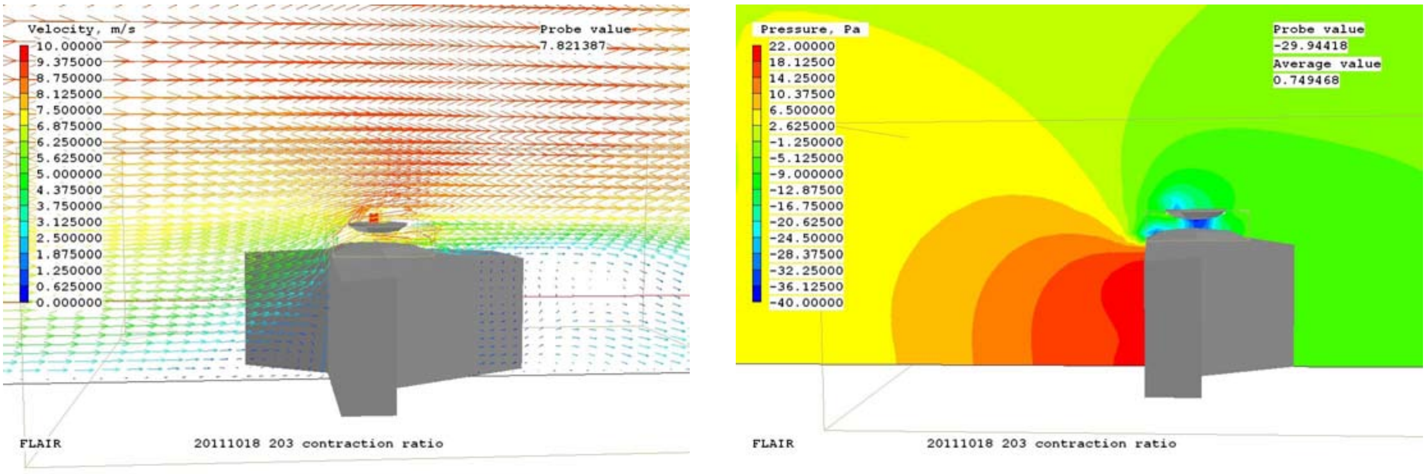
General

In CFD (Phoenics) and TRNSYS/TrnFlow a model is developed. Also a building with a central air supply and central exhaust is simulated.



$$\Delta p_{stack,chimney} = \rho_{ref} \cdot T_{ref} \cdot (T_e^{-1} - T_{chimney}^{-1}) \cdot g \cdot H_{stack} \ [Pa]$$

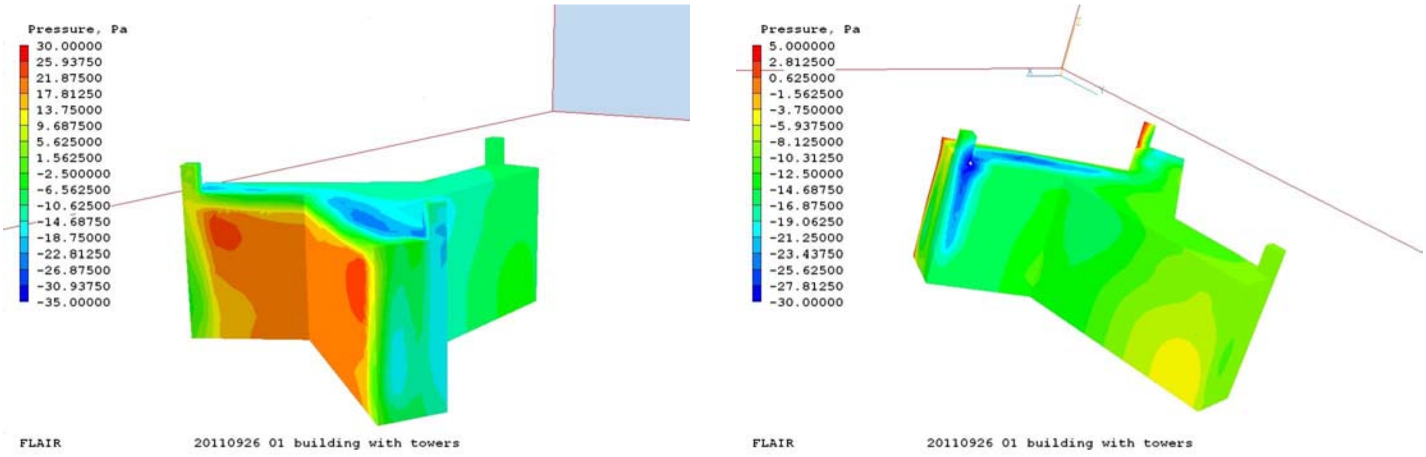
Figure 1. Diagram of the basic-TRNSYS/TrnFlow-calculation model evaluated in CFD (Phoenics) as well. Moreover, other chimney-types are evaluated, see Figure 2 and 3.



Increased under-pressure due to the venturi-effect in case of a centralized chimney

a. The velocity of 5 m/s is increased to circa 8 m/s due to the shape of the roof.

b. The resulting under-pressure is 30 Pa.



Over- and under-pressure of decentralized chimneys

c. Zone with overpressure for air inlets. This is about 2 m below the rooftop.

d. Under-pressure of decentralized chimneys, integrated in the façade, which can be used as solar chimneys as well.

Figure 2. Advanced use of over- and under-pressure for natural ventilation systems, several options.

The following setpoints and parameters are used:

- Minimum temperature 20°C
- Maximum temperature 25°C
- Opening of the building from 7:00 am – 19:00 pm
- The ventilation system is shut off when the building is not in use
- Internal heat load 35 W/m^2
- Insulation closed parts of the façade U = 0.23 W/m^2K
- Insulation glass + window-frame U = 1.6 W/m^2K, g-value = 0.67
- Glass percentage 30%
- Sunshade, g-value = 0.40
- Infiltration rate 0.1 h
- Ventilation, > 50 m^3/h per person
- Size of the building 13,050 m^2 gross floor area
- Size of the solar collector, width 7 m, height 28.5 m (East, South and West)

CFD-results

The exhaust system has one or three chimneys. The position of the air inlet is near the top of the building in a

Table 1. Air flows and total driving pressure differences for the different storeys [required $Q_v = 0.5\ m^3/s$ per office floor]

Storey	Average Maximum air flow	Average air flow	Relative Standard Deviation	Average maximum driving pressure difference	Average minimum driving pressure difference	Average driving pressure difference	Relative Standard Deviation
	$[m^3/s]$	$[m^3/s]$	[%]	[Pa]	[Pa]	[Pa]	[%]
0^{th}	3.19	1.26	28	329	3.3	39.3	70
1^{st}	3.03	1.16	29	326	4.0	39.4	69
2^{nd}	2.79	1.03	30	329	4.1	39.4	69
3^{rd}	2.59	0.92	31	328	4.0	39.4	69
4^{th}	2,91	0.98	33	329	4.0	39.5	69
5^{th}	3.15	1.00	36	329	3.9	39.6	69
6^{th}	3.22	0.95	41	330	3.8	39.6	69
7^{th}	3.29	0.88	49	331	3.8	39.8	69
average		**1.02**				**39.6**	

Table 2. Part of occupation time with sufficient ventilation [$Q_v > 0.5\ m^3/s$ per office floor]

Storey	North wing W orientation of solar chimney	South-East wing SW-SE orientation of solar chimney	South-West wing SE-SW orientation of solar chimney
	[%]	[%]	[%]
0^{th}	99.3	99.5	99.5
1^{st}	99.1	99.3	99.3
2^{nd}	98.3	98.8	98.7
3^{rd}	96.8	97.7	97.4
4^{th}	97.8	98.6	98.4
5^{th}	97.7	98.7	98.4
6^{th}	93,5	97.0	95.8
7^{th}	78.1	86.7	83.7
average	**95.1**	**97.0**	**97.0**

Table 3. Energy consumption.

	Heating energy $[MJ/(m^2 \cdot y)]$		Gas consumption for heating$[m^3/(m^2 \cdot y)]$
Building total	226.9		7.2
Fan energy consumption			
Building case	Fan energy consumption building case [kWh]	Fan energy consumption in 100% mechanical drive case [kWh]	Energy savings relative to 100% mechanical drive case [%]
Buoyancy, wind and sun 10 Pa	11	927	99
Sustainable (low pressure system) 200 Pa	10,635	18,792	43
Conventional 1.000 Pa	75,796	93,960	20

Table 4. Average driving pressures of physical elements.

	Average Total driving pressure, average storey	Buoyancy, average storey	Wind, average storey	Solar contribution to stack pressure in a solar chimney with South-East/ South-West orientation, average storey
ΔP average [Pa]	39.6	19.6	18.5	2.1
Pa > 0 during occupation [%]	100.0	98.2	100.0	71.2
Pa > 5 during occupation [%]	99.9	92.1	62.0	12.3
Pa > 10 during occupation [%]	98.0	79.4	45.4	0.3
Pa > 20 during occupation [%]	80.1	47.2	30.0	0.0

Table 5. Contribution to the driving pressure of the individual components.

	Stack pressure in Solar chimney plus shunt duct South-East / South-West orientation	Solar contribution to stack pressure in a solar chimney plus shunt duct South-East / South-West orientation	Under pressure on exhaust due to 'venturi' roof	Under pressure on exhaust due to local 'venturi' exhausts directly on the chimneys
ΔP average [Pa]	21.7	2.1	18.3	9.2
Pa > 0 during occupation [%]	100	72	100	100
Pa > 5 during occupation [%]	98	17	68	51
Pa > 10 during occupation [%]	89	0	51	31
Pa > 20 during occupation [%]	55	0	31	13

zone with overpressure (**Figure 2c**). The position of the exhaust on the roof is in the centre or near the façade. The under-pressure in the exhaust can be increased by a venture-shape (**Figure 2a and b**). The exhaust system can – if located near a façade – make use of solar energy as well.

The CFD-simulations show that near the centre of the building there is always the possibility to add an inlet with a positive pressure.[3]

TRNSYS/TrnFlow-results

Table 1 shows that the average pressure difference is circa 39 Pa, which makes it more interesting to add other components such as heat recovery or electrostatic filters.

From **Table 1 and 2** can be concluded that the building is on average 2 times over-ventilated and with a maximum of circa 6 times. This is due to the combination of very low outdoor- temperatures and much wind.

In order to reduce the complexity of the simulation-model, the openings are designed with a fixed size. This results in relatively high air flows in winter with outside temperatures around zero. Another point of attention is simultaneously reduction of heating and cooling. Additional reduction of energy is possible with heat recovery in the exhaust.

With a better flow- and temperature-control and heat recovery the calculated heating energy of 7 m³ natural gas equivalent per m²/y (**Table 3**) could be reduced significantly and will probably result in a heat consumption close to the passive standard of 1.5 m³ natural gas equivalent per m²/y.

However, one of the most striking improvements of natural ventilation is the reduction of fan energy. Most of the energy-savings are possible when a high pressure ventilation-system is changed in a low pressure system (Gräslund, 2008). Comparing a mechanical ventilated building with a very low pressure-difference of 10 Pa, natural ventilation with a solar chimney and a venturi-roof, can reduce the energy consumption already with 99%. Comparing a low pressure mechanical system of

---

[3] The low pressures near the roof may partly be the effect of the coarse grid of CFD-simulation.

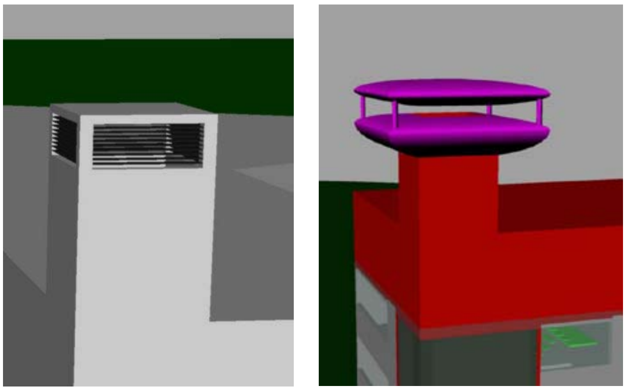


Figure 3. Two options of decentralized chimneys. The venturi-shape gives the best results.

200 Pa the savings are still substantial (43%). Finally, the application of solar chimneys and a venturi-roof can reduce the energy consumption of a 1,000 Pa (improved standard) system with 20% (**Table 3**).

The following table presents what the contribution is of buoyancy, wind and sun separately related to the required pressure difference in the system:

When a decentralized venturi-roof (**Figure 3**) is applied the positive effect of the wind will be smaller, but will still be significant.

The contribution of buoyancy, wind and sun on the different components are presented in more details in **Table 5**.

Discussion

1. **The research shows the high capacity of natural forces to reduce fan-energy, even for completely mechanical driven systems.**
2. **Most of the savings are possible by designing a low pressure ventilation-system.**
3. **For a medium sized building in a moderate climate an average natural pressure difference of 39 Pa is achievable. The contribution of each of the forces has to be assessed individually.**
4. **Depending on the control-qualities of the ventilation-system, and the availability of heat recovery, a low energy consumption for heating and cooling is possible, near the level of passive-standards. In order to assess this in detail more research will be required.**
5. **Integration of operable windows still needs more attention. Design-possibilities are return valves, more flow-controllers in the system or separate inlets and exhausts for each building compartment (Short, 2004).**

Literature

1. Bordass B, Cohen R, Sandeven M, Leaman A. Assessing building performance in use: energy performance of the PROBE buildings. Building Research and Information 29 (2) (2001) 114-128.
2. Hellwig R.T., Brasche S., Bischof W.. Thermal Comfort in Offices – Natural Ventilation vs. Air Conditioning, Proceedings of congress Comfort and Energy Use in Buildings – Getting it Right, Winsor 2006.
3. Brager G., Baker, L., Occupant Satisfaction in Mixed-Mode Buildings. Proceedings of Conference: Air Conditioning and the Low Carbon Cooling Challenge, Cumberland Lodge, Windsor, UK, 27-29 July 2008. London: Network for Comfort and Energy Use in Buildings.
4. Lomas KJ. Architectural design of an advanced naturally ventilated building form. Energy and Buildings 39 (2007) 166–181.
5. Krausse B, Cook M, Lomas K. Environmental performance of a naturally ventilated city centre library. Energy and Buildings 39 (2007) 792–801.
6. Khan N, SU Y, Riffat SB. A review on wind driven ventilation techniques. Energy and Buildings 40 (2008) 1586 – 1604.
7. Blocken B, Hooff T van, Aanen L. Bronsema B. Computational analysis of the performance of a venturi-shaped roof for natural ventilation: venture-effect versus wind-blocking effect. Computers & Fluids 26 April 2011.
8. Christensen MS. Natural Ventilation with Heat Recovery and Cooling (NVHRC). Rehva Journal September 2010.
9. Gräslund J. Simple and reliable constant pressure ventilation for nZEB. Rehva Journal May 2011.
10. Short CA, Lomas KJ, Woods BA. Design strategy for low-energy ventilation and cooling within an urban heat island. Building Research and Information 32 (3) (2004) 187-206.