Passive ventilation systems with heat recovery and night cooling

C.A. Hviid
Alectia A/S, Teknikerbyen 34, DK-2830 Virum, Denmark
S. Svendsen
Technical University of Denmark
Department of Civil Engineering, Brovej bygn. 118, DK-2800 Lyngby

ABSTRACT

In building design the requirements for energy consumption for ventilation, heating and cooling and the requirements for increasingly better indoor climate are two opposing factors. This paper presents the schematic layout and simulation results of an innovative multifunctional ventilation concept with little energy consumption and with satisfying indoor climate. The concept is based on using passive measures like stack and wind driven ventilation, effective night cooling and low pressure loss heat recovery using two fluid coupled water-to-air heat exchangers developed at the Technical University of Denmark. Through building integration in high performance offices the system is optimized to incorporate multiple functions like heating, cooling and ventilation, thus saving the expenses of separate cooling and heating systems. The simulation results are derived using the state-of-the-art building simulation program ESP-r to model the heat and air flows and the results show the feasibility of the proposed ventilation concept in terms of low energy consumption and good indoor climate.

1. INTRODUCTION

Several investigations document the effect of indoor climate on the performance of office workers (Seppänen et al., 2006). Other investigations show that the productivity increase of an improved ventilation system with higher air change and better temperature control is significantly larger than the total costs of the ventilation system (Wargocki and Djukanovic, 2005)

While the ventilation technologies are always improved energy-wise and efficiency-wise it is not possible to meet tomorrows demand of better indoor climate while cutting energy consumption as demanded by the Kyoto-protocol. This leads to a widening gap between the required reduction in the use of fossil fuels and the demand for improved indoor climate. One solution is to shift the ventilation use from active (mechanical) to passive ventilation systems. Passive in this context means ventilation solutions that exploit natural driving forces and the building envelope physics to establish and maintain a satisfying indoor climate without the consumption of electrical energy. The concept has particular potential in temperate climates with moderate wind velocities and large daily temperature differences (Kolokotroni and Aronis, 1999; Olsen and Chen, 2003). In order for a passive ventilation system to be competitive efficient heat recovery is essential. A master thesis by Anderson and Vendelboe (2007) performed at the Technical University of Denmark tests a prototype of a heat exchanger suitable for passive systems.

This paper describes and simulates a proposed passive ventilation system with equal performance – in terms of indoor climate – to conventional mechanical ventilation and cooling system while saving significant amounts of energy.

2. PASSIVE VENTILATION DESIGN

The proposed passive ventilation systems have been developed with several performance parameters in mind:

- Low energy consumption
- Equal indoor climate quality compared to mechanical ventilation
- Low total costs
- Flexible solution
- Does not occupy more space than a conventional mechanical ventilation system

In order to meet these demands we propose a ventilation system with intake at ground level and exhaust above the roof. The duct system consists of large main ducts for intake and exhaust. Via a diverging duct smaller supply ducts feed fresh air to the work-spaces that are situated vertically above each intake. Exhaust ducts from each work-space extracts the stale air and via a converging duct and a large main duct is exhausted to the outside. Figure 1 shows the schematic layout of the proposed system.

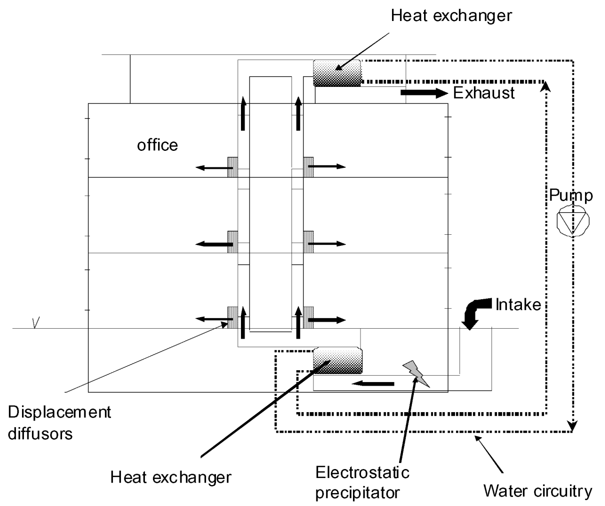

Figure 1: Cross-section of a building with a passive ventilation system.

There are several advantages to this duct layout:

- Vertical supply and exhaust ducts enhances the stack effect
- Intake and exhaust are placed where the prevailing wind pressures are – respectively – positive and negative. This enhances the effect of wind
- Central intake and exhaust is required for heat recovery and filtering capabilities. Filtering is done by an electrostatic precipitator in the supply air with very low pressure loss, high efficiency and low energy consumption
- Duct sizing and not presssure-loss inducing dampers ensures equal ventilation rates to all rooms
- Evenly distributed intakes and exhausts along the building maintains the flexibility of the building
- Duct layout is simple, requiring more floor area but saving space above acoustic ceilings

3. SIMULATION SETUP

The passive ventilation system is simulated using the state-of-the-art building simulation program ESP-r from University of Strathclyde, Glasgow, Scotland, (ESP-r, 2008). ESP-r is a unix-based program and as such we have been running ESP-r under the Linux emulator Cygwin. Cygwin enables the user to run unix-based software in a Linux environment on a Microsoft Windows computer. ESP-r is chosen because it is continuously developing and has a comprehensive validation history. The employed version of ESP-r is 11.5.

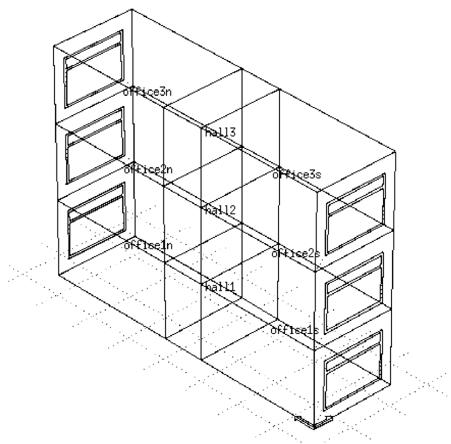

Figure 2: Cross-section of simulated building.

3.1 Dimensions, layout

The simulated part is a cross section of a long flat-roofed building with rectangular 2:1 footprint.

In order to evaluate the proposed system we establish a reference based on a cross section of a three-storey office building as shown on Figure 1. The cross section comprises six single offices with connecting hallways. The basement which contains the ventilation system intake is not shown.

The façades are oriented towards North and South because these orientations represent worst-case with regard to ventilation and night cooling efficiency.

3.2 Constructions

Table 1 contains descriptions of the constructions with the calculated heat transfer coefficients.

Table 1: Constructional details from outside to inside with heat transfer coefficients.

	Materials	U-value W/m²K
Façade	Brick 100 mm Mineral fibre 200 mm Breeze block 100 mm	0.18
Roof	Roofing felt 12 mm Mineral fibre 300 mm Concrete 200 mm Air 100 mm Gypboard 13 mm	0.12
Decks	Flooring 13 mm Cement screed 10 mm Concrete 150 mm Air 100 mm Gypboard 13 mm	-
Ground	Gravel 150 mm EPS 300 mm Concrete 150 mm Cement screed 10 mm Air 50 mm Flooring 12 mm	0.09
Internal partitions	Gypsum 13 mm Mineral fibre 100 mm Gypsum 13 mm	-
Window	Wooden frame 4-15Ar-SN4 Frame part: 19%	1.2 g-value: 0.51

Transparent area of the façade: 40%.

3.3 Internal load

Table 2 specifies the internal loads during working hours and outside working hours. The periods are constant through the year and weekends are considered outside working hours. The lighting load is also applied in the hallways.

Table 2: Internal loads in offices.

	Hours		W/m²	
	Work hours	Outside work h.	Work hours	Outside work h.
People	8-17	17-8	5	0
Lighting	8-17	17-8	7	0.7
Equipm.	8-17	17-8	4	0.4

3.4 Solar shading

The predefined constructions in ESP-r are not suitable for high-performance offices in temperate climates. For this reason we use WIS (van Dijk and Oversloot, 2003) to construct a new double glazing with retractable blinds. The thermal and angular optical properties are added and the resistance-value *R* of the air-gap is adjusted, so the overall thermal heat loss coefficient *U* was in accordance with the *U*-value calculated by WIS. Due to the limited capabilities of automatic shading devices in ESP-r, the yearly shading of the window was modelled as a glazing with external venetian blinds with incremental tilt angle of 30° in the interval 23-26 °C. Thus shading is activated and adjusted to a tilt angle of 0° at the indoor air setpoint of 23°, 30° at 24.5°C and 60° at 26°C. The risk of glare is handled by including a setpoint of incident radiation of 270 W/m² causing the shading to activate and adjust to a tilt angle of 60°.

3.5 Air flow network

The passive ventilation system is modelled using the coupled plant and air flow network option in ESP-r. The network is established by specifying internal nodes representing the pressure and temperature in each room and the temperature in the ducts and linking them with external nodes representing the outdoor weather conditions. The links consists of ducts, grilles and other pressure loss inducing elements in the air network. Typically the relation between mass flow and pressure difference is expressed with power formulas.

3.6 Heat exchangers

The heat exchangers are represented with the following expression:

$$\dot{m} = a \times \Delta P^b \quad (1)$$

where:
a: dimensionless coefficient set to 0.19
b: dimensionless coefficient set to 0.43
m: mass flow rate in kg/s
ΔP: pressure drop in Pa

A heat exchanger comprises several hundred meters of plastic tubes arranged in a staggered grid. Air flows across the tubes at velocities ~0.25 m/s and the heat capacity flows of the tube fluid and the air are kept equal. Thus energy is transferred in a counter-flow manner. Heat recovery is achieved by coupling two heat exchangers using a water circuitry with a domestic pump. The details of the heat exchangers and heat recovery system are described in Anderson and Vendelboe (2007).
The heat exchangers are bypassed outside the heating season to reduce the pressure loss.

3.7 Duct system

The intake is placed near the ground on the north façade and the outlet is placed on the roof. The ducts listed in Table 3 are all of standard sizes.
Dynamic pressure losses from bends are specified with a loss factor for the average air velocity.
The wind pressures on the building are calculated from pressure coefficients for a 2:1 building.

Table 3: Duct sizes.

	mm
Main intake duct at ground level	1000-630
Supply & exhaust 1st floor rooms	250
Supply & exhaust 2nd floor rooms	250
Supply & exhaust 3rd floor rooms	315
Main exhaust duct on roof	630

From coefficient tables we know that negative pressure prevailes on a flat roof and on the façade positive pressure in the wind direction and negative pressures on the opposite side.
Open grilles are placed at the intake and exhaust and between ducts and rooms.

3.8 Controls

The desired ventilation rate is specified by CEN 15251 indoor climate class II. This gives a required minimum airflow in the main intake duct of 0.160 m³/s. The ventilation system is controlled by a damper in the main intake duct. The control is proportional meaning that the damper is 100 % open for zero airflow and 10 % open for airflow 4 times the desired airflow. A number of 10 % is due to simulation aspects in ESP-r. Outside heating season in the working hours ventilation is achieved with openings in the façade and single-side and/or cross ventilation. The passive system – however – continues to contribute to the night cooling. Table 4 lists the activation of the different systems.
In order to achieve stable results, the building timestep is set to 6 steps/hour with a plant timestep of 20 steps/building timestep.

Table 4: The activation of passive system and windows

	Heating season		Summer	
	Work hours	Outside work h.	Work hours	Outside work h.
Passive system	On	Off	Off	On
Openings in façade	Off	Off	On	Off

4. RESULTS

The results shown are chosen to represent critical performance parameters: indoor air temperature and ventilation rate in critical rooms.
Air temperature is shown for South-facing rooms and ventilation rate for North-facing rooms. The latter is due to the fact that colder rooms contribute less to the stack effect.
Figure 3 depicts the whole-year ventilation rate through the main supply duct.
Figure 4 depicts duration curves of ventilation rate for critical rooms during the heating season filtered by occupancy. Figure 5 depicts whole-year duration curves of indoor air tem-

perature in critical rooms filtered by occupancy.

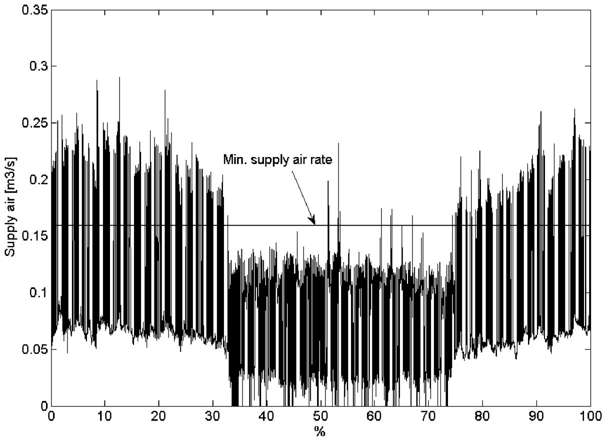

Figure 3: Yearly airflow in main intake duct.

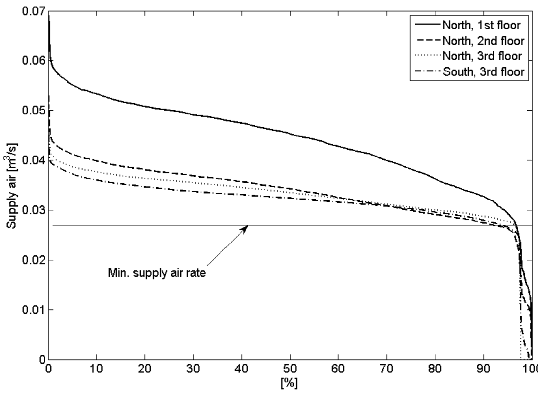

Figure 4: Duration curves of ventilation rates of hand-picked rooms during heating season.

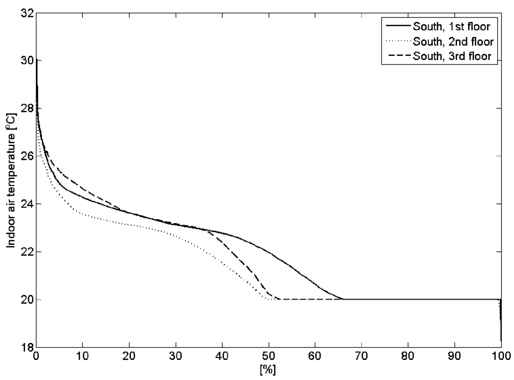

Figure 5: Yearly duration curves of indoor air temperatures.

4.1 Energy consumption

The amount of energy consumed by the building is listed in Table 5 together with the 2008 energy frame for new buildings in Denmark. The energy demand is calculated by the Danish energy frame documentation tool Be06 (2008), because several of the elements of the energy frame require special and time-consuming setup and simulation in ESP-r.
We use ESP-r to show the feasibility of the passive system in terms of ventilaton rate and indoor climate and Be06 in terms of energy. Thus the ventilation rate keyed into Be06 is the required minimum supply air rate from Figure 3, because in practise the intake damper would be controlled to obtain this air rate.
With regard to the cooling effect of the night ventilation during summertime, the keyed-in ventilation rate value in Be06 is set to 0.11 m^3/s as an average value obtained from Figure 3.

Table 5: Relative energy consumption

Primary energy kWh/m^2	Mech. vent. and cool.	Passive vent., night cool., mech cool.
Heating	100 %	103 %
Cooling	100 %	55 %
Fans	100 %	0 %
Lighting	100 %	100 %
Hot water	100 %	100 %
Total	100 %	60 %
Danish	2006	2010
Building Code	100%	53%

The energy delivered is in primary energy (electric energy consumption is multiplied by 2.5) and includes energy for heating, cooling, fans, lighting and domestic hot water. The reduction in the Danish energy frames from 2006 to 2010 is included to demonstrate how a passive ventilation system with night cooling reduces the mechanical cooling load and thus is an efficient energy measure on the road to the future frame of 2010.

5. DISCUSSION

It is clear from Figure 3, Figure 4 and Figure 5 that the passive system is able to provide sufficient ventilation during the heating season. The distribution of air between offices may be further optimized by choosing duct sizes that correspond to equal pressure losses. This however requires non-standard duct sizes. Introducing dampers is not desirable as the air velocities in the ducts are outside the working interval of dampers and that dampers introduce unnecessary pressure losses.

From Figure 3 it is clear that the ventilation rate provided by the passive system becomes unstable during the summer due to small stack effect and less wind. Hence comfort ventilation during the summer must be provided by other means, e.g. through openings in the façade. Despite the inadequacy of the passiv system to provide ventilation in a summer day situation, the system does provide a significant amount of free cooling on a whole-year basis even with no more thermal mass than that of the decks and the façade.

The proportional damper control in ESP-r is not adequate for controlling the ventilation system in terms of energy consumption. This is illustrated on Figure 3 where the minimum setting of the damper (10 % open) lets 40 % of the minimum supply airflow through. However this also illustrates the driving potential of stack and wind in ventilation.

Thus the energy consumption in the building is compared to the current and future energy frame of the Danish Building Code showing a significant decrease in energy consumption. This said, the energy required for the electrostatic precipitator and the circuitry pump is not quantified but rather assumed to be negligible.

6. CONCLUSION

The simulations performed in this paper indicate that passive ventilation has potential over conventional mechanical ventilation. In conjunction with adequate night cooling both ventilation and cooling tasks are performed satisfactorily. Consequently energy consumption for fans and mechanical cooling can be saved in a passive ventilation system. If the system is equipped with low pressure loss heat recovery and electrostatic filtering it may perform the task of ventilation, cooling and heating in high performance offices with comparable flexibility and total costs to that of conventional mechanical systems.

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