Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

SIMULATION OF THE PERFORMANCE OF A HYBRID VENTILATION SYSTEM IN DIFFERENT CLIMATES

Pavel Charvat[1], Miroslav Jicha[1], Aikaterini Niachou[2] and Mat Santamouris [2]
[1]Brno University of Technology, Faculty of Mechanical Engineering
Technicka 2896/2, 616 69 Brno, Czech Republic
[2] National and Kapodistrian University of Athens, Athens, Greece

ABSTRACT

The paper deals with the computational simulations of the performance of the hybrid ventilation system for the moderate climate, which was developed within the framework of the RESHYVENT project. The main goal of the simulations was to investigate the performance of the system in urban environment under different climatic conditions, representing different potential of natural driving forces (wind, buoyancy). The TRNSYS 15 with the TRNFlow air flow network module was employed as a simulation tool.

INTRODUCTION

A hybrid ventilation system is a ventilation system that utilizes natural driving forces (natural ventilation) as long as possible and employs mechanical forces (mechanical ventilation) when necessary. The main goal of this approach is to minimize energy consumption while maintaining good indoor air quality and thermal comfort of occupants.

Four diffrent concepts of a hybrid ventilation system for four climates in Europe (warm/mild, moderate, cold and severe) have been developed within the framework of the EU project RESHYVENT (RESidential HYbrid VENTilation). One of the work packages of the RESHYVENT project was aimed at the impact of the urban environment on the performance of hybrid ventilation systems (Niachou at al., 2003).

Computational simulations described in this paper were performed in order to investigate the performance of the hybrid ventilation system for the moderate climate in urban environment under various climatic conditions.

The RESHYVENT hybrid ventilation system for the moderate climate employs natural air supply and natural or mechanical air exhaust. The operation mode of the exhaust (natural/mechanical) depends on the ventilation demand and available natural driving forces. The system consists of self-regulating air inlets, DC fan, motorized damper, flow meter, central control unit, CO_2 sensors and ductwork. The demand control of the ventilation system is based on monitoring of CO_2 in rooms (Jacobs at al. 2003).

There is a CO_2 sensor and a self-regulating air inlet in each room. The self-regulating inlets are usually positioned above windows. These inlets are able to maintan a constant flow rate for the presure difference across the facade higher than 1 Pa. A draft risk can be significantly reduced this way.

When the CO_2 concentration in all rooms is below a certain level (e.g. 800 ppm) ventilation system ventilates only at the minimum level (exhaust air flow rate is for example 10 $dm^3\,s^{-1}$). When the concentration of CO_2 in a room increases to 800 ppm, then the inlet in this room opens. The inlet opens to a certain target flow rate, which depends on the nominal flow rate of the inlet and the gradient of increase of the CO_2 concentration.

The air flow rate in the exhaust increases to a value which is the sum of the basic ventilation flow rate and the target flow rates of the opened inlets. The ventilation system first tries to achieve the exhaust flow rate by adjusting the motorized damper in the vertical exhaust duct (stack). If natural driving forces are not sufficient then the fan is switched on and its speed adjusted to match the demanded flow rate.

When the concentration of CO_2 in a room decreases to a certain level (e.g. 600 ppm), the inlet in the room closes, and the exhaust air flow rate is adjusted to match the current ventilation demand. It is done by adjustment of the fan speed (if fan is needed) or adjustment of the motorized damper position (in natural ventilation mode).

An occupant always has an option to overrule the automatic control of the system. The air inlets can be opend or close manually by means of a remote controller. There is a switch in a kitchen and a bathroom, which allows the occupant to increase the ventilation rate during cooking or showering. Many parameters, like set points (concentrations of CO_2) for opening and closing the inlets, can be set by the user in the central control unit. A prototype of the RESHYVENT hybrid ventilation system for the moderate climate has been installed in a demonstration house in the campus of the Brno University of Technology in the Czech Republic.

CASE STUDY DESCRIPTION

The simulations of the performance of the hybrid ventilation system were done for an apartment in an apartment building situated in an urban canyon. The apartment was modeled as a single zone by means of the TRNSYS TYPE 56 with TRNFlow features.

Urban Canyon

Figure 1 shows the dimensions of the urban canyon and its orientation to north. An apartment, which was the object of the simulation, was located in the apartment building labeled "A" in Figure 1. The floor of the apartment was 14 m above the ground level. The apartment was modeled as a single zone with the dimensions W x L x H =10 m x 10 m x 2.7 m.

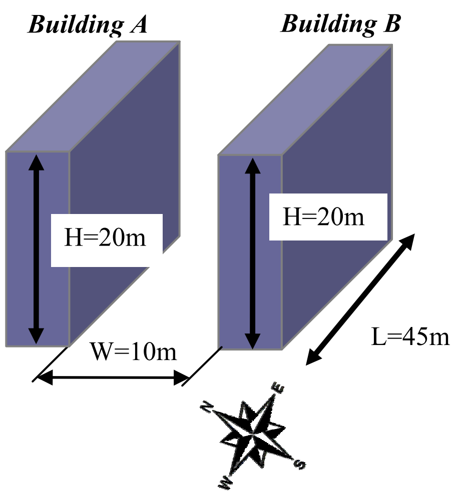

Figure 1 Geometry of the urban canyon

The apartment had two external walls; one facing the canyon and the other facing the backyard. The U-value of the external walls was 0.32 W m^{-2} K^{-1}. The area of windows (glazing) was 3 m^2 in case of the canyon facade and 2.5 m^2 in case of the backyard facade.

The air leakage of the apartment was N_{50} = 2.5 ACH h^{-1}. The air leakage was modeled by means of a crack in each of the external walls (facades). The cracks were positioned in the middle of the apartment height (1.35 m above the floor). The mass flow rate characteristic of each of two cracks was:

$$\dot{Q} = C\,\Delta p^{n} = 0.008508\,\Delta p^{0.66} \quad [\text{kg s}^{-1}], \qquad (1)$$

where $\dot{Q}$ [kg s^{-1}] is mass flow rate, C [kg s^{-1} @ 1 Pa] is the mass flow coefficient and Δp [Pa] is the pressure difference across the facade.

Hybrid ventilation system

The model of the hybrid ventilation system consisted of self-regulating air inlets supplying outside air into the apartment (zone), exhaust duct, and a fan. The inlets had a nominal flow rate of 26 dm^3 s^{-1}, and were positioned on the external walls as indicated in Figure 2. The inlets were 1.8 m above the floor level.

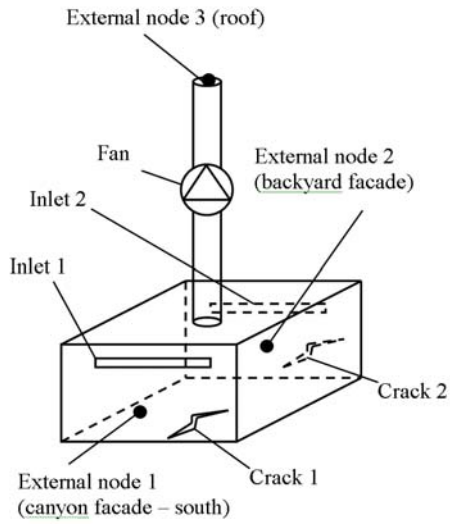

Figure 2 Model of the apartment

The self-regulating inlets (Figure 3) are able to maintain a constant flow rate, when the pressure difference across the facade is equal or higher than 1 Pa. This feature of the inlets reduces draft risk and therefore increases thermal comfort of occupants.

The flow sensor in a self-regulating inlet monitors not only the flow rate, but also the flow direction. The inlet closes when a backflow (flow direction from a room to the outside) is detected.

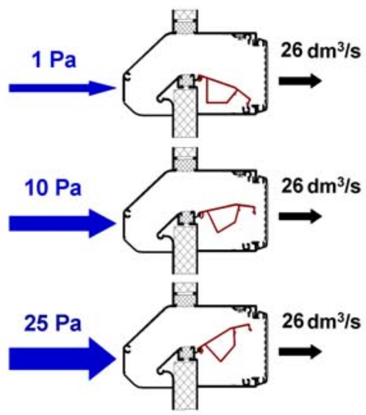

Figure 3 Self-regulating air inlets

The inlets were modeled by means of the test data type. The characteristic of the self-regulating inlet (with the nominal flow rate of 26 dm^3 s^{-1}) is in Table 1.

Table 1
Characteristics of the inlets

ΔP [Pa]	Flow rate [$dm^3\ s^{-1}$]
0	0
0.1	8.2
0.2	11.6
0.3	14.2
0.4	16.4
0.5	18.4
0.6	19.0
0.7	21.7
0.8	22.5
0.9	24.0
1	26.0
5	26.0
10	26.0
20	26.0
50	26.0

The vertical exhaust duct was 224 mm in diameter and 4.3 m in length. The duct ended 1 m above the roof level. The overall dynamic loss coefficient of the duct Zeta = 2.2 was considered for both flow directions. The axial fan, which is used with the hybrid ventilation system, has a very small resistance when switched off. The characteristic of the fan when switched off was:

$$\dot{Q}_{\text{Fan off}} = C\,\Delta p^{n} = 1\,\Delta p^{0.5} \quad [\text{kg s}^{-1}] \qquad (2)$$

where $\dot{Q}_{\text{Fan off}}$ [kg s^{-1}] is the air mass flow rate through the fan when switched off, C [kg s^{-1} @ 1 Pa] is the air mass flow coefficient and Δp [Pa] is the pressure difference across the facade.

The impact of the urban environment was characterized by the C_p values and the wind velocities recalculated for the canyon situation. The C_p values were specified in external nodes on the external walls of the apartment and on the roof (Figure 2 and Table 2).

Table 2
C_p values on the roof and facades

wind direction	C_p values		
	node 1 canyon	node 2 backyard	node 3 roof
0°	-0,149	-0,160	-0,360
45°	-0,327	-0,275	-0,417
90°	-0,469	-0,191	-0,473
135°	-0,251	-0,465	-0,782
180°	-0,262	-0,218	-0,361
225°	-0,046	-0,095	-0,417
270°	-0,453	-0,986	-0,473
315°	-0,700	-0,053	-0,772

Occupancy scheme

The apartment was occupied by four people; two adults and two children. The occupancy scheme is shown in Table 3.

Table 3
Occupancy of the apartment

Time	Adult 1	Adult 2	Child 1	Child 2
0 - 1				
1 - 2				
2 - 3				
3 - 4				
4 - 5				
5 - 6				
6 -7				
7 - 8				
8 - 9				
9 - 10				
10 -11				
11-12				
12-13				
13-14				
14-15				
15-16				
16-17				
17-18				
18-19				
19-20				
20-21				
21-22				
22-23				
23-24				

Two air pollutants were taken into account in the simulations. The occupants were the only source of CO_2 in the apartment. This source changed with time according to the occupancy scheme. The same source strength was considered for both adults and children. The source strength was 6.6 10^{-6} kg s^{-1} of CO_2 for each person.

Another pollutant was the TVOCs. A constant emission of 3.1 10^{-8} kg s^{-1} of the TVOCs was considered for the whole apartment.

The outdoor concentration of the pollutants was considered constant in time. The outdoor concentration of CO_2 was 400 ppm and the outdoor concentration of the TVOCs was 1 mg m^{-3}.

Weather data

Weather data of ten European cities representing different climatic conditions in Europe were used in the simulations. The weather data was obtained by means of the METEONORM data base.

The accuracy of the weather data was not the main concern. The aim of the simulations was to find out how the system performs in different climates, and not how it would perform in a particular city.

The weather data of the cities shown in Table 4 were used in simulations (Long. stands for longitude, Lat. is latitude, T_a is average air temperature and ws is average wind speed in Table 4).

Table 4
Geographical locations of the cities

City	Long.	Lat.	T_a [°C]	ws [m/s]
Amsterdam	4.54 E	52.21 N	9.7	5.7
Berlin	13.25 E	52.32 N	9.3	4.5
Brno	16.40 E	49.13 N	8.4	3.6
Copenhagen	12.34 E	55.43 N	7.9	4.7
Glasgow	4.15 W	55.53 N	8.5	4.5
Madrid	3.43 W	40.25 N	14.8	2.9
Oslo	10.45 E	59.56 N	5.1	2.3
Paris	2.20 E	48.52 N	10.9	4.5
Stockholm	18.05 E	59.21 N	6.7	3.5
Zurich	8.33 E	47.23 N	8.9	2.0

The wind velocities from the weather data files were recalculated for the urban canyon situation. These calculations were done by the University of Athens, according to metodologhy developed in previous projects.

The majority of the cities in Table 4 have moderate climate. One city with the cold/severe climate (Oslo) and one city with the warm climate (Madrid) were included in the list in order to estimate the performance of the hybrid ventilation system under "extreme" conditions. Stockholm represents cold climate and Paris is somewhere in-between the moderate and mild climate.

Control strategy

The operation (control) of the hybrid ventilation system was simplified in the simulations. The apartment was modeled as a single zone, and so the CO_2 concentration was uniform over the entire apartment. Therefore, both inlets opened and closed at the same time.

The inlets opened when the CO_2 concentration in the apartment (zone) increased to 800 ppm. The inlets closed when the CO_2 concentration decreased to 600 ppm.

As mentioned before occupants can manually increase the ventilation rate when cooking or showering. This manual-control mode was simulated by increase of the demanded flow rate in certain time periods. The system operated in the manual-control mode three times a day; between 6 A.M. and 8 A.M., between 5 P.M. and 7 P.M. and between 10 P.M. and 11 P.M. The exhaust air flow rate of 42 $dm^3.s^{-1}$ was required in this mode. The air inlets were opened in the manual-control mode regardless of CO_2 concentration.

The demanded flow rate for the period of 24 hours calculated with regard to the occupancy scheme and the manual-control mode is in Table 5.

Table 5
Demanded flow rates

Time	Demanded flow rate [$dm^3\ s^{-1}$]
0 A.M – 6 A.M.	28
6 A.M – 8 A.M.	42
8 A.M – 5 P.M.	21
5 P.M – 7 P.M.	42
7 P.M – 10 P.M.	28
10 P.M – 11 P.M.	42
11 P.M – 12 P.M.	28

If the air flow rate through the exhaust duct, after opening of the inlets, was lower than the demanded flow rate, specified in Table 5, then the fan switched on and ran at the demanded flow rate. If natural driving forces increased so much that the demanded flow rate could be achieved by natural driving forces, the fan switched off. When CO_2 concentration decreased to 600 ppm the inlets closed and the fan (if it was switched on) switched off.

Unlike in case of the real system, there was no minimal ventilation flow rate guaranteed in the CO_2-controlled ventilation mode. Unless the CO_2 concentration reached 800 ppm the inlets were closed and the fan was switched off. During that time only infiltration through the cracks induced by temperature difference and wind effects was considered.

Heating and cooling were also specified for the apartment (zone). The heating set point was 16 °C and the cooling set point was 26°C.

RESULTS

Hour-by-hour simulations of the performance of the hybrid ventilation system for the annual weather data of ten European cities were performed. The TRNSYS vs. 15 with the TRNFlow air flow network module (Weber at al., 2003) was employed as a simulation tool.

The main goal of the simulations was to estimate percentage of time during which the hybrid ventilation system would operate in the natural and mechanical mode. The results of the simulation are shown in Table 6.

Table 6
Fan running time and inlet opening

CITY	FAN switched on [% of hours]	INLETS opened [% of hours]
Amsterdam	44.7	70.8
Berlin	42.3	73.4
Brno	38,6	74,0
Copenhagen	36.5	70.1
Glasgow	40.0	73.1
Madrid	56.8	81.1
Oslo	29.3	71.9
Paris	46.0	74.3
Stockholm	34.5	72.7
Zurich	40.4	77.7

The indoor air quality was also a concern in the simulations. The average concentrations of CO_2 and TVOCs and the average air changes can be found in Table 7.

Table 7
Concentrations of pollutants and air change

CITY	average concentration		average ACH [hod^{-1}]
	CO_2 [ppm]	TVOCs [mg m^{-3}]	
Amsterdam	718	1.96	0.48
Berlin	724	1.97	0.47
Brno	727	1.98	0,46
Copenhagen	716	1.95	0.48
Glasgow	723	1.98	0.46
Madrid	770	2.10	0.40
Oslo	716	1.94	0.48
Paris	734	2.00	0.45
Stockholm	720	1.96	0.47
Zurich	741	2.02	0.44

Another outcome of the simulations was the pressure difference across the inlets, while these were opened. The self-regulating inlets are able to control the air flow rate for the pressure difference higher than 1 Pa. Table 8 indicates the percentage of time during which the pressure difference across the inlets was higher than 1 Pa.

Table 8
Pressure difference across the inlets

CITY	canyon facade $\Delta p > 1Pa$ [% of hours]	backyard facade $\Delta p > 1Pa$ [% of hours]
Amsterdam	39.1	16.0
Berlin	28.6	12.1
Brno	17.6	11.0
Copenhagen	25.0	18.0
Glasgow	28.1	14.8
Madrid	12.4	5.5
Oslo	7.1	6.1
Paris	26.0	14.6
Stockholm	17.5	10.9
Zurich	7.0	3.7

DISCUSSION

Not surprisingly, the climatic condition had a significant impact on the mode of operation of the hybrid ventilation system.

The ventilation system operated for the longest time in the mechanical mode in case of Madrid (57 % of time). That was nearly twice more than in case of Oslo (29 % of time). Madrid and Oslo, however, represented "extreme" climatic conditions. The application of the modeled hybrid ventilation system is aimed at the places with moderate climate.

The buoyancy force, caused by the indoor-outdoor temperature difference, seemed to have a higher impact on the operation mode of the ventilation system than the wind speed. The fan ran fewer hours in case of Oslo (the city with the coldest, but calm climate) than in case of Amsterdam (the city with the windiest weather).

The impact of the climatic conditions on the opening time of the inlets was not as significant as in case of fan running time. The inlets were opened 81% of hours in case of Madrid and 70% of hours in the case of Copenhagen. These differences were caused by the pressure difference across the inlet. More time is needed to draw air in when the pressure difference is lower.

The pressure difference across the facades (inlets) was lower than 1 Pa for a significant amount of time. It means that the self-regulating inlets operated most of the time in the regime where flow rate is dependent on pressure difference. The consequence of this is longer time that is needed to bring the CO_2 concentration down (since the air flow rate through the inlet is lower than the nominal one).

The average CO_2 concentration was, because of the demand control, very similar in all studied cases as. The concentration of CO_2 in none of the cases exceeded 1200 ppm during simulation. The average concentration of TVOCs is also very similar in all cases. The concentration of TVOCs several times exceeded 3 $mg.m^{-3}$ in the simulations. However, the “correct” strategy when dealing with the TVOCs in residential buildings is to decrease the source strength and not to increase the ventilation rate.

Energy consumption was not analyzed in the simulations described in this paper. However, some previous studies (e.g. Cron at al., 2003) showed that the hybrid ventilation systems with the demand control can compete even with the balanced mechanical ventilation systems with heat recovery under some circumstances.

CONCLUSIONS

The hybrid ventilation systems, unlike the pure natural ventilation systems, are able to maintain required indoor air quality regardless of weather conditions. Much attention has therefore been paid to the performance of hybrid ventilation systems in office and residential buildings over the last decade. The performance of a natural or hybrid ventilation system, from the computational point of view, represents a more difficult task than the performance of a mechanical ventilation system. It is because the air flow rates significantly depend on the climatic conditions. A simulations of the performance of a natural or hybrid ventilation system requires coupling of the thermal and air flow models (Axley at al., 2002). Fortunately, many contemporary simulation tools are able to solve these kinds of problems.

It is not possible to generalize the results of the simulations described in this paper. The results were obtained for a specific geometry, occupancy scheme and other factors. The huge advantage of computational simulations is that such generalization is not necessary. The results for another case can “easily” be obtained by another simulation.

Carbon dioxide as a pollutant is unavoidable in the places where people live. Even though the CO_2 is not a dangerous pollutant, its concentration can be very effectively used as a measure of indoor air quality in residential buildings. The simulations showed that the average air change was very similar in all cases with the demand control based on CO_2 concentration. The differences would probably decrease with decreasing air-leakage of the apartment. The average air change rates in the Table 7 are total air change rates including both infiltration and ventilation.

As so far, there has not been much experimental data available about the performance of the modeled hybrid ventilation system. Some experiments regarding the indoor air quality have been performend in the demonstration house in Brno, the Czech Republic. These experiments showed that the RESHYVENT hybrid ventilation system for the moderate climate was able to maintain CO_2 concentration in rooms below 1200 ppm (Jicha at al., 2004).

ACKNOWLEDGEMENT

This work was part of the EU fifth framework project No. ENK6-CT2001-00533 “RESHYVENT”.

REFERENCES

Axley J., Emmerich S., Dols S., 2002, Walton S., An approach to design of natural and hybrid ventilation systems for cooling buildings, Indoor Air 2002, Monterey, USA.

Cron F. Inard Ch. 2003. Analysis of hybrid ventilation performance in France, The 8th International IBPSA Conference, Eindhoven, the Netherlands.

Jacobs P., and de Gids W.F. 2003. RESHYVENT - Demand controlled residential hybrid ventilation, 24th AIVC Conference, Washington, USA.

Jicha M., Charvat P., de Gids W.F. and Meester A. 2004. A Czech demonstration house with hybrid ventilation, 25th AIVC Conference, Prague, Czech Republic.

Niachou A., Santamouris M., Livada L., 2003 A first study of natural and hybrid ventilation hybrid ventilation systems in urban environment, 24th AIVC Conference, Washington, USA

Weber A. Koschenz M. Dorer V. Hiller M. Holst S. 2003, TRNFlow, a new tool for the modelling of heat, air and pollutant transport in buildings with TRNSYS. The 8th International IBPSA Conference, Eindhoven, the Netherlands.

Wood A., Lisham B., 2004, Wind-buoyancy interaction in natural ventilation, ROOMVENT 2004, Coimbra, Portugal.