Evaluation of hybrid ventilation control strategies in residential buildings

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ABSTRACT

This paper deals with the development and the evaluation of hybrid ventilation control strategies, using both natural and mechanical mode, in residential buildings. The case study is a single dwelling and it includes a mechanical ventilation system based on the french national regulation and a hybrid ventilation system used in the framework of the European project RESHYVENT. Two demand control strategies have been developed for hybrid ventilation system, the first one is based on the occupant detection and the second one is based on the CO_2 levels in the dry rooms. For the evaluation of hybrid ventilation control strategies, yearly simulations have been performed in four European climates (Athens, Nice, Stokholm and Trappes) using SIMBAD Building and HVAC Toolbox. The assesment criteria used are related to indoor air quality and to energy consumptions. The main conclusion of this work is the ability of hybrid ventilation systems to improve indoor air quality and to reduce fan energy consumption with respect to reference system while maintaining the same building energy consumption for heating.

1. INTRODUCTION

The quality of indoor air has an immediate impact on occupant health and productivity. The main pollutants sources are the occupants metabolism, the occupants activities (cooking, washing…), the furniture and the building materials. Ventilation is used to dilute the pollutants to an acceptable concentration and to remove moisture. Since the pollutants could be related to occupant presence, the use of constant ventilation rate leads to over ventilation during reduced occupancy periods and cause energy loss in terms of both the thermally conditioned air and the energy use for the fan. With demand controlled ventilation based on indoor air pollutant concentrations or occupancy detection sensors, the ventilation is modulated below the design supply airflow while maintaining adequate ventilation rate for acceptable indoor air quality level. In addition, hybrid ventilation system, which is a combination between the natural ventilation and the mechanical one, could reduce the fan running time and improve indoor air quality. The control system is a key factor in such situation for switching between the natural and the mechanical modes with an acceptable magnitude (Heiselberg, 2002). The aim of this paper is to evaluate hybrid ventilation control strategies in residential buildings using airflow models implemented in the MATLAB/SIMULINK graphical environment.

2. MODELS IMPLEMENTED

2.1 Airflow models

The simulation of airflow zone model is based on “pressure airflow network” from Orme (1999). This model is used to calculate air flow rates into and out of the zone and between adjacent zones. In this network, each zone is represented by one node and is connected to other zones by flow paths. The air infiltration/exfiltration model is described in Millet et al., (1998).

Several types of air inlets (De Gids 1997; Jardinier and Simonnot, 1990) are integrated in

MATLAB/SIMULINK. Inlets can be active or passive. Active inlets can be connected to building management system. For passive inlets, it could be either uncontrolled, like crack, where the airflow rate through the inlet is variable and depends on external and internal air conditions (wind pressure, air temperature…) or self-controlled, like pressure controlled inlets where the airflow would be constant. The plant components implemented are ducts, variable speed fan, static extractor, extract opening, T- joint.

The Simulink loop solver uses Newton’s method with weak line search to solve algebraic equations. This method is very robust and avoid convergence problem due the choice of the initial condition. For the plant simulation, the equation loop or the inverse solver technique is used. The models developed are detailed and validated in Jreijiry et al., (2003).

The plant is simulated based on the fact that the algebraic sum of the pressure drops in any closed loop should be zero and in any junctions the air-mass balance should be maintained.

2.2 Indoor quality model

Two types of models for indoor air quality that are currently used are (Axley, 1988; Knoespel et al., 1991): (1) microscopic models, which use a two or three-dimensional fluid mechanics code to describe airflow and pollutant distribution in a ventilated room; (2) macroscopic models, which describe pollutants transport through a multiple zone ventilation system. In this study, the macroscopic model is used. The pollutant transport model assumes no chemical reactions between pollutants, no adsorption with building materials and is based on a mass balance pollutant in each zone.

2.3 Relative humidity model

To simulate the sorption processes, a hygroscopic model proposed by Duforestel and Dalicieux (1994) was used. One buffer represents all hygroscopic materials in one room. It is composed of two volumes: (1) buffer’s surface, with variable moisture density, exchanging vapour with the ambient air and buffer’s heart; (2) buffer’s heart, with constant moisture density.

2.4 Coupling airflow model and thermal model

In building simulation, the temperature has an effect on ventilation due to stack effect and the airflow rates influence the heat balance equations. The thermal model previously implemented in the SIMBAD Toolbox (Riederer, 2002) consists of an envelope model, a simple radiation model using a mean radiant temperature node and a model of room air assuming well-mixed air. Several methods have been proposed to couple an airflow model to a thermal model (Hensen, 1995): the sequential method, the « ping-pong » method (each model uses the results of the other model in the previous time step), the « oignon » method (the two models iterate within one time step until a criteria of convergence is achieved) and the « full integration method ». Hensen (1995) compared « ping-pong » and « oignon » methods for different time steps. The main results were that these two methods are able to generate accurate results but it is necessary to reduce the time step for the « ping-pong » method to increase the accuracy. For this study, numerical tests showed that the « ping-pong » method gives accurate results when using a time step equal to one minute (Jreijiry, 2004).

3. CASE STUDY

As an application, a single family dwelling with two floors is simulated (see Fig. 1). The dwelling is heated by a hot water radiator system and the ventilation system is either a reference system or a hybrid ventilation system described in section 3.1. Pollutant generation and water vapor production are based on the IEA Annex 27 scenario (Millet et al., 1998).

3.1 Definition of the ventilation systems

3.1.1 The reference ventilation system

It is a mechanical exhaust system with self-

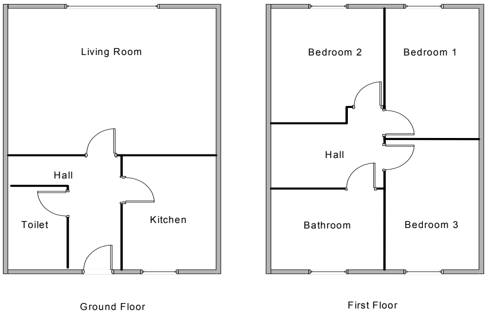

Figure 1: Single family dwelling simulated.

regulating air inlets. One air inlet (45 m^3/h at 20 Pa) is placed in the living room and one in each bedroom (30 m^3/h at 20 Pa). The air is extracted from the service rooms (kitchen, bathroom and toilet). The extract grille of the kitchen has two positions (middle and high). The fan has a constant speed and is running continuously.

3.1.2 The hybrid ventilation system

The hybrid ventilation system is a combination of a low-pressure mechanical exhaust system with natural supply inlets coupled with a natural ventilation mode. The air is extracted from the service rooms. The air inlets (three in the living-room and one in each bedroom) and the extract grilles are controlled with eight positions.The low-pressure fan has three speed levels.

3.2 Definition of the control strategies

The reference system is controlled by a time scheduler acting on the kitchen extract grille. Two hours a day from Monday to Friday and three hours a day the week-end, the extract grille is on the high position unless it is on the middle position.

Concerning the hybrid ventilation system, the first control strategy, called HV1, is based on: (1) Presence detectors in the bedrooms, the toilet and the living room; (2) Relative humidity sensors in the wet rooms. Every 10 minutes, the control algorithm HV1:

- defines a target airflow based on sensor detection,
- defines the total target airflow which is the maximum of the target fresh air and the target extracted airflow (minimum target airflow is 40 m^3/h),
- calculates the fan speed level based on the comparison between the stack effect available (depending on the difference between indoor and outdoor temperatures) and the pressure loss through the whole ventilation system using an analytical solution of a network of airflow components,
- computes a new target airflow per room in the case where there is a difference between the target fresh airflow and the target extracted airflow to balance the fresh and the extract airflow,
- calculates the positions of the inlets and extract grilles.

The second ventilation control strategy, called HV2, is based on: (1) Presence detector in the toilet; (2) CO_2 sensors in the living room and bedrooms; (3) Relative humidity sensors in the wet rooms. In the control algorithm HV2, every 10 minutes:

- Inlets open based on CO_2 level in the dry rooms and maximum relative humidity level RHmax in the wet rooms.
- Extract grilles open based on RH level in the wet rooms and the maximum CO_2 level in the dry rooms CO_2max.
- Fan speed starts to increase when CO_2max > 1050 ppm or RHmax > 60%. Fan speed reach its highest level when CO_2max >1750 ppm. In the other case, the fan is switched off when the difference between extract and outdoor temperatures < 8°C.

4. RESULTS

The evaluation of ventilation control strategies is made with respect to indoor air quality (indoor CO_2 concentration), energy consumptions for heating and electrical consumptions of the fans.

The simulations have been performed for a year and four climates: Trappes and Nice (France), Athens (Greece) and Stockholm (Sweden). The simulation time step is one minute.

Furthermore, dimensionless criteria are computed as follows:

$$C = \frac{C_{CO2}(\text{HV1 or HV2})}{C_{CO2}(\text{REF})} \tag{1}$$

where:

C_{CO2} (HV1 or HV2) total indoor CO_2 concentration higher than 1050 ppm for the hybrid ventilation system.

C_{CO2} (REF) total indoor CO_2 concentration higher than 1050 ppm for the reference ventilation system.

$$EH = \frac{E_H(\text{HV1 or HV2})}{E_H(\text{REF})} \tag{2}$$

where:

E_H(HV1 or HV2) heating energy consumption for the hybrid ventilation system

E_H(REF) heating energy consumption for the reference ventilation system

$$EF = \frac{E_F(\text{HV1 or HV2})}{E_F(\text{REF})} \quad (3)$$

EF(HV1 or HV2) electrical consumption of the fan for the hybrid ventilation system

EF(REF) electrical consumption of the fan for the reference ventilation system

Figures 2 to 5 show the results obtained for each case.

Figures 2 to 5 show that the indoor air quality is greatly improved with the demand controlled ventilation system compared with the reference system. In fact, the CO_2 concentration is reduced from 40% to 50% with the HV1 strategy and from 60% to 80% with the HV2 strategy. The strategy HV2 has a better indoor air quality performance than HV1 because it includes a measurement of CO_2 level in a closed loop control.

Furthermore, the values depend on the climate because of the stack effect available. Obviously, the better results are obtained with the colder climate (Stockholm) where the use of natural ventilation is highest (see Fig. 6).

With the hybrid system, the electrical consumptions of the fans are widely reduced (more than 90%) due to the use of natural ventilation and a low-pressure fan.

On the whole, the energy consumptions for

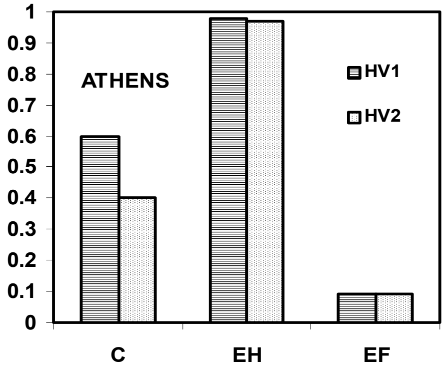

Figure 2: Evaluation of control strategies for Athens.

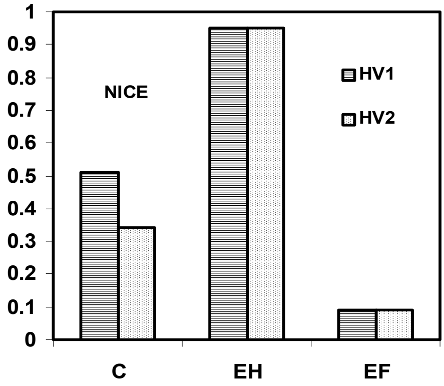

Figure 3: Evaluation of control strategies for Nice.

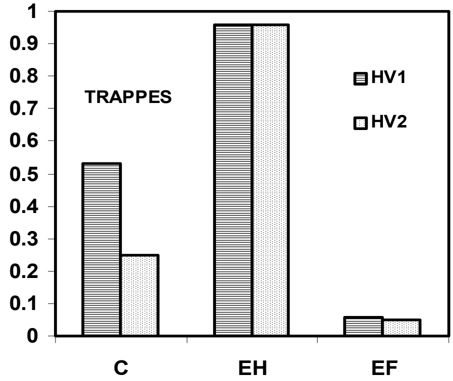

Figure 4: Evaluation of control strategies for Trappes.

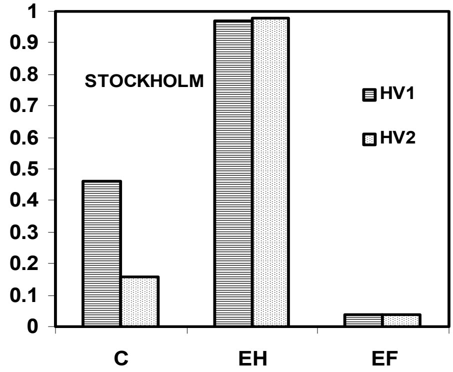

Figure 5: Evaluation of control strategies for Stockholm.

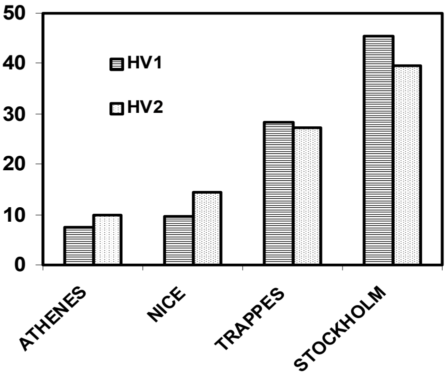

Figure 6: Percentage (%) of natural ventilation use (fan off).

heating are of the same order of magnitude for all the systems of ventilation. The slight differences between the reference system and the hybrid system are due to the total air mass flows extracted which are slightly lower for the latter.

4. CONCLUSION

This study showed the capability of the models implemented in the graphical environment MATLAB/SIMULINK to evaluate control strategies of hybrid low-pressure ventilation systems. The simulations have been carried out over a year, with a short time step and for four European climates. Furthermore, two hybrid ventilation control strategies have been proposed and evaluated for a single family dwelling. The evaluation of these strategies showed that both strategies have better performances with respect to indoor air quality and electrical consumptions of the fan compared to a reference ventilation system because they optimize the use of the natural ventilation mode.

REFERENCES

Axley, J., 1988. Integrating microscopic and macroscopic air movement and contaminant dispersal in buildings. Proceedings of NSF/ASHRAE Symposium. Atlanta, USA.

De Gids, W., 1997. Controlled air inlets. NATVENT work package 3. http://projects.bre.co.uk/natvent

Duforestel, T. and P. Dalicieux, 1994. A model of hygroscopic buffer to simulate the indoor air humidity behaviour in transient conditions. Proceedings of EPIC Conference, Lyon, France

Heiselberg, P., 2002. Principles of hybrid ventilation. Aalborg University, Denmark.

Hensen, J.L.M., 1995. Modelling coupled heat and airflow : ping-pong versus onions. Proceedings of 16th AIVC Conference, Palm Springs, USA.

Jardinier, P. and J. Simonnot, 1990. Principle and aim of a natural humidity controlled ventilation system. Proceedings of International CIB W67 Symposium, Rotterdam, Netherlands.

Jreijiry, D., A. Husaunndee, C. Inard, J.G. Villenave, 2003. Control of ventilation in buildings using SIMBAD Building and HVAC Toolbox. Proceedings of Building Simulation 03, Eindhoven, Netherlands.

Jreijiry, D., 2004. Modélisation numérique des systèmes de ventilation hybride et développement de stratégies de contrôle associées pour les bâtiments résidentiels. Thèse de Doctorat, Université La rochelle, France.

Knoespel, P.D., J.W. Mitchell and W.A. Beckman, 1989. Macroscopic model of indoor air quality and automatic control of ventilation. ASHRAE Trans., Vol. 97, Part 2, pp. 1020-1030.

Millet, J.R., J.G. Villenave, L.G. Manson and W. De Gids, 1998. Evaluation and demonstration of domestic ventilation systems. IEA Annex 27, Vol. 2.

Orme, M., 1999. Applicable models for air infiltration and ventilation calculations. AIVC Technical report.

Riederer, P., 2002. Thermal room modelling adapted to the test of HVAC control systems. PhD Thesis, Ecole des Mines de Paris, France.