ABSTRACT

This paper deals with the development and the evaluation of hybrid ventilation control strategies, using both natural and mechanical modes, in residential buildings using a graphical simulation tool. The description of a library of airflow components and macroscopic pollutants models used to simulate the demand controlled ventilation based on indoor pollutant concentrations is provided. The paper discusses the issue of implementation of ventilation control strategies based on occupancy and indoor air quality using "Stateflow" and integration into thermal-airflow modelling using "Simulink".

The case study is a single family dwelling that is used within the European project RESHYVENT. Two demand control strategies have been developed for the hybrid ventilation system. Yearly simulations have been performed in four European climates using the SIMBAD Building and HVAC toolbox, for the evaluation of hybrid ventilation control strategies. The assessment criteria used, are related to indoor air quality, to thermal comfort, to energy consumption and to the stability of control strategies.

This work shows the possibility of using a graphical simulation environment for thermal-airflow computation. It is applied to the assessment of hybrid ventilation systems and concludes that the latter can improve indoor air quality and to reduce fan energy consumption with respect to reference system while maintaining the same building energy consumption for heating.

KEYWORDS
Building Simulation, Graphical Modelling, Thermal-airflow coupling, Indoor Air Quality, Ventilation, Control Strategies

INTRODUCTION

Ventilation is required in buildings to provide fresh air to the occupants, avoid condensation due to a high indoor air humidity level and remove pollutants due to occupants, and pollutants emission of building materials. Significant energy saving can be expected if the flow rate for ventilation is reduced to a minimum level while keeping an acceptable air quality in the building. Therefore, new demand controlled ventilation strategies modulate the airflow rate to avoid an over-ventilation of the building. These strategies are based on occupancy detection or pollutants indoor level measurements such as carbon dioxide, relative humidity, Volatile Organic Components (VOC). In addition, hybrid ventilation system, which is a combination of natural and mechanical ventilation modes, could reduce the running time of fans and improve indoor air quality. The control system is a key factor in such a system for switching between the natural and the mechanical mode with an acceptable magnitude (Heiselberg et al, 2002). Multizone Simulation tools coupling between airflow and thermal phenomena in building are an attractive approach to evaluate hybrid ventilation control strategies (Delsante et al. 2000).

The aim of this paper is to show the implementation of the airflow models in a graphical environment, SIMBAD building and HVAC toolbox, that is primarily used for thermal simulation. Special attention is paid to the graphical representation of the thermal and airflow phenomena in a multizone building. It is then applied for the evaluation of hybrid ventilation control strategies in the framework of the European projet RESHYVENT.

MULTI-ZONE MODELLING IN THE GRAPHICAL ENVIRONMENT

In buildings, there is a complex interaction between physical phenomena (Hensen 2001): (1) outdoor climate (temperature, wind speed and direction); (2) indoor climate or ambiance; (3) occupancy; (4) technical systems (ventilation systems, heating systems…); (5) control strategies. The representation in a graphical environment might lead to an excessive number of links between models and thus makes the overall model difficult to be understood by the user.
The development of SIMBAD Building and HVAC toolbox (Husainnandee et al., 1997), which is a library of HVAC components models for the design and test of control systems had to tackle this issue. The toolbox (SIMBAD 2002) has been developed using the graphical environment MATLAB/Simulink. Simulink uses hierarchical top-down and bottom-up modelling approaches (Simulink 2003).

The structure and parametering of the models in the current library are defined in (Husainnandee et al., 1999), using the systemic approach based on the definition of: (1) Elementary blocks; (2) Subsystems or Macro-block; (3) System-Block; (4) Connection vectors. The elementary blocks are the HVAC components and are also called “component blocs”. The Macro-block corresponds to a complex component of the HVAC system. The System-Block is a combination of components-blocks and macro-blocks which may represent a HVAC plant linked to building zones.

Connections vector have been defined in Simbad to transfer data from one block to another and to avoid excessive use of links.

In order to evaluate ventilation control strategies, airflow models had to be implemented in the toolbox and the structure of the overall building system had to be reviewed.

**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 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 permeability model described in Millet et al (1998) calculates the air infiltration rates.

Several types of air inlets (De Gids 1997; Jardinier et al 1990) are integrated in SIMBAD. 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 (Figure 1) 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 simulation is on the fact that the algebraic sum of the pressure drops in any closed loop should be zero and in any junction, the conservation of air should be satisfied.

![Figure 1: Airflow zone modeling and components](image)

**Indoor air 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 SIMBAD, the macroscopic model is implemented. SIMBAD airflow model is base upon the network technique where each building zone is representing by one node at uniform pressure, temperature, and pollutant concentration, and nodes are connected by airflow paths.

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 as given in Equation (1) (Knoespel et al. 1991). In the following equations, the subscript p, in and out indicates the pollutant, into the zone and out of the zone respectively:

$$\frac{d m_p}{dt} = m_{p,in} - m_{p,out}$$  \hfill (1)

By replacing the mass flow rate by the volume flow rate, the final form of the general pollutant balance equation for a zone:

$$\frac{d C_p}{dt} = \frac{Q_{in}}{V_a} C_{p,in} - \frac{Q_{out}}{V_a} C_{p,out}$$  \hfill (2)
By including all possible airflow paths into or out
the zone i, Equation 2 is now written as:

\[
\frac{dC_{p,i}}{dt} = \frac{S_{pi}}{V_{ai}} + \frac{Q_{pri}}{V_{ai}}C_{p,ai} - \frac{\sum_{j=1}^{N} Q_{ij} C_{p,j}}{V_{ai}} - \frac{\sum_{j=1}^{N} Q_{ji} C_{p,i}}{V_{ai}}
\]  

(3)

The first term on the right hand side of Equation 3 is the pollutants volume source located in zone i.

Equation 3 is implemented in SIMBAD and the transient solution of this equation requires a small simulation time step when there is a changing of sources level or changing of airflow rates.

**Relative humidity model**

Indoor water vapour level depends on ventilation rates, on the outdoor specific humidity, indoor water vapour sources, surface condensation and water vapour sorption process due to the indoor furnishings and building materials. Experimental studies showed that more than one third of the airborne moisture can be absorbed by indoor surfaces (Kusuda 1981). To simulate the sorption processes, a hygroscopic model proposed by Duforestel et al. (1994) is implemented in SIMBAD. One buffer represents all hygroscopic materials in one room. It consists 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.

**Graphical implementation**

Two approaches have been developed to simulate a multizone building in SIMBAD: the first one is called “Horizontal approach” where each phenomenon (emitter, occupants, lighting…) is defined in for each zone (Husaunndee et al 1999). The second approach is called “vertical approach” where the same phenomenon of all zones is defined on the same block (Riederer et al 2001). These two approaches have mainly paid attention to thermal phenomena (see Figure 2) and signals transfer with control unit and they are not able to simulate airflows and pollutants exchange in a multizone building.

This new approach is based on the vertical approach. It lies on the definition of macro blocks representing the building zones or technical systems and the definition of adequate connections vectors especially for flow rate-pressure determination. The building is divided into n zones with individual numbering. The global connecting vectors are automatically generated and have a dimension depending on the number of zones n.

**Figure 3: Zone modeling for airflow and thermal phenomena**

The ventilation system is divided into two parts:

- Airflow components connected to the zones (Air inlets, extract grilles, doors…). These models are integrated in the zone model with the thermal models, the airflow model and the pollutants models (see Figure 3)

- The ventilation system (ducts, fan, damper…). These are integrated in the Airflow technical systems

Connections vectors to transfer data are:

- State variable vectors for building containing for each zone the following information: temperature, humidity, indoor pressure, indoor CO₂ concentration, indoor VOC concentration, air change volume.

- Air vector containing the air characteristics through an airflow component (Air inlets, duct…). It contains the following information: temperature, humidity, pressure inlet, CO2 concentration, VOC concentration, air flow through the component.

- Communication vectors for control signals

- Energy flux vectors representing energy supplied to the zones (heating/cooling system)

- Indoor disturbance vector for occupancy, equipments (Heat gains and pollutants generation)

In each zone model, the combination of the “Air vectors” of all the airflow components connected to the zone generates a matrix containing the characteristics of all the incoming and outgoing airflows. This matrix is used to calculate the conservation of mass in the zone for humidity,
pollutants, airflows and the energy balance for the zone.

Figure 4 is an overview of the graphical representation of a multizone model. The “Building block” contains zones models, the “Air Plant block” contains the ventilation systems, the “Heating system block” contains heat production, water distribution and the emitters, the “Control system block” includes the central HVAC unit control, the “Weather data block” gives information about the outdoor climate, the “Radiation processor block” computes the solar radiation on each façade of the building.

The dwelling is heated by a hot water radiator system and ventilated by a hybrid ventilation system which is a combination of a low-pressure mechanical exhaust system with natural supply inlets coupled with a natural ventilation mode.

The air inlets and extract grilles are controlled with 8 positions and the fan has 3 speed levels. The level 0 means that the fan is switched off. Pollutants generation and water vapor production are based on the IEA Annex 27 scenario (Millet et al 1998).

**Definition of control strategies**

The first ventilation control strategy, called VH1, is based on: (1) Presence detectors in the bedrooms and the Toilet; (2) Movement or agitation detector in the living room; (3) Relative humidity sensors in the wet rooms. Every 10 minutes, the control algorithm VH1:

- 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 m3/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 VH2, is based on: (1) Presence detector in the Toilet; (2) CO2 sensors in the living room and bedrooms; (3) Relative humidity sensors in the wet rooms. In the control algorithm VH2, every 10 minutes:

- Inlets open based on CO2 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 CO2 level in the dry rooms CO2max,
- Fan speed starts to increase when CO2max > 1050 ppm or RHmax > 60%. Fan speed reach its highest level when CO2max > 1750 ppm. In the other case, the fan is switched off when the difference between extract and outdoor temperatures < 8°C.

For both strategies, the control of heating radiators is made by thermostatic valves and the set point temperature is 20°C.

The control strategies are implemented in the Stateflow environment (Stateflow 2002) which is dedicated to the description of finite state machines and the modelling of complex logic and state diagram in the Simulink graphical environment. The implementation of such sequential logical is straightforward in this environment and it enables direct visualisation of states during the simulation. Figure 8 shows the implementation of part of a control strategy.

**Evaluation of control strategies**

The evaluation of ventilation control strategies is made with respect to:

1. **Indoor air quality criteria (Cv)**
   - Local occupant exposure to a pollutant p above a level Bp:
     \[ Cv_p = \int (C_p(t) - B_p) \, dt \]
   - Occupants exposure in a dwelling to a pollutant p above a level Bp:
     \[ Cv_{p,dwelling} = \sum_{i=1}^{N} \int (C_p(t) - B_p) \, dt \]
   where N is the total number of dry rooms in the dwelling.
2. **Thermal comfort criterion (CT)**
   - Local occupant exposure to operative temperature > 26°C:
     \[ CT = \int (T_{rs} - 26) \, dt \]
   - Occupants exposure in a dwelling to operative temperature > 26°C:
     \[ CT_{dwelling} = \sum_{i=1}^{N} \int (T_{rs} - 26) \, dt \]
3. **Energy consumptions criterion**
4. **Control criterion (actuators movements).**
The simulation has been performed for a year for 4 climates: Trappes and Nice (France), Athens (Greece) and Stockholm (Sweden). The simulation time step is one minute.

Figure 9 and Figure 10 show that VH1 mainly controls grilles while VH2 acts primarily on the fan speed. This is due to the fact that the control algorithm of fan speed for VH2 is a closed loop one based on CO2 level. The VH1 strategy uses an open loop control based on presence detection.

Table 1 shows that the fan control is stable for both strategies since the frequency of changers per hour is low for both strategies, irrespective of the climate tested.

This implies that the proposed hybrid ventilation strategies to switch between natural and mechanical mode are stable.

<table>
<thead>
<tr>
<th>Fan speed change per hour</th>
<th>Frequency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 2 3 4 5 6</td>
</tr>
<tr>
<td>Athens</td>
<td>93,2 0,1 5,2 0,4 0,4 0,0 0,4</td>
</tr>
<tr>
<td>Nice</td>
<td>90,5 0,6 7,0 0,1 0,2 0,3 1,3</td>
</tr>
<tr>
<td>Stockholm</td>
<td>88,3 0,2 7,6 0,6 1,4 0,4 1,5</td>
</tr>
<tr>
<td>Trappes</td>
<td>87,4 0,4 8,0 0,7 0,8 0,5 2,2</td>
</tr>
<tr>
<td>VH1</td>
<td></td>
</tr>
<tr>
<td>Athenes</td>
<td>78,5 0,0 14,6 0 3,4 0,0 3,4</td>
</tr>
<tr>
<td>Nice</td>
<td>75,9 0,0 14,0 0,0 4,0 0,0 5,0</td>
</tr>
<tr>
<td>Stockholm</td>
<td>60,5 0,1 24,0 0,2 7,4 0,6 7,2</td>
</tr>
<tr>
<td>Trappes</td>
<td>68,4 0,0 17,7 0,0 6,5 0,5 6,9</td>
</tr>
<tr>
<td>VH2</td>
<td></td>
</tr>
</tbody>
</table>

Both strategies optimise the use of natural ventilation. Obviously the use of natural ventilation is highest in the colder climate (Stockholm) as expected.

The simulation results are further analysed with respect to a reference system. This system is an extract mechanical system based on the French Health regulation with two fan regime:

- Normal mode with an extracted airflow of 105 m3/h,
- Forced mode with an extracted airflow of 180 m3/h during cooking activities (2 hours per day).
Table 2: Energy consumption

<table>
<thead>
<tr>
<th>City</th>
<th>Fan Energy Consumption (KWh)</th>
<th>Reference system</th>
<th>VH1</th>
<th>VH2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athens</td>
<td>349</td>
<td>31</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Nice</td>
<td>349</td>
<td>31</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Stockholm</td>
<td>349</td>
<td>15</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Trappes</td>
<td>349</td>
<td>20</td>
<td>21</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 shows that both strategies, VH1 and VH2, reduce by 90% the fan energy consumption with respect to reference system. In addition, VH1 uses lower fan speeds than VH2 and the fan is switched off for 50% of the simulation period. Hence the VH1 fan energy consumption has been reduced by 45% and the heating energy consumption is reduced by 4% with respect to VH2 (see Table 2).

To compare the developed strategies, the relative performance of different criteria are calculated with respect to reference system (see Figure 12). The strategy VH2 has a better indoor air quality performance than VH1). In fact only the VH2 strategy includes a measurement of indoor air quality (CO₂ level) being a closed loop control. Moreover, both strategies reduce about 40% the occupant exposure in the dwelling to high CO₂ concentrations with respect to reference system. For the heating energy consumption, a small reduction is occurred since the mean Air Change Volume is close for all systems.

For the thermal comfort, Figure 12 shows that the occupant exposure to operative temperature higher than 26°C in the habitable rooms during the unheating period is reduced by 10%.

The same tendency for thermal comfort and energy consumption applies for the other three climates that were evaluated. An in-depth evaluation of the control strategies is provided in Freijiry (2004).

CONCLUSION

A new structure for implementation of multi-zone building in a graphical environment has been developed. This structure gives an overall methodology for the coupling between thermal models, airflow models and pollutants models graphically thanks to the proposed connections vectors that represent the transfer of mass and energy with the building system. These vectors also allow for the definition of new pollutants if there is a need for control on new types of pollutants in future development.

Besides, this paper showed the capability of SIMBAD toolbox to implement control strategies and to simulate a whole building with a short time step. Moreover, 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 good performance with respect to indoor air quality and both of them optimize the use of the natural mode and are able to switch between the natural and the mechanical modes with an acceptable magnitude of fan regime variation. Moreover, the assessment of the developed hybrid ventilation with respect to a reference system improve the indoor air quality and reduce the fan energy consumption by 90% while maintaining the energy heating consumption and occupant thermal comfort close to each other.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_p )</td>
<td>concentration of pollutant p</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( m_p )</td>
<td>mass of pollutants p</td>
<td>kg</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>mass airflow rate</td>
<td>kg/s</td>
</tr>
<tr>
<td>( Q )</td>
<td>air infiltration volume flow rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>( Q_{i,j} )</td>
<td>airflow from zone i to zone j</td>
<td>m³/s</td>
</tr>
<tr>
<td>( Q_{j,i} )</td>
<td>airflow from zone j to zone i</td>
<td>m³/s</td>
</tr>
<tr>
<td>( S_p )</td>
<td>pollutant volume source</td>
<td>kgp/s</td>
</tr>
<tr>
<td>( T_{rs} )</td>
<td>operative temperature</td>
<td>°C</td>
</tr>
<tr>
<td>( V_a )</td>
<td>air volume in the zone</td>
<td>m³</td>
</tr>
</tbody>
</table>

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