CONTROL OF VENTILATION IN BUILDINGS USING SIMBAD BUILDING AND HVAC TOOLBOX

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ABSTRACT

There is a growing need for more complex control of ventilation systems to satisfy energy and environmental issues.

SIMBAD Toolbox (SIMulator of Buildings And Devices), developed in the SIMULINK graphical environment is a library of HVAC components models that is used in the field of control of HVAC system. Currently, it deals mainly with heating/cooling systems. Prior modelling of airflow components in SIMBAD Toolbox is therefore necessary to extend the capabilities of the toolbox.

This paper presents the integration of airflow modelling in the SIMULINK graphical environment and the coupling with a thermal zone model to quantify the impact of natural ventilation and mechanical ventilation techniques. The paper gives a description of the library of airflow components that have been added in the toolbox.

INTRODUCTION

This paper presents the work done in SIMBAD project to extend the capabilities of the toolbox to deal with airflow models.

A number of interzonal models have been developed to calculate air flows in both single and multizone buildings. On other hand, there is a need for airflow models adapted for control study in order to develop and test optimum control strategies of ventilation systems . In control studies, the simulation time step should be very short to be able to simulate the dynamics of the system and to evaluate its stability. Moreover, when calculating contaminant concentration variation, the final results depend on the time step length chosen by the user (Furbinger et al., 1996).

 SIMBAD is a library of HVAC components models for the design and test of control systems that has been developed using the graphical environment MATLAB/ SIMULINK (Husanndee et al., 1997). The latter has a large number of control adapted Toolboxes (Fuzzy logic, neural network, optimization, Stateflow…).

SIMBAD has been mainly used with heating/cooling systems. Our aim is to simulate air flow to test ventilation control strategies. This model will be coupled with an existing thermal model in SIMBAD while maintaining the modular features of the environment to build systems graphically.

SIMULATION MODELS

The simulation of an airflow model is based on "Pressure Air flow Network" (Orme, 1999). This model is used to calculate flow rates into and out the zone and between connected zones. In this network, each zone is represented by one node and is connected to other zones by flow paths.

The pressure distribution around a building is determined by the wind characteristics, the temperature difference inside and outside the building and the mechanical ventilation used .

The wind average dynamic pressure at the height z is given by :

$$P(z) = Cp\, \rho_{air}\, \frac{U(z)^2}{2} \qquad (1)$$

The wind speed and direction are available from meteorological data and the speed is measured at a fixed height, usually 10m. An approximation correction equation to account for height difference and particular terrain is used in British Standard Institution (Orme, 1999) :

$$\frac{U(z)}{U(z_{ref})} = kz^a \quad (2)$$

k and a depend on the terrain characteristic.

The pressure coefficient Cp depends mainly on the building shape, the wind direction and the surroundings.

Cp values could be found from tables or could be calculated by parametrical programs (Grosso et al., 1995).

The thermal buoyancy force, or stack effect, is due to density difference between the inside and the outside of a building and between connected zones.

We assume no stratification inside the zones (isothermal zones), and therefore the inside zone pressure due to the stack effect at a height z is as follows :

$$P(z) = P_0 - \rho g z \qquad (3)$$

where P_0 is the bottom static pressure of the zone.

The density variations due to pressure variations are negligibly small, the air density in the zone can be given by (Hensen, 1993):

$$\rho = \rho_0 \frac{T_0}{T} \qquad (4)$$

For a given boundary conditions, we apply the mass conservation law for each node. The flow of air into the room is defined as positive and the flow of air out of the room is defined as negative. The air flow through an opening is determined by a power law equation of the form:

$$q_v = C_Q.(\Delta P)^n \qquad 0.5 \leq n \leq 1 \qquad (5)$$

This leads to a system of equations in which the unknowns are the internal pressure for each node $P = (P_1, P_2, \ldots, P_n)$. The mass balance is written as follows:

$$f(P) = \begin{cases} \sum_{i=0, i\neq 1}^{N} q_{m\,i,1} + q_{fan1} = 0 \\ \\ \sum_{i=0, i\neq N}^{N} q_{m\,i,N} + q_{fan\,N} = 0 \end{cases} \qquad (6)$$

$q_{mi,j}$ is the mass flow rate between zone i and j, $q_{fan\,i}$ is the flow rate of the mechanical ventilation in the zone i and $f_i(P)$ represents the mass balance equation of the zone i.

This system of equations is usually solved by using Newton-Raphson method :

$$P_m = P_{m+1} - \frac{f(P_m)}{J(P_m)} \qquad (7)$$

The jacobian matrix J is formed with the partial derivatives of mass balance system with respect to the zones pressures $(P_1, P_2, \ldots, P_n)$.

The convergence of this method depends on the choice of the initial guess. There is also a singularity in the Jacobian matrix when the pressure difference tendes to zero. To specify the initial guess, Walton proposed to consider the solution of the system (6) with a linear approximation relating the flow to the pressure drop in each airflow component (Walton, 1989).

Moreover, to avoid problem when the pressure drop tendes to zero, Walton used a linear characteristic of the flow through an opening and which corresponds to the laminar regime.

On the other hand, the convergence is very slow under certain condition due to the power law of airflow in openings (Feustel et al., 1990). The Newton-Raphson can be modified to avoid convergence problem with non linear equations by finding an appropriate relaxation coefficient λ. Different methods are used to define relaxation coefficient (Herrlin, 1991). In that case, the equation (7) can be written as follow:

$$P_m = P_{m+1} - \lambda \frac{f(P_m)}{J(P_m)} \qquad (8)$$

In SIMULINK, to solve f (P) =0, a special block is used to model algebraic equations and to specify an initial guess. The SIMULINK loop solver uses Newton's method with weak line search to solve the algebraic equations (SIMULINK, 1998); this method is very robust to avoid convergence problems due to the choice of the initial condition.

The plant is simulated by assuming that the algebraic sum of the pressure drops in any closed loop should be equal to zero and in any junctions the air mass balance should be maintained.

AIRFLOW MODELS IN SIMBAD

SIMULINK uses hierarchical top-down and bottom-up modelling approaches (SIMULINK, 1998). Block is composed from several levels of model detail. We simulate a model by implementing the algorithms of the physical concepts describing the models. For each block, SIMULINK allows creating a dialog box, called Mask, which will appear by clicking over the block. The Mask editor enables user to specify initial conditions and model parameters (Figure 3). Connections vector have been defined in SIMBAD to transfer data from one block to another and to avoid excessive use of links. Vectors already defined are: Weather vector, Air vector, Water vector and Control vector. The Air vector contains the following informations : temperature, humidity ratio, pressure and mass flow rate. In future work, we should add the CO_2 level to test ventilation strategies based on indoor CO2 concentrations.

To develop and evaluate natural air supply, there is a need to have an interaction between these inlets and the ventilation system, with regard to the indoor air quality in buildings, especially for natural ventilation (De Gids, 1997).

In SIMBAD, we have implemented several types of air inlets. For all this types, we define the height above the zone floor, and its orientation. Inlets can be active or passive.

In active inlets, the airflow rate is controlled by the position of the grid with a small motor. This type of inlet can be connected with building management system. In active pressure controlled air inlets, a device measures the pressure difference across it and control the position of the grid to keep a constant airflow rate (De Gids, 1997).

Passive inlets could be uncontrolled, like crack, or self-controlled like pressure controlled inlets. For the uncontrolled type, the air flow rate through the inlet is variable and depends on external and internal air conditions (wind pressure, air temperature…). In the self-controlled type, the airflow would be constant for a difference pressure higher than a predifined value (Figure 2).

In this section we will describe two types of controlled inlets :

1) Humidity controlled inlet (Villenave et al.,1995) : The aim of this inlet is to vary airflow in relation with indoor relative humidity (figure1). The user has to define the lower and upper limit for the relative humidities and the air flows. Figure 3 shows the dialog box which should be filled by the user.

2) Pressure controlled inlet: The aim of these inlets is to maintain constant natural supply airflow q_{v0} independent of stack effect and wind pressure. The idealized characteristic of these inlets for the reference difference pressure is described in figure 3, the user should put the response pressure Dp_{set} and this parameter could be given from manufacturer catalogue (figure 2).
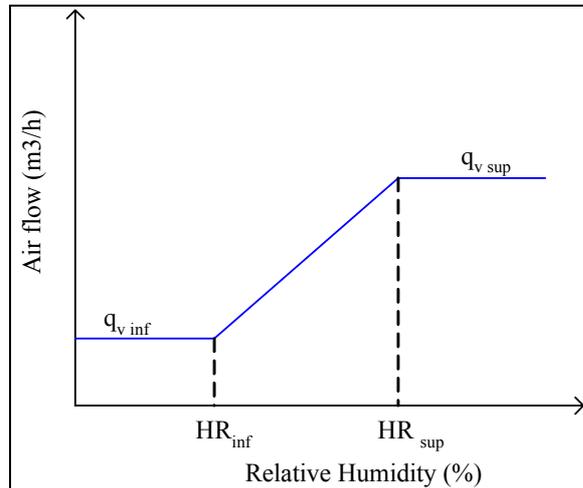

Figure 1 : characteristic of humidity controlled inlet under reference conditions

To compute air leakage due the airtightness of the building the user should define the air infiltration rate q_{v0} under reference difference pressure, usually 4 Pa, and the permeability model calculates the air infiltration rate by (Villenave et al., 1995):

$$q_m = \rho \, q_{v0} \left(\frac{\Delta P}{4} \right)^{0.667} \qquad (9)$$
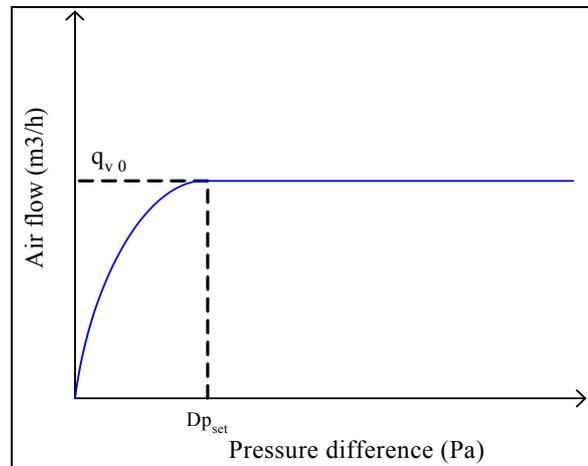

Figure 2: characteristic of Pressure controlled inlet under reference conditions
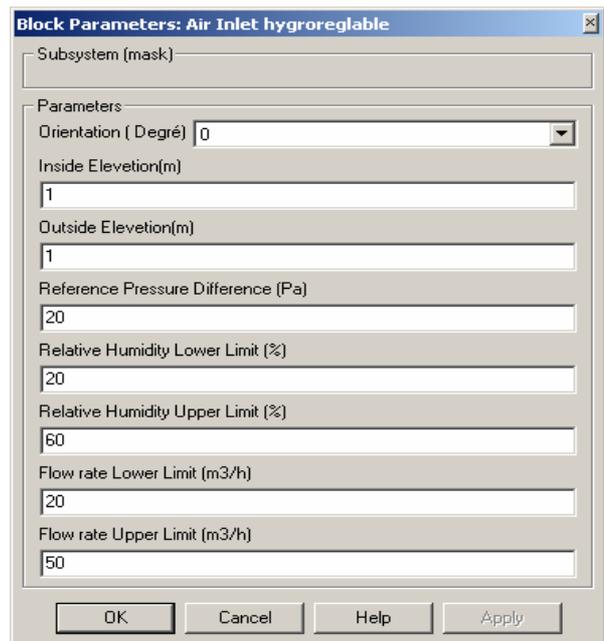

Figure 3: Parameters specifying the humidity controlled inlet

For the plant simulation, we use the equation loop or the inverse solver. The plant components have air flow and the outside pressure as inputs of the model and the output is the inlet pressure. The expression of pressure drop is:

$$\Delta P = \frac{\xi \rho \, v^2}{2} \qquad (10)$$

The plant components implemented in SIMULINK are:

- Duct,
- Variable speed fan,
- Chimney,
- Static extractor,
- Extract opening,
- T- joint.

The fan is simulated to be able to build a hybrid ventilation system. When it is switched on, there is a head pressure depends on the fan characteristic curve. When the fan is switched off, it is considered as a passive component with a pressure drop.

VALIDATION

To test the model developed, we simulate the cases defined in the analytical evaluation of COMIS (Furbinger et al., 1996). For each test case, the SIMBAD numerical results are compared to analytical solutions. These tests consist of crack networks in very simple situations with few indoor nodes and are used to check:

- wind consequences with no stack effect
- stack effect with no wind effect
- wind and stack effects
- influence of the number and the height of the link
- influence of the vertical and horizontal nodes
- influence of reference height

We find a good agreement (within 1%) between the SIMBAD numerical results and analytical results for these tests.

Another test defined by Walton considers the network of fluid flow components which is drawn in figure 4 which is a relatively complex network of airflow components. It involves 12 nodes and 20 fluid type of components arranged in series and in parallel.
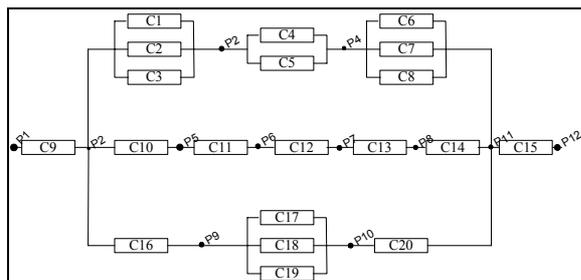

Figure 4 : Network of the Walton Airnet Test

From equation (5), we can write for this type of components:

$$q_m = C_d A \sqrt{2\rho\Delta p} = C\sqrt{\Delta p} \qquad (11)$$

For this network, we can replace the entire flow components by an equivalent one with a powerlaw coefficient C_{tot}.

By using the value of table 1 and constant air density of 1.20415 kg/m^3, we find for this network the equivalent powerlaw coefficient equal to 0.123856 kg/(s.Pa$^{0.5}$). For pressure difference of 100 Pa, SIMBAD gave a mass flow rate value of 1.23856 kg/s.

Table 1 : characteristic of airflow components

Component	C_d	$A(m^2)$
C1	0.6	0.01
C2	0.6	1.0
C3	0.6	2.0
C4	0.6	0.05
C5	0.6	0.06
C6	0.6	1.0
C7	0.6	1.0
C8	0.6	1.0
C9	0.6	1.0
C10	0.6	1.0
C11	0.6	0.01
C12	0.6	1.0
C13	0.6	0.02
C14	0.6	2.0
C15	0.6	1.0
C16	0.6	0.02
C17	0.6	2.0
C18	0.6	0.01
C19	0.6	1.0
C20	0.6	0.03

COUPLING THE AIRFLOW MODEL AND THE SIMBAD THERMAL MODEL

In Building simulation, the temperature has an effect on ventilation due to the stack effect, and the airflow rates influence the heat balance equations.

The thermal model in SIMBAD consists of a (SIMBAD, 2001) :

- Detailed envelope model (5 separate elements including a window model),

- Simple radiation model using a mean radiant temperature node,

- Model of room air assuming well-mixed air.

For each time step, the temperature of the air nodes could be calculated by solving the heat balance equation.

Different methods have been proposed to couple an airflow model to a thermal model (Kendrick, 1993), (Hensen, 1995):

- The sequential method: the two models run independently, and the output history of thermal model is used as inputs to the airflow model.

- The "ping-pong" method: each model uses the results of the other model in the previous time step.

- The "onion" method: the two models iterate within one time step until some criteria of convergence is achieved.

- The "full integration" method: the equations describing the airflow and thermal transfer are solved simultaneously. Such approaches are still under development (Allard, 1998).

Hensen compare ping-pong and onion methods for different time steps (Hensen, 1995). The main results were that these methods are able to generate accurate results, but it's necessary to reduce the time step for "ping-pong'" method to ensure the accuracy.

The main advantage of the "ping-pong" and "onion" methods is that they permit coupling between two modular codes:

- COMIS-EnergyPlus are coupled using "ping-pong" method (Huang et al., 1999).

- COMIS-TRNSYS are coupled using "onion" methods (Dorer et al, 2001).

In SIMULINK, the airflow and thermal models are implemented in two Macro blocks (Figure 5). The algebraic loop occurs because the input of Airflow model is driven by its output by a feedback path through thermal model. SIMULINK have algebraic loop solvers attempt to resolve this situation iteratively (SIMULINK, 1998). SIMULINK iterates between the two models to find the solution with respect to the predefined convergence criteria, this is "onion method".
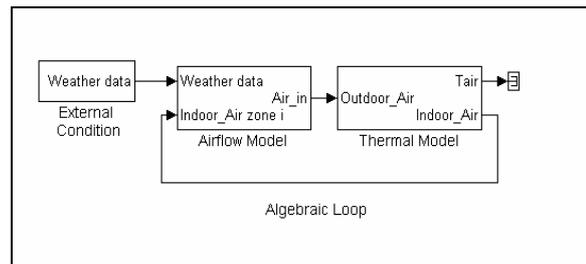

Figure 5 : Coupling Airflow and thermal Model

Figure 5 shows a coupling between a thermal and airflow model in SIMBAD. Ventilation components are defined in the airflow "Macro bloc" model which calculates the air flows incoming and outgoing depending on the external conditions given by the weather data and the internal conditions given by Indoor-Air vector. At the same time, the thermal model uses the value of airflow to calculate the indoor air temperature. SIMULINK will iterate between this two models until achieved the criteria of convergence.

APPLICATION

This section deals with a practical use of the graphical environment for ventilation control study by coupling developed models in this paper to a control strategy implemented in Sateflow, which is Matlab adapted control toolbox.

We will describe an office with a ventilation control strategy (figure 6). The airflow openings have constant sections and the ventilation strategy is based on an occupancy ventilation rate which depends on an occupancy sensor and the temperature difference between the inside and the outside of the office as follows :

- when there is no occupant, the ventilation system is switched off.

- when there is an occupant presence, the ventilation system maintain the occupancy ventilation rate unless if a high difference between inside and outside temperature exists (about 25°C). For this case, the controller will reduce the occupancy ventilation rate.

We can see from the example described above, that the Matlab/SIMULINK environment allows a description of all systems and is veru suitcasr for implementing of control strategies.
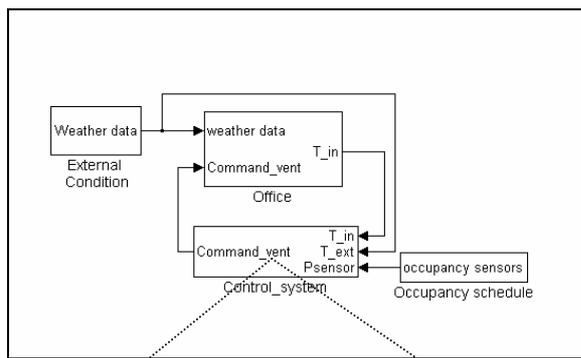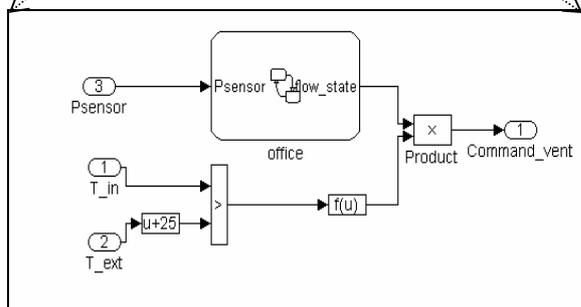
Figure 6 : whole system in SIMBAD

Figure 7 : the control strategies implemented in Stateflow

CONCLUSION

In this paper the implementation of an airflow model in SIMULINK has been described. In addition, a validation of this model has been done.

A coupling with the existing thermal model of SIMBAD has been elaborated.

This paper has showed the capabilities of SIMBAD to simulate, with short time step, a whole building in the graphical environment including airflow and thermal simulation with various utilities (Weather data, occupancy profiles…).

The developed models allow user to test control strategies and evaluate supply air components. The user could also adapt components to the industrial existing products by using parameters from manufacturer's catalogue.

The future work will be focusing on implementing new models to evaluate the impact of the ventilation on the Indoor air quality.

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NOMENCLATURE

English letter symbols

C_P	Pressure coefficient	[-]
C_d	Discharge factor	[-]
C_Q	volume flow rate coefficient	$[Pa/m^3.s^{-1}]$
q_m	Mass Flow rate	[kg/s]
q_v	Volumetric Flow rate	$[m^3/s]$
N	Number of zones	[-]
T	Temperature	[°C]
t	Time	[s]
U(z)	Wind speed at height z	[m/s]
v	Air velocity through an airflow component	[m/s]
z	Height	[m]
z_{ref}	Height for wind velocity measurements	[m]

Greek letter symbols:

ρ	Air density	$[kg/m^3]$
ξ	Head loss factor	[-]
ΔP	Pressure difference across an airflow component	[Pa]

Subscripts:

0	reference conditions
i	current zone number
inf	lower limit
j	zone adjacent to zone i
m	iteration number
sup	upper limit