AIRFLOW THROUGH LARGE VERTICAL OPENINGS IN MULTIZONE MODELLING

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ABSTRACT

In multizone models used to predict thermal comportment of buildings and inside air quality, representation of the airflow through large vertical openings is very important. Both physical representativeness and numerical stability of the large opening model are essential for a successful multizone modelling.

The widely used, Bernoulli equation based model is compared to a new proposition. In the new model the large opening space is divided into two parts, and the horizontal pressure gradient is assumed constant over each part. The resulting expression of the mass flow is numerically simpler and more stable for the practical implementation. A very good agreement is found between the physical comportment of the new model and the usual, hydrostatic pressure based model. The transient comportment of both models is validated using published experimental results of a two-cell test facility.

INTRODUCTION

Thermal comportment of buildings is a very complex problem. Different modes of heat and mass transfer appear in complex volumes and the interaction between different phenomena can be important. It is therefore impossible to represent all phenomena related to buildings at different scales. For example, the detailed analysis of the air path through the cracks is not compatible with computations of energy consumption over a heating period. To study the global comportment of buildings we need some simple but reliable models capable to predict correctly temperatures and air quality inside.

These goals can be fulfilled by multizone models, combining thermal description of building envelope with representation of interzonal airflow.

Some multizone models are more interested in the energy comportment, than in detailed computations of the airflows. The heat losses induced by the airflow can be included as parameters, *TRNSYS* software (SEL, 1994) can be named as an example. Other models are designed to allow detailed computations of the air infiltrations. *COMIS* (Feustel and al., 1990) is a well known example of the airflow model. *COMIS* uses temperature as input data, but it can also be connected to a thermal program. However, this approach, separating the airflow and the energy computations can not take into account the complete interactions between pressure and temperature.

Consequently, the comprehensive multizone models are needed to analyse the global building behaviour. As both the energy comportment and the air quality are our main interests, we use such a comprehensive model where the complete coupling between the moist air flow and the energy behaviour is implemented. Temperatures, pressures and moisture contents are unknowns of the problem and the entire system of non-linear equations is solved simultaneously. This multizone model is implemented in the building thermal simulation environment *CLIM2000* (Bonneau and al., 1993).

In the coupled energy - airflow models, the representation of the air flow through large vertical openings is very important, because of both physical and numerical reasons. In fact, the buoyancy driven heat or contaminant flow through open doors or windows accounts for an important part of global exchanges. The numerical importance of this model results from great numerical sensibility of the widely used Bernoulli equation, which can cause the divergence of the equation system. These numerical difficulties can be bypassed in some situations, when thermal and airflow systems are disconnected, that means when the complete interaction between temperature and pressure is neglected.

However, in the complete system of equations, considering interactions between temperature and pressure, the numerical difficulties exist, particularly if open doors are simulated. The mathematical confirmation of this situation was found after analysing the condition number of the jacobian matrix associated with the equation system. The condition number found was very high (10^7-10^9) for any configuration including an open door model.

For practical application of the model, its physical representativeness has to be confirmed and its numerical solution must be easily computable. Consequently, we are led to study in detail the large opening model. Indeed, the popular Bernoulli model is very difficult to solve, when used in coupled energy - airflow multizone models. In such situations the temperatures and the pressures on both sides of the large opening are unknowns, and the significant sensitivity of the airflow formula to air density variations can lead to numerical divergence. Two questions are then of main interest :

- the ability of a simple steady state, Bernoulli equation based model to represent correctly the transient state under variable boundary conditions ;
- the research of a new model for the flow through an open door, which would be physically equivalent to the usual description, and numerically more stable.

Indeed, a numerically stable model would be very advantageous for practical use in coupled energy - airflow multizone modelling. It would ease numerical computations and therefore allow to analyse more complex configurations.

The transient comportment of the airflow through the door during an opening-closing cycle, has already been studied (Wilson and Kiel, 1990, Lane-Serff and al., 1987). However, these studies concerned essentially pure cases of natural convection and only opening-closing cycles. Whereas we are interested here in the analyse of mixed convection, coupled with the variation of some boundary conditions (for example modification of temperature or ventilation rate), which represent the majority of practical cases.

In multizone modelling the global comportment of two rooms connected through an open door is much more important than a precise description of the airflow through the opening. We are more interested in the evolution of state of the air inside the rooms than in a very accurate computations of the airflow through the door. The large opening model is then just a tool to represent the physical coupling of two rooms through an open door.

The detailed comportment of two rooms coupled through an open door is then of main interest. To reach our goal we use a specific approach, combining experiments and computational fluid dynamics (CFD). In the first stage of this research, experimental results certificate the reality of our analyse. This will be presented in the following. In the next stage, a CFD model will be constructed. This model will be also validated using experimental results and then confirmed operating a parameter study. The different configurations of this validated model will be used to generalise the results from the first step. Indeed, the computational fluid dynamics is very helpful to increase the volume of information available. Valid and well understood CFD models help to understand more in detail the measured data, and allow to test easily different configurations.

MULTIZONE MODELLING

Multizone models are building simulation tools for calculating heat and mass flows between rooms. As stated in the introduction, we use a comprehensive model, where the complete coupling between moisture, airflow and temperature is implemented. Description of the airflow is based on the popular pressure network model, where one room is assumed to have uniform characteristics. Each studied physical magnitude is then described by a node : pressure, temperature, humidity and/or contaminant concentration nodes. The links between nodes represent the flows of modelled physical magnitudes.

Usual expressions for the airflow are generalised, considering the moisture content. Also both, the temperature and the moisture content influence the air density and the buoyancy driven flow. Energy calculations include both, the dry air and the water vapour contributions as well.

The equation system is constructed writing mass and energy balance equations for each room. As stated before, the whole system of equations is solved simultaneously, using *ESACAP*, the numerical solver included in *CLIM2000* software (Skelboe and Stangerup, 1983). The steady state equations are first solved using a combination of a gradient and a Newton methods. Steady state values are then used to initialise the transient state resolution. Differential equations are integrated using backward differentiation formulas of variable step and order.

The main advantage of the coupled approach is the representation of real interactions between different variables. In the reality, the gravitational airflow depends on the air density, varying with the temperature, and vice versa the air temperature depends on the airflow.

We are particularly interested here in the large openings, hence in the next section we will concentrate on the detailed description of the large vertical opening model.

AIR FLOW THROUGH LARGE OPENING

The most popular models representing mass and heat flow though an open door are based on Bernoulli equation. This approach was first proposed by Brown and Solvason (1962), and then used by many others (see for example IEA 1992, Allard and Utsumi, 1992) . The main assumptions are :

- steady state, horizontal, laminar flow ;
- non viscous fluid ;
- semi-infinite spaces on both sides of the door.

Using the Bernoulli equation we obtain the following expression for the air velocity in the aperture :

$$u(z) = \Delta P(z)\sqrt{\frac{2}{\rho\left|\Delta P(z)\right|}} \qquad (1)$$

Where $\Delta P(z)$ is the difference of total pressures on both sides of the opening, far enough from the opening to assume that the air velocity is equal to 0. ρ is the density of the transported air. Supposing that the pressure distribution is hydrostatic in both rooms we can estimate the horizontal pressure gradient :

$$\Delta P(z) = P_{1B} - \rho_1(z)gz - P_{2B} + \rho_2(z)gz \qquad (2)$$

The mass flow is then easy to obtain using the following integration :

$$\dot{m}_{12} = C_d L\int_a^b u(z)\rho(z)dz \qquad (3)$$

The integration bounds a and b correspond to the physical limits of the airflow and are either 0, H (total height of the opening) or z_n (position of the neutral axis). This last value is the solution of the following equation :

$$\Delta P(z_n) = 0 \qquad (4)$$

The effects of viscosity and flow contraction are taken into account in equation (3) using experimentally found discharge coefficient C_d.

In multizone modelling we always deal with mixed natural-forced convection and with varying pressures. Therefore, the position of the neutral axis is unknown and have to be computed using :

$$z_n = \frac{P_{1B} - P_{2B}}{g(\rho_1 - \rho_2)} \qquad (5)$$

Air velocity is given by the equation (1) but we need one more information about the air density in each zone. Some codes use a vertical profile of the temperature as an input (*COMIS*, Feustel and al. 1990). This last assumption can give a better estimation of the energy flow but requires some additional knowledge. The temperature profile can not be obtained running the usual multizone model : it can be only introduced as a part of boundary conditions. We assume therefore that the air temperature and thus the air density are uniform.

In this case an analytical integration is possible, but several configurations have to be treated. Some of the 8 different configurations induced by the airflow direction and pressure horizontal gradient are presented in figure 1.

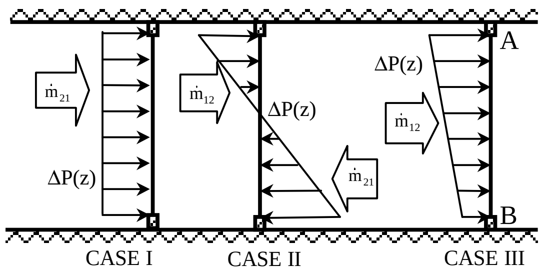

Figure 1. Different configurations of the airflow through large opening

The following equations represent the air mass flow through the large opening in case II.

$$\dot{m}_{12} = \frac{2\sqrt{2}}{3}C_d L\frac{\sqrt{\rho_1}}{g\left|\rho_1 - \rho_2\right|}\left(P_{1A} - P_{2A}\right)^{3/2} \quad (6)$$

$$\dot{m}_{21} = \frac{2\sqrt{2}}{3}C_d L\frac{\sqrt{\rho_2}}{g\left|\rho_1 - \rho_2\right|}\left(P_{2B} - P_{1B}\right)^{3/2} \quad (7)$$

However, the practical implementation of the presented large opening model in a simulation code is not straightforward. The neutral axis calculation requires the division by $\Delta\rho$ (see equations (6) and (7)), which can reach very small numerical values. Also the computation of the $(\Delta P)^{3/2}$ is delicate, because this power function has no derivatives in 0.

Two different linearisations have the to be performed for a practical implementation of the above model :

- when $\Delta\rho\rightarrow 0$, we switch the flow configuration, for example from case III to case I in figure 1. This induces the discontinuity of both the mass flow value and all its derivatives.
- when $\Delta P\rightarrow 0$, power function has to be linearised, this leads to the discontinuity of derivatives with respect to pressure.

Combining the effects of different flow configurations with the numerical switches introduced by linearisations leads to as much as 28 different expressions to describe the airflow through a large opening. This situation presents an important numerical inconvenience because of the discontinuities introduced not only in the derivatives but also in the airflow values. During the numerical resolution at each iteration a different expression can be used and the resolution of the non-linear problem can fail.

The model based on the Bernoulli equation and on hydrostatic pressure assumption presented above will be referred to as "usual model" in the following.

To simplify the numerical computations, we propose a new model to estimate the flow through a large opening. The main idea is to divide the large opening into two equal parts. The horizontal pressure gradient over each part is assumed uniform and equal to the pressure difference in the middle of each part (at 1/4 and 3/4 of the aperture height), as represented in figure 2. Corresponding pressure differences can be then expressed as follows :

$$\Delta P_{bottom} = P_{2B} - 0.25\rho_2 gH - P_{1B} + 0.25\rho_1 gH \quad (8)$$

$$\Delta P_{top} = P_{1B} - 0.75\rho_1 gH - P_{2B} + 0.75\rho_2 gH \quad (9)$$

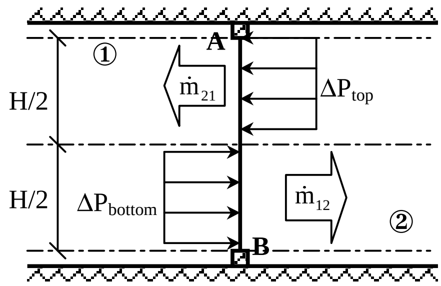

Figure 2. New model of pressure horizontal gradient in large opening

We can still use equations (1) and (3) to compute the mass flow through the opening. For the situation represented in figure 2 we get :

$$\dot{m}_{21} = 0.5 C_d LH \sqrt{2\rho_2}\sqrt{\Delta P_{top}} \quad (10)$$

$$\dot{m}_{12} = 0.5 C_d LH \sqrt{2\rho_1}\sqrt{\Delta P_{bottom}} \quad (11)$$

We can easily notice that the proposed model is numerically much simpler than the usual one presented before. Naturally, the direction of the flow in both parts of the opening depends on the sign of pressure horizontal gradient. Only four different cases can then be distinguished according to flow directions in top and bottom parts of the opening (bottom 1→2 - top 2→1 ; bottom 2→1 - top 1→2 ; both 1→2 ; both 2→1). We also avoid the division by $\Delta\rho$ and the only linearisation needed will be for $\sqrt{\Delta P}$ in the neighbourhood of 0 (no derivation possible). This leads to 16 different expressions to describe the air flow, and the discontinuity in the flow values is removed. The derivatives with respect to pressure are still discontinue, however in the practical applications the discontinuity induced by linearisation for $\Delta\rho$ was found more harmful.

From the physical point of view, this model is able to represent either one-way flow or the two-way flow in the opening. As in a complete multizone model both temperatures and pressures are unknowns, the balance equations are solved to find temperatures and pressures on both sides of the opening. The mass flows depends on the air density on both sides of the opening and the net flow verifies the mass balance of the rooms.

The values of the discharge coefficient C_d have to be corrected, because the ideal, non-viscous flow (C_d=1) computed using equations (10) and (11) will be different from the flow computed using equations (6) and (7). However, this correction term is not very important, considering the global multizone model. We should remind, that pressures and air densities on both sides of the opening are the unknowns of the problem, and will be computed simultaneously with the flow values. In addition, the large opening model is only a tool to predict the coupling between two rooms connected by an open door, and not to analyse the detailed airflow.

The new model is also different from the method introduced by Walton (1984), where the large opening was divided into a number of small openings where the pressure gradient was assumed constant. Unlike Walton approach, the new model does not require the neutral axis computations, and is therefore much easier for the practical use.

The last observation concerns the validity of main hypothesis of the Bernoulli equation. In the real cases, such situations as fully developed, horizontal laminar flow are seldom met. However, this model shows a good agreement with measurements in estimating the mass flow, as well as the heat flow, when the thermal stratification of rooms is not very important (IAE, 1992). The additional assumption on pressure distribution introduced by the new model do not alter this observation. Therefore we can expect that despite the additional simplification the new model will still reproduce the real comportment of the flow.

EXPERIMENTAL VALIDATION

In this section, we want to verify, if the simple, steady-state models are able to predict transient comportment of a space consisting of two rooms connected through an open door. We will then compare the multizone model predictions with the experimental results from Burchiu (1998). His work was performed on the *MINIBAT* experimental facility situated at Cethil Laboratory in Lyon.

The *MINIBAT* facility has two single volumes (3.1m x 3.1m x 2.5m each) connected by a doorway. One face is a thick single glazing which can be exposed to various climatic conditions simulated by the climatic housing. Other walls are bounded by air volumes regulated at constant temperature. The longitudinal section of *MINIBAT* test cell is presented in figure 3.

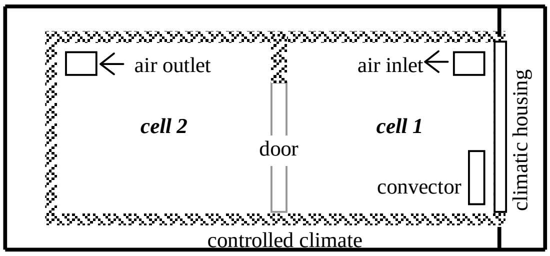

Figure 3. MINIBAT test cell (Burchiu 1998)

During the experiment, external space temperature was kept at about 20°C, the climatic housing temperature at 0°C and the inlet air temperature at 10°C. The initial ventilation rate was 48 m^3/h and no heating power was injected. The variable conditions in the experiment are the following (see figure 4) :

- starting an electric convector (hour 2:50) ;
- stopping the mechanical ventilation (hour 30:00).

The boundary conditions : outside temperatures and mass flow were measured, as well as the temperature profiles in the door and on the median axes of both cells. Moreover, during the permanent states, air velocities were measured in the opening.

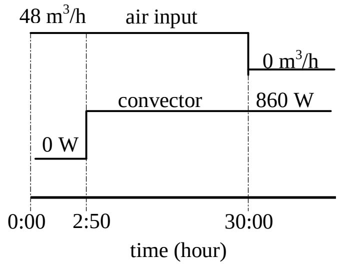

Figure 4. Experimental conditions

The experimental results are compared with the predictions of two versions of the multizone model :

- case 1 : using the original one-neutral axis model ;
- case 2 : using the proposed two-parts-uniform-pressure-difference model.

The discharge coefficients are identical for both multizone models, no correction term was taken into account.

The temperature evolution is then presented in figure 5. The experimental results represent the mean temperature over the height in cells 1 and 2.

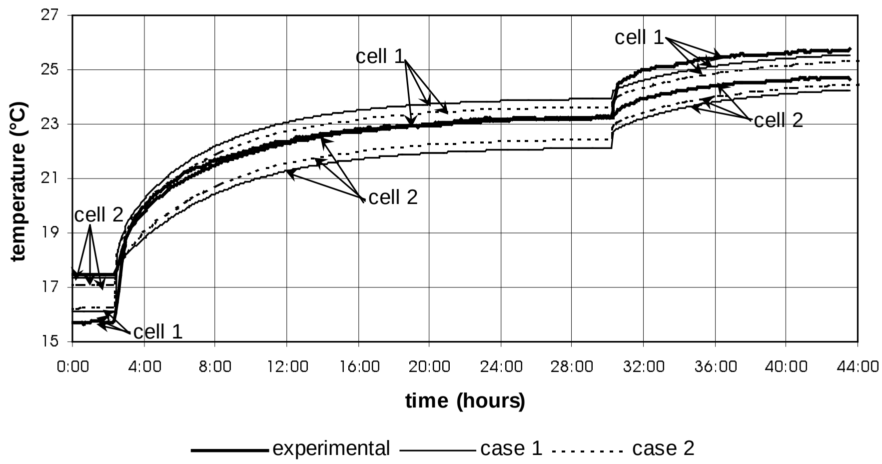

Figure 5. Evolution of the temperature in MINIBAT test cell

From figure 5 an overall good agreement can be seen between both models and the experimental data. Both multizone models represent correctly the time constants of the cell. For both changes in boundary condition the response of the model is very similar to the response of the cell. It is a very important observation. This means that the steady state flow model combined with the transient state thermal model can correctly represent the coupled thermo-aeraulic comportment of a multi-room space.

Second very important comment concerns the similarity of the results obtained using the two multizone models. The maximum disparity in temperature predictions for both models is less than 0.3°C. Taking into account the level of precision in multizone modelling this disparity is negligible. This confirms our predictions that the simplification of the pressure gradient distribution in the opening should barely affect the flow computations in multizone modelling.

However the steady state results are not entirely satisfactory. In the first and last parts of the experiment the predicted results are very close to the reality (error less than 0.7°C, this value is correct taking into account the precision of measurements : about 1°C). But in the medium part of the experiment the models are not very efficient in predicating the experimental data. The experimental mean temperatures are almost identical for both cells, whereas the simulated values differ for about 2°C.

This is mainly due to the strong thermal stratification induced by the electric convector. In neither of multizone models the thermal stratification is represented, hence the heat flow through the opening is not estimated correctly.

DISCUSSION AND PERSPECTIVES

From the experimental results we can confirm a very good agreement of the new model with the usual one. The predicted temperatures are very close, even if no correction term was introduced to adapt the discharge coefficient to the new model.

Some other calculations were performed to compare the proposed large opening model with the usual Bernoulli equation based model. For a larger number of rooms and open doors both models still show a very good agreement.

Also the numerical resolution was found easier. Using the new model in a few multi-room configurations the non-linear system of equations was easily solved by *ESACAP*. Whereas, in identical configurations the same numerical solver failed to converge when the usual model was implemented.

Using the results from the previous section we can comment on the limits of both models. In fact they are very similar. As both models are based on the isothermal room assumption, they can not predict correctly the heat flow when rooms are strongly thermally stratified.

In addition, simulated configuration is very specific. The geometry is symmetrical in relation to longitudinal axis, and cell dimensions are not very important. The cold air inlet is situated in front of the door, with the electric convector right beneath (see figure 3). The hot plume from the electric convector go up the facade, and then mix with the cold air inlet and do not decay before reaching the opposite wall. This means that part of the heated air goes directly to the second volume, before a real mixing is performed in the first cell. In this particular case the typical multizone model can not represent correctly the reality.

Probably for some different geometrical configurations (e.g. the electric convector on the lateral side) the airflow through the door will be different and the multizone models would provide a better representation.

To verify this assumption and to enlarge test possibilities, a CFD model of the *MINIBAT* test cell will be constructed and validated in the next stage of this research. Using CFD model, we will continue the validation of the new multizone model in different configurations. We plan to test different variations in boundary conditions (such as inlet temperature variations, ventilation flow variation, …) and several geometrical configurations (convector and the air inlet on lateral sides of the cell, …).

We will also perform a new numerical study on the non-linear system of balance equations when the new model is implemented, to quantify the numerical gain due to more stable expression of the new model.

CONCLUSIONS

Steady state models are found efficient in representing dynamic airflow in a multizone space. Steady state models assume that the flow is balanced in each zone at any moment. This implies that the airflow between two rooms reaches the destination room immediately, which is obviously not true in the reality. However, as in physical situations thermal building behaviour is more smooth than the airflow modifications, the assumption of immediate balance for the airflow fits well the real data.

It was also found possible to describe the coupling of two rooms through an open door using a simple expression. The mathematical formula used in the new model is simpler that the usual Bernoulli model and is better adapted to the coupled energy - airflow calculations. Indeed the new expression is far less sensitive to temperature variations during non-linear iterations. This is a great advantage over the Bernoulli model, where the numerical resolution in the case of coupled energy - airflow simulations was found extremely complex.

The new model is able to predict correctly the physical coupling of two rooms connected through an open door, and is reliable for numerical resolution. We recommend therefore the proposed model to replace the usual, hydrostatic pressure based expression in multizone models.

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NOMENCLATURE

ρ : density of the moist air [kg/m^3]
C_d : discharge coefficient [-]
g : gravitational acceleration [m/s]
H : large opening height [m]
L : large opening width [m]
$\dot{m}$: mass flow of the moist air [kg/s]
P : absolute total pressure [Pa]
T : temperature [°C]
u : air velocity [m/s]
z : vertical abscissa in the large opening [m]

subscripts

1 : room 1
2 : room 2
12 : from room 1 into room 2
A : top of the large opening
B : bottom of the large opening
bottom: bottom half of the large opening
top : top half of the large opening