MODELLING SUPPLY-AIR WINDOW IN A BUILDING SIMULATION CODE

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ABSTRACT

The concept of a supply-air window is to allow air renewal circulating between glasses before entering inwards. Based on this principle, a part of heat transfer through the glasses is recovered by air renewal. Actually, the way to consider it in a building simulation code is not satisfactory. This article proposes a model that can be implemented easily in many building simulation codes.

This model is based on the analytical solution of the problem of air circulating between isotherm panes differentially heated. It has been implemented in Buildings library of Modelica. Short wave radiation is considered by using the equation of Window software. Long wave radiation is considered using radiosity model. A special attention is taken to consider convective heat transfer coefficient between air space and glasses. The results obtained are compared to those of a commercial computational fluid dynamics (CFD) code (Fluent).

INTRODUCTION

The work presented here is on the same base than the one presented in (Gloriant et al., 2013). The introduction, the problem formulation and the indicator definition are quite similar but the rest of the article presents the improvement of the model. The problem raised in (Gloriant et al., 2013) was that the model adapted to building performance simulation was not usable without a CFD calculation. A solution is proposed in this paper.

The main difference between a standard window and a supply air window consists in the presence of natural or forced convection generated within the gaps between the panes of glass. Airflow inside the window caused by a depressurization in the room is performed with an extraction system. Thus, the heat loss by the window is recovered providing the preheating of the incoming air.

The method developed in this article can be used for every kind of supply-air window. It could also be used for exhaust-air window. Window's frame is not considered. For more clarity, a precise example is studied in this article. It is the case of a Paziaud[®] window that is a triple glazed-window with a Ushaped air channel (see Fig 1). This window was designed at the beginning of the eighties by Jacques Paziaud and was used in many buildings in the north of France. More than 1.500 dwellings and a few tertiary buildings were equipped in the past 30 years.

Few institutional studies have been achieved on triple-glazed windows. Kim and Yang (Kim and Yang, 2002; Kim et al., 2006), investigated flow and heat transfer characteristics of a Paziaud window but only for the exhaust mode during the cooling season.

The main constraint for modeling an airflow window in a building simulation tools is the computing time. Indeed, most of the building thermal performance tools (EnergyPlus, TRNSYS, Esp-r, Pléiades Comfie, Buildings etc.) use a multizone approach that considers one calculation node per zone for air temperature determination. Consequently, a building is represented by a few calculation nodes (most of the time, less than 20). Heat transfer in walls is often implemented with a finite difference method also with a limited number of nodes (less than 10 usually) or a method using a model reduction (z-transform for example) that is more efficient in terms of computing time. For long-wave radiative heat transfers, simplifications are often done on view factor calculation and on linearization of heat transfer equations in order to reduce the number of equations. All these efforts allow to make building simulation with a standard office computer in a reasonable CPU time.

Moreover, it would be nonsense to implement a detailed Computational Fluid Dynamic (CFD) model for the airflow window description. That is the reason why it is interesting to develop simpler models, based on a physical approach, that are less time consuming. The problem is that these models often need parameters or correlations that can only be obtained by experimentation or by CFD simulations. In this work, CFD steady-state simulations are achieved providing pre-calculation windows parameters which are used subsequently in simpler models of building dynamic simulations.

In order to take into account a ventilated window in building dynamic simulation, several phenomena must be modeled:

- Conductive heat transfer in the panes of glass.
- Convection and long wave radiation between the inner glass and inside environment, the outer glass and outside environment and between the panes of glass.
- Convective heat transfer between the panes of glass and airflow. This point is the most difficult to model because the convective coefficients in air space are not known a priori.
- Solar radiation absorbed by the panes of glass.

The existing models for ventilated windows simulate the system performance by considering an energy balance in the window. They differ in the determination of zones in which an energy balance is realized, in the method to obtain the exchange rate in the air space and in the initial choice of convection characteristics (natural or forced, laminar, mixed or turbulent, steady or unsteady). Let's note that the convection nature depends on the environment and window's configuration but the laminar condition is proved optimal to obtain the best performance (Tjelflaat and Bergensen, 1985).

The first one who developed a computer program is Wright (Ferguson and Wright, 1984; Wright, 1986) considering a laminar, steady and fully developed airflow in forced convection conditions. Glass panes temperature is assumed isothermal. Thus, a ventilated window with 2 panes of glasses is composed of 5 nodes; where 2 of them represent the indoor and outdoor temperatures, 2 others are the panes of glass temperatures and the last one is the airflow cavity. In a similar manner, Ismail et al (Ismail and Henríquez, 2006) proposed in their study to divide the window in the flow direction into n layers of 5cm thickness. Consequently, he obtained n times more nodes than Wright's system. McEvoy et al (McEvoy et al., 2003) assumed isothermal the glazing temperature but treated the air cavity with 2x4 zones.

In the Wright's study, the heat transfer between air and glass is obtained by expressing the two dimensional temperature solution in terms of Stieljes integrals (Cess and Shaffer, 1959). His approach consisted in defining the performance's system

beforehand. Then the window can be taken into account in a building simulation for a limited number of performance criteria. Consequently, the resolution problem in the building and in the window is not simultaneous and the Wright's model would be adapted to building simulation only if the defined performance criteria are constant that is not the case for a ventilated window. A non-sequential method seems necessary but supposes to treat the heat transfer between airflow and panes of glass with a different approach. That's the choice of Carlos et al (Carlos et al., 2011) who uses correlations defined in ISO standard (ISO-15099, 2003) and based on a Wright's study (Wright, 1996). This model assumed that the heat received by the airflow from the "warm" pane of glass and the heat received by the "cool" pane of glass from the airflow are expressed with an identical heat transfer coefficient. This coefficient is calculated from air velocity and another convective coefficient obtained by correlations. This hypothesis is absolutely not justified in the case of unsymmetrical heating in a rectangular duct. An interesting study on the modification of this model is proposed by Raffnsøe (Raffnsøe, 2007).

PROBLEM FORMULATION

A laminar forced convection airflow is considered. Air enters within the window at the external temperature of 0 °C, circulates inside the U-shaped conduct heating up by means of the heat flux coming from the internal environment, and enters the room at an unknown temperature. The heat flux passing through the glass "i" is called Φ_i (in W/m²). Horizontal surfaces are considered adiabatic.

The temperature difference between both environments is 20 °C. Concerning the boundary conditions of the external glazed surfaces, two heat transfer coefficients are defined, h_{int} and h_{ext} corresponding to the internal and external environments. Two mean radiant temperatures $T_{r int}$ and $T_{r ext}$ are also defined at these side walls. The horizontal surfaces of the window are modeled as insulated surfaces. An incident solar radiation I_s is also considered.

The values of these parameters are defined in accordance with the ISO standard (ISO-15099, 2003) and are presented in figure 1.



Fig 1. Schematic diagram and boundary conditions

In this study, the influence of pressure difference and solar radiation on heat fluxes crossing the different panes as well as the air temperature entering the room, are investigated:

- The pressure difference is varied between 1 Pa and 8 Pa corresponding to an average velocity in the cavities between 0.25 m/s and 1.1m/s. The range is chosen so that the convection is forced (Gr/Re²< 1) and the airflow laminar (Re < 2300). Let's notice that the Reynolds and Grashof numbers are based on the hydraulic diameter (Shah and London, 1978).
- The thermal behavior of the airflow window changes with the external environment. This paper focuses on winter conditions at low outside temperature. The presence or not of solar radiation corresponding respectively to daytime and nighttime (or daytime with overcast skies) is investigated.

Let's note that solar radiation is not directly simulated but treated from terms sources injected in each pane of glass. The absorption and transmission parameters of global window are calculated from Window-software and manufacturer's parameters (see table 1).

Table 1. Radiation parameters of glasses us	sed in the
ventilated window	

	GLASS 1	GLASS 2	GLASS 3
manufacturer's	4mm	6mm	4mm
reference	Planibel	Planibel G	Planibel G
	Clearvision	pos.2	pos.2
emissivity(int/ext)	0.84/0.84	0.84/0.17	0.84/0.17
solar absorption	1.7%	20.8%	9.5%
solar transmission		45.75%	

GLOBAL PERFORMANCE INDICATORS

In building simulations, two main indicators are used to characterize a window. Their definitions are given in an international standard (ISO-15099, 2003) specifying the experimental conditions to obtain them. The first one, U-value, is the heat loss factor providing heat transfer through the window per square meter for a temperature difference of one degree between inside and outside temperatures. The second one, (τ_s) (also called g according to EN 410), is the solar heat gain coefficient which indicates the rate of solar radiation impacting the heat balance indoor. It includes the direct transmission ($\tau.I_s$) and the part of solar radiation absorbed by the window and afterwards released inward (α_{int} .I_s). Solar heat gain factor (τ_s) is often replaced by the shading coefficient (SC) which is the ratio of (τ_s) and a reference corresponding to the solar heat gain factor of a simple clear 3 mm thick glass.

These coefficients can be adapted to the case of supply air windows. The heat fluxes across the panes are not constant in a ventilated window and it must be determined which heat flow rate must be considered. Wright (1986) defined an effective Uvalue called " U_e " that can be evaluated in the same test conditions than those of the standard considering the heat flux on the exterior pane of the window Φ_1 . Another U-value can be defined (called here U_{dvn}) considering the heat flux on the exterior pane of the window Φ_3 . In this case, it should be associated with a performance indicator linked to the supplied air (called R_{dvn}). These indicators can be considered as the characteristics of a classical system equivalent to a window with a U-value U_{dyn} based on real surface heat loss and a heat recovery system on extracted air with a performance value R_{dyn} (Gloriant et al., 2012).

Wright (1986) also defined an effective shading coefficient SC_e . Indeed the airflow in the window increases the part of solar radiation absorbed by the window and released inward.

To calculate (τ_s) in the case of the supply-air window, three contributions must be considered: the direct transmission $(\tau.I_s)$, the part of solar radiation absorbed by the internal pane of glass and afterwards released inward by convection and long-wave radiation $(\alpha_{int}.I_s)$ and the part of solar radiation recovered by air $(\alpha_{air}.I_s)$.

MODELING APPROACH

The window presented here was first modeled using Computational Fluid Dynamics (CFD). This model uses the commercial software Fluent. It allows to better understand window functioning, and to know precisely air temperature and velocity evolution everywhere in the window. The problem of this kind of model is that it cannot be used for global building annual simulation. That is why a second model Adapted to Building Simulation (called here ABS) was developed.

CFD Model

Steady state numerical simulations of 2D laminar forced convection airflow in a Paziaud[®] window are performed with Fluent[®].

Thermophysical properties of the fluid are supposed depending on the temperature and are in accordance with the ISO standard (ISO-15099, 2003). Fluid properties are taken as polynomial functions and the incompressible ideal-gas law is applied to account for density variation.

A non uniform structured mesh composed of 79 216 nodes refined close to the glasses and close to the inlet and outlet is employed. A grid dependence

study has been undertaken to ensure the adequacy of this mesh density.

Spatial discretization of the governing equations is achieved by means of the finite volume method using the pressure-based solver. The equations discretization was carried out using second order schemes for pressure and momentum (upwind scheme) and first order upwind schemes for energy and radiation. Momentum and pressure-based continuity equations are solved simultaneously with the coupled algorithm. The radiation model used to solve the longwave radiative transfer is the Discrete Ordinates radiation model (DO) (Fiveland, 1984). Short wave radiation were pre-calculated using Window software and considered as an heat source spread throughout the thickness of the glass.

Convergence criteria were set at 10^{-6} for continuity, 10^{-7} for energy and 10^{-8} velocity and radiation.

As it is shown in the next paragraph, this model is used to calculate convective heat transfer coefficients h_c inside both air gaps. It is done considering the mean air temperature weighted by air velocity T_m , mean surface temperature T_s and mean convective heat flux on the surface considered Φ . Then h_c is calculated using:

$$h_c = \Phi/(T_s - T_m) \tag{1}$$

ABS model

The main difficulty of this problem is the consideration of vented air space. The modelling proposed in ISO standard considers a monodimensional heat transfer in the glasses whose temperatures are taken uniform. Temperature evolution in the vented air gap is analytically calculated considering a fixed and uniform convective heat transfer coefficient at the interface glass / air. The air temperature evolution obtained is a decreasing exponential as a function of the height in the air gap. One of the hypothesis used here was questioned by Raffnsøe (2007). It concerns these convective heat transfert coefficients. In the standard, the same value (h_{cv}) is taken on the both side of the air gap using the formula :

$$h_{cv} = 2 h_{cdv} + 4 V_i \tag{2}$$

Where V_i is the mean air velocity and h_{csv} is the convective heat transfer coefficient in the case of non vented air space. Raffnsøe showed that taking the same coefficients on the both side of the air space leads to wrong results. This has been confirmed by our CFD simulations. The first way to solve this problem is to use coefficients pre-calculated by Fluent as a function of air flow rate (throughout the rest of the document, this way to do will be called ABS1). The problem is that it requires to use a CFD calculation for each geometrical configuration. Another way is to use a correlation. Despite an indepth investigation in the literature, no correlation

was found that leads to different coefficients in both sides. The only way found to reveal this difference is to use an analytical result presented in (Shah and London, 1978). In this book, a relation is given between local Nusselt number and the ratio of convective heat flux on each surface (Φ_1 and Φ_2) that are considered fixed and uniform:

$$Nu_{1} = \frac{140}{26 - 9 \cdot \frac{\phi_{2}}{\phi_{1}}} \text{ and } Nu_{2} = \frac{140}{26 - 9 \cdot \frac{\phi_{1}}{\phi_{2}}} \quad (3)$$

The use of this equation makes the resolution independent to CFD calculation. Throughout the rest of the document, this way to do will be called ABS2.

Both models were implemented in Modelica language using Buildings library (Wetter et al., 2011). Radiation model is directly managed by this library. Long wave radiation is considered using radiosity model with surface factors equals to 1 in the air gaps. Short wave radiation model uses Tarcog (Tarcog, 2006) algorithm that is the same than the one used in Window 7 software.

Modelica is an object oriented language based on equations. The model is then divided in sub-models containing equation systems that can be connected to existing models (see Fig 2). In the case presented, for example, the model of glass layer comes from buildings library and the model of vented air space was developed for this particular case.



Fig 2. View of Modelica model for triple glazed supply-air window: CenterOfGlassPaziaud

We can see here that Modelica allows making easily other models with only one vented air space just using graphical environment (see Fig 3).



Fig 3. View of Modelica model for double glazed supply-air window

RESULTS

Some results concerning the comparison of CFD model and ABS1 model were presented in (Gloriant et al., 2013). The main conclusion was that using convective heat transfer coefficient pre-calculated via Fluent in ABS model gives quite accurate results in terms of outlet air temperature and global indicators $(U_e \text{ and } \tau_S)$.

Convective heat transfer coefficients

Firstly, it is interesting to look at the results of convective heat transfer coefficients obtained by CFD (see Fig 4).



Fig 4. Evolution of convective heat transfer coefficients with airflow rate

The equation (1) used to calculate h_c leads to negative values for high airflow rate. Even if it has no physical sense to define a negative h_c , it can be explained by the fact that convective heat transfer on the internal surface of medium glass reaches negative value due to radiative exchanges. This phenomenon does not occur when radiative exchanges are not considered.



Fig 5. Evolution of the temperature in a horizontal section

Fig 5 presents the evolution of temperature in a horizontal section of the window. We can see that the profile of temperature in the second air gap decreases close to the medium glass before increasing. The decreasing shows that the medium glass loses energy by convection in the second air gap even if mean air temperature in this air gap can be higher than the surface temperature.

Fig 4 also shows the evolution of h_c calculated by model ABS2 using equation (3). One can see that for each air gap, one convective heat transfer coefficient increases and the other decreases and that h_c can reach negative values, as it was noticed in CFD calculation. However, the values of calculated coefficients are quite far from CFD values. Moreover, the evolution is not continued certainly due to the non-linearity of the problem introduced by equation (3). Consequently, this relation is not very satisfying to calculate correctly h_c . We will see in the rest of the paper the effect on global results on the window.

Outlet air temperature evaluation

Fig 6 presents the outlet air temperature.



Fig 6. Outlet air temperature of the window

The difference between ABS1 and ABS2 is quite important for high airflow rate. The difference of temperature at $32 \text{ m}^3/\text{h}$ is about 0.7°C .

Global indicators

Fig 7 shows global indicators of the window defined previously.



Fig 7. Global indicators of the window

The most important of them is the effective U-value U_{eff} . For low airflow rate, the difference between ABS2 value and CFD value is higher than for high airflow rate. It seems that considering that h_c reach a value close to zero on the more external surface of the air gap is a quite good approximation. That is to say that for high airflow rate, most of the heat losses of the window is due to long wave radiation.

CONCLUSION AND PERSPECTIVES

In this paper, it was shown that it is possible to model thermal behaviour of a supply air window by a quite simple model based on analytical results. This model includes calculation of convective heat transfer coefficients in air gaps. These coefficients are quite different to the values that can be obtained by CFD calculation and the results on global evaluation on the window are note completely satisfactory. An improvement of the relation used to find convective heat transfer coefficients is in progress.

After improving these results, the next step will be to take into account the effect of the frame that can bring heat to glasses as boundary effect and to compare numerical values to experimental values that are in progress in our laboratory.

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