Zonal Modeling of Double-Skin Facades

T.E. Jiru[1], F. Haghighat[1], M. Perino[2] and F. Zhanghirella[2]

[1] *Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada H3G 2W1*
[2] *Dipartimento di Energetica, Politecnico di Torino, Corso Duca degli Abruzzi 24,Torino, Italy*

ABSTRACT

This article presents the application of the zonal approach for modeling airflow and temperature distribution in Doube-Skin Facades (DSF). The airflow rate was calculated by using the power-law model (PLM) and integral form of the energy equation was used to evaluate the temperature distribution. The predicted temperature distribution was compared/ verified using measured values and parametic studies were conducted to identify the influence of height, flowrate and pesence of shading device on the temperature gradient in the cavity. The results indicate that the zonal appraoch can provide information on the performance of DSF faster and can be applied easily at very low computational resource.

KEYWORDS

Zonal approach, Power law model, Double-Skin Facades, Verification, parametric study.

INTRODUCTION

Zonal models are intermediate between CFD and single-zone models. They can generate results faster than CFD and more accurately than single-zone models. They provide global information on the distribution of airflow and temperature in a room and they have also been used to predict moisture distribution, thermal comfort, contaminant distribution and personal exposure in rooms (Haghighat et al. 2001; Ren and Stewart, 2003). Nevertheless, the zonal approach has not been applied to predict the performance of Double-Dkin Façades (DSF).

DSF are building envelopes, which are composed of two glasses, a ventilated air cavity in between and solar control devices placed within the cavity. The ventilated cavity functions as a thermal buffer by reducing problems such as undesired heat gain during the cooling season, heat loss during the heating season and thermal discomfort due to asymmetric thermal radiation.

Numerical models have been used for studying the performance and optimization of DSF. Models that have been used for the prediction and analysis of the performance of DSF include CFD (Manz 2004), lumped models (Park et al. 2004) network models (Tanimoto and Kimura, 1997) and control-volume models (Saelens, 2002). Control-volume models have similarity with zonal models but in the application of the control-

volume models the airflow has to be known a priori and it is not part of the numerical solution. Moreover, the extension of the control-volume models to other shading devices such as venetian blinds is not straight forward, as it requires pressure distribution in the cavity. Therefore, in order to enhance the prediction capability of simpler model such as the control-volume model for the DSF with venetian blinds, the PLM model was applied in this study.

CASE DISCRIPTION

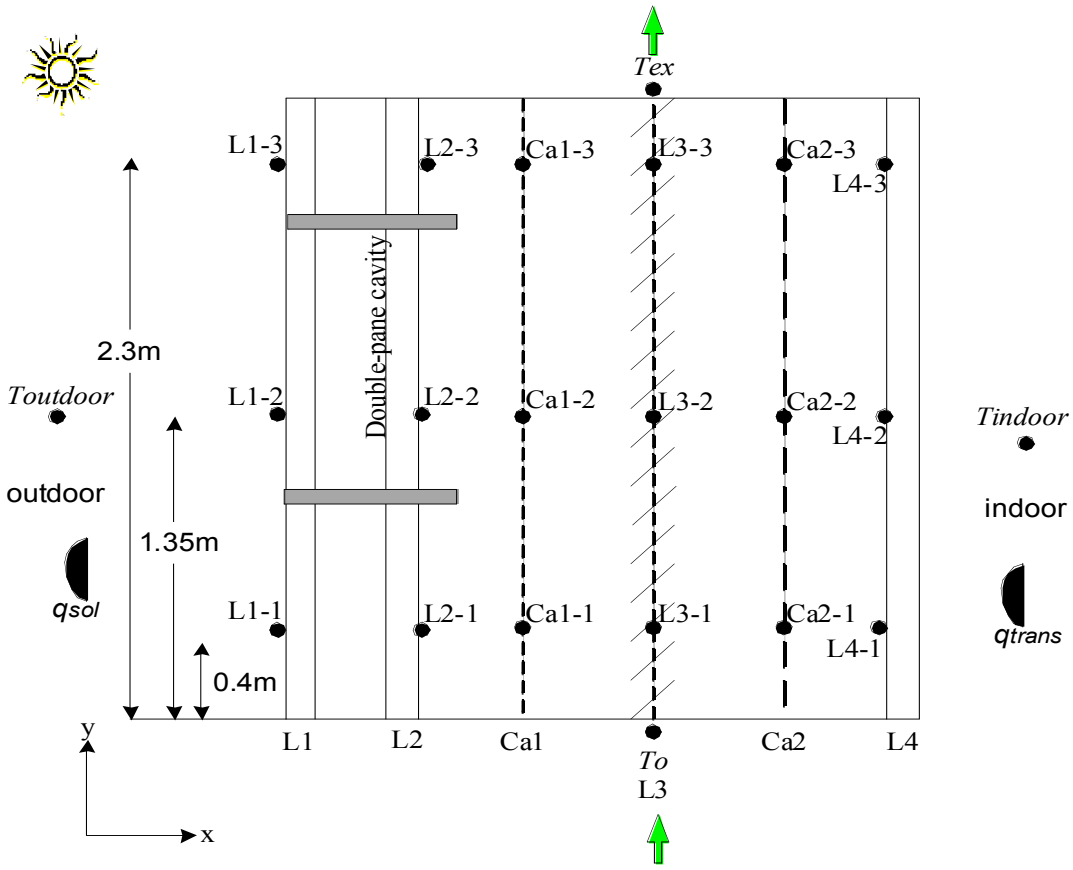

Figure 1 Schematic of mechanically ventilated double-skin façade. T_o is the air temperature at the inlet, T_{ex} is the air temperature at the exit, T_{indoor} is the room air temperature, $T_{outdoor}$ the outside air temperature, q_{sol} is the total solar radiation, q_{trans} is the transmitted solar radiation.

The case used for the development and verification of the DSF models is an experimental test cell at the Department of Energy Studies, Politicnico di Torino, Italty. The test cell was 2.5m high, 1.6m wide and, 3.6m long. The south facing side of the cell, which was 1.6m wide and 2.5m high, has a DSF with an outer double-pane façade, and an inner façade as shown in Figure 1. The outer double-pane façade, L1 and L2, was divided into three parts: upper, middle and lower. L1 and L2 were 8mm and 6mm thick clear glasses. The air cavity between L1 and L2 was 15mm wide. The internal pane, L4, was 6mm thick clear glass, which could be opened in order to make the gap accessible. The air cavity between L2 and L4 is

14.8cm wide and can be enlarged up to 30cm. A venetian blind, L3, was installed in the air cavity between L2 and L4. The slats have small pores and were inclined at 45° from the horizontal. The air from the test cells enters into the DSF cavities through an opening located at the bottom of the DSF, which is then extracted at the top of the DSF by a fan.

The test cell was equipped with a continuous monitoring system to measure energy consumption, indoor air temperatures, heat fluxes through the façade, temperature distributions in the air gap and on the façade surfaces, and airflow rate. The sensors in the DSF system were positioned at 0.4cm, 1.35m, and 2.3m from the floor as (see Figure1). The average volumetric flow rate at inlet was 54.2 m^3/h. The measured outdoor and indoor boundary conditions (on April 23, 2005) are shown in Figure 2.

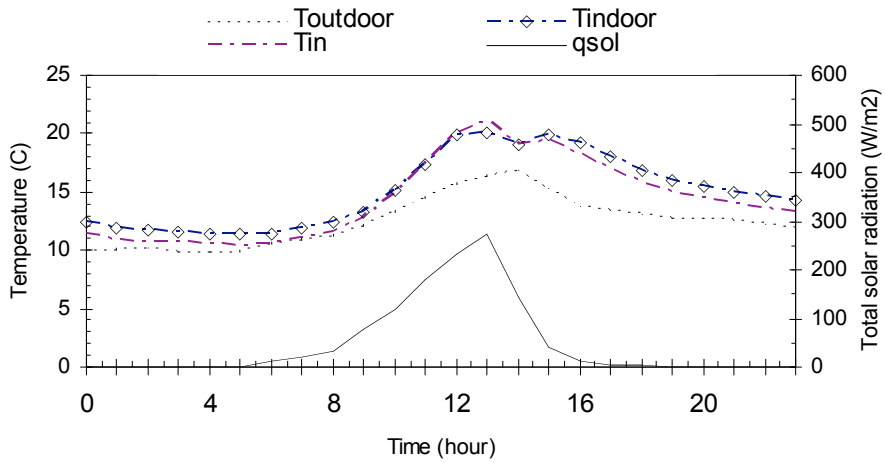

Figure 2 Measured inlet and boundary conditions.

MODEL DEVELOPMENT

Safer et al. (2004) in their CFD model for a DSF used a simple homogeneous porous media model similar to the Quadratic equation, used for infiltration, to calculate the airflow rate through the venetian blinds. Moreover, Tanimoto and Kimura (1997) have used power-law relation for calculating the airflow through the blinds using the network approach. The main difference between the present zonal approach and Tanimoto and Kimura (1997) approach is that in the latter the total airflow in the outer and inner cavity is calculated using the power-law equation but the airflow through each blind is approximated as a fraction of the total airflow rate, which is proportional to the distance of the blind from the bottom of the DSF. However, in this study, the airflow rate through the blinds is directly calculated using the PLM, which is similar to the Safer et al. (2004) approach except that the latter used the quadratic model. Moreover, the pressure drop for banks of tubes in cross and parallel flow is commonly calculated using an equation similar to the PLM. Therefore, the application of the PLM assumes each slat of the venetian blind as long horizontal cylinder in the ambient fluid except when the venetian blinds are completely closed. The PLM can be given as:

$$m_{i,j} = KA\rho\left(\frac{2\Delta P_{i,j}}{\rho}\right)^{1/2} \qquad (1)$$

Where $m_{i,j}$ is the mass flow rate, kg/s; A is the area of a cell, m^2; ρ is the density of air, kg/m^3; $\Delta P_{i,j}$ is the pressure difference, Pa; K is the flow coefficient (usually assigned a constant value of 0.83).

The energy balance equation for DSF includes the absorbed solar radiation, long wave radiation exchange between layers, convective heat transfer between the cavity air and the layers, and conduction in the DSF layers (glass and shading device). Hence, the energy balance for any cell in layer of the DSF system can be given as:

$$m_{Li,j}c_{p,Li}\frac{T_{Li,j}}{dt} = q_{cond,Li,j} + q_{conv,Li,j} + q_{rad,Li,j} + A_{Li,j}\alpha_{Li}q_{sol,Li} \qquad (2)$$

Where $m_{Li,j}$ is the mass of the glass cell j in layer i, kg; $c_{p,Li}$ specific heat capacity of layer i, J/kg/k; $q_{cond,Li,j}$ is the heat transferred due to conduction to cell j in layer i, W; $q_{conv,Li,j}$ is the heat transferred due to convection to cell j in layer i, W; $q_{rad,Li,j}$ is the heat transferred due to long wave radiation to cell j in layer i, W; $q_{sol,Li,j}$ is the total solar radiation flux on cell j in layer i, W/m^2;$A_{Li,j}$ is the area of cell j in layer i, m^2; α_{Li} is the absorptance of layer i.

In the zonal approach, the layers are divided into a number of cells and Equation 2 is then applied for each cell. In developing the thermal models for conduction, convection and radiation, it was assumed that material properties such as specific heat capacity and thermal conductivity are constant and the cavity air is treated as a non-absorbing and non-emitting medium; heat transfer in the lateral direction is negligible: the thermal models for cavity air are two-dimensional; and the elements are all diffuse-gray surfaces for long wave radiation analysis. This was found to be satisfactory when the enclosure has multiple surfaces (Siegel and Howell, 1992). For diffuse surface, the reflectivity is independent of the outgoing or incoming directions, and the emissivity and absorptivity of a gray surface are independent of the wavelength.

MODEL VERIFICATION

In order to avoid overheating of the DSF cavity and the venetian blinds, and to monitor the energy exchanged as the ventilating air flows through the cavity, temperature distributions in the outer cavity (Ca1), inner cavity (Ca2), venetian blinds (L3), and the exhaust temperature should be predicted. Moreover, the temperature distribution in the inner glass (L4) should be known in order to evaluate the thermal comfort in the room. Thus the comparisons of the measured and predicted temperature distributions were done for the air in the outer cavity, the venetian blinds, the air in the inner cavity, and the inner pane at the positions (1) 40cm, (2) 135cm and (3) 230cm (see Figure 1). The comparison of the temperature of exhaust air with experimental data was also done. Figures 3a to 3c depict the temporal and spatial variation for Ca1, Ca2, and L4. The temporal variation of the exhaust temperature is shown in Figure 3d.

In all of the figures the predicted temperature follows the experimental data and the prediction error increases during higher solar radiation, and attains a maximum value around 13:00 hour. The prediction error for the outer cavity, the inner cavity, and the inner glass, shown in Figures 3a to 3c, is mostly at the top position than at the middle and bottom. The errors could be due to the complicated long wave exchange with the venetian blinds and the other surfaces; the lumping of the diffused and reflected solar radiation into the total radiation instead of treating them separately due to shortage of measured data; three-dimensional effects such as reverse flow and local short circuit caused by the outer façade frames (used to partition the outer pane into three parts); the complicated airflow through the venetian blinds; the heat transfer through the frames; air leakage; experimental errors; and the uncertainty of surface heat transfer coefficients.

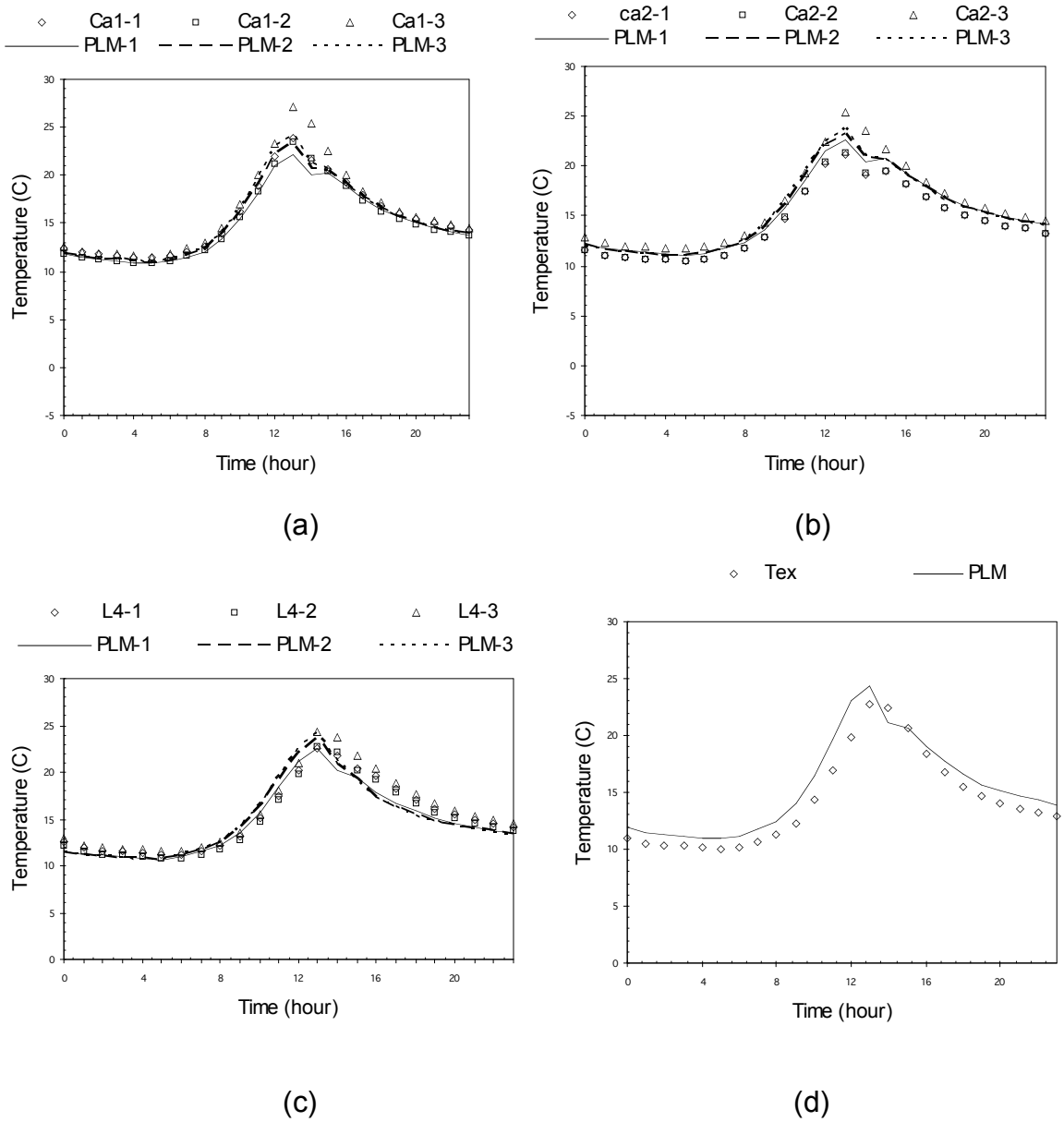

Figure 3 Comparison of predicted and measured temperature (refer Figure 1 for the notation). (a) outer cavity (b) inner cavity (c) inner glass and (d) exhaust air.

A more detailed model such as CFD could be used to reduce the errors. But the occurrence of errors of these magnitudes could be difficult to avoid even if CFD was employed (see Manz, 2004). Therefore, from the perspective of the simplified approach pursued for thermal and airflow modeling of the DSF, the results obtained in this study show that the zonal model can be used to assess the performance of the DSF system with venetian blind by providing information which is not possible for the lumped and the control-volume models. The lumped model only uses a single node for each part of the DSF system, whereas the control-volume approach is good for estimating the vertical stratification of temperature when the shading device is a roller screen.

The zonal models were also used to evaluate the influence of inlet flow rate (M_0), the height of the DSF (H), the presence and absence of venetian blinds on the temperature change of the cavity air from inlet to outlet $(T_{ex}-T_{in})$. The result shows that the influence of changing the values of each parameter is more apparent during the day than during the night. Furthermore, increasing H increases $T_{ex}–T_{in}$, a practical problem for DSF used for multistory buildings; the presence of venetian blinds increases $T_{ex}–T_{in}$, which shows that although venetian blinds reduce the direct solar gain, they can increase the indirect gain if the DSF cavity is not properly ventilated. This is why increasing M_0 decreases $T_{ex}–T_{in}$, making the air in the cavity cooler.

CONCLUSIONS

This paper has shown the capability of the zonal model to predict the performance of the DSF with a reasonable accuracy providing information which is not possible for the lumped and the control-volume models. Parametric studies were also conducted to illustrate the application of the validated zonal model. The result of the parametric study shows that increasing H and the presence of venetian blinds increases outlet-inlet temperature difference, $T_{ex} –T_{in}$, while increasing M_0 decreases $T_{ex} –T_{in}$. Furthermore, the developed zonal model can be integrated with energy simulation model to get a more detailed information on DSF in particular and envelopes in general.

References

Haghighat, F., Li, Y. and Megri, A.C.(200)1. Development and validation of a zonal model- POMA. *Building and Environment* 36: 1039-1047.

Stewart, J. and Ren, Z. (2003). Prediction of indoor gaseous pollutant dispersion by nesting sub-zones within a multi-zone model. *Building and environment* 38:635-643.

Manz, H. (2004). Total solar energy transmittance of glass double facades with free convection. *Energy and Buildings* 36: 127 136.

Park, C.S., Augenbroe, G., Messadi, T., Thitisawat, M. and Sadegh, N. (2004). Calibration of a lumped simulation model for double-skin façade system. *Energy and Buildings* 36: 1117-1130.

Saelens, D. (2002). Energy Performance Assessment of Single Storey Multiple-Skin Facades. *Ph.D. Thesis*, Katholieke Universiteit Leuven, Leuven, Belgium.

Tanimoto, J., and Kimura, K .(1997). Simulation study on an airflow window system with an integrated roll screen. *Energy and Buildings* 26: 317-325.

Safer, N., woloszyn, M., and Roux. JJ. (2005). Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin façade equipped with venetian blind. *Solar Energy* 79: 193-203.

Siegel, R., and Howell, J.R.(1992.) Thermal Radiation Heat Transfer, 3rd Ed.,Hemisphere Publishing Corporation.