ANALYSIS OF TWO DIFFERENT APPROACHES TO SOLVE THE HEAT TRANSFER THROUGH SINGLE- AND DOUBLE-GLAZING SYSTEMS IN WHOLE BUILDING ENERGY SIMULATION

Roberto Zanetti Freire, roberto.freire@pucpr.br
Walter Mazuroski, waltermazk@gmail.com
Pontifícia Universidade Católica do Paraná - PUCPR,
Laboratório de Sistemas Térmicos - LST,
Rua Imaculada Conceição, 1155,
CEP. 80215-901, Curitiba - Paraná - Brasil

Marc Olivier Abadie, mabadie@univ-lr.fr
University of La Rochelle,
Laboratoire d'Étude des Phénomènes de Transfert et de l'Instantanéité : Agro-industrie et Bâtiment – LEPTIAB,
17000 La Rochelle - France

Nathan Mendes, nathan.mendes@pucpr.br
Pontifícia Universidade Católica do Paraná - PUCPR,
Laboratório de Sistemas Térmicos - LST,
Rua Imaculada Conceição, 1155,
CEP. 80215-901, Curitiba - Paraná - Brasil

Abstract. *In recent years, several intensive studies have been carried out in order to reduce the energy consumption of buildings. One solution lies on whole building energy simulation that permits to analyze the heat (and moisture) transfer through the building envelope and, consequently, is a way to understand how to improve the building performance. This papers aims to analyze the modeling level needed to successfully evaluate the heat transfer through glazing parts of windows in such whole building simulations as it is well-known that windows are the thermally weakest elements of the building envelope.*

In this way, predictions of glazing surface and zone air temperatures and energy demand obtained using both resistive and finite-volume based models are compared. Results show that for common window glazing structure and outdoor/indoor perturbations, differences between the two models are small. However, in the case of glazing presenting higher solar absorption and thermal inertia, the use of the finite-volume based model is required to accurately predict the glazing internal surface temperature and correctly analyze the building behavior such as energy consumption and condensation on the window glazing surface.

Keywords*: Glazing, Heat Transfer, Solar Radiation, Absorption, Modeling.*

1. INTRODUCTION

Glazing systems are usually thermally weak systems and are responsible for an important amount of heat losses or gains that can greatly affect the whole energy consumption of modern buildings. Works that have been proposed in the last few years, e.g. Askar *et al.* (2001), Bahaj *et al.* (2008), Loutzenhiser *et al.* (2008), Poirazis *et al.* (2008), Papaefthimiou *et al.* (2009), Tanaka *et al.* (2009) and Urbikain and Sala (2009) justify the increasing interests in the glazing systems research area, mainly when they are coupled to building structures.

The level of complexity required to numerically evaluate the effect of heat transfer through multilayered glazing systems on the building energy consumption clearly depends on the glazing properties and the external perturbations. Various simplifications regarding the treatment of heat transfer through glass panels are used in current building energy simulation programs such as EnergyPlus (Crawley *et al.*, 2004) and TRNSYS (Klein *et al.*, 2004). A two-node (four-node) approach for single (double) glazing system (the so-called "Resistive Model") has been used as a model to calculate the heat transfer through the glazing thickness. These simplifications are perfectly acceptable when dealing with glazing of small thickness for which thermal inertia is actually negligible but when applied to thicker or multilayered glazing, such as the one that are more and more commonly used in modern buildings, it may not represent the complex non-uniform distribution of conducted and absorbed solar radiation.

Some studies (Powles *et al.*, 2002, Ismail and Henriquez, 2003, and Strobel *et al.*, 2007) showed that neglecting the glazing thermal inertia and/or considering the solar absorption in a simplified way could lead to notable errors on the evaluation of the glazing surface temperature and the Solar Heat Gain Coefficient. Evidently, those errors are amplified for thicker and more absorbing glazing materials.

It should be noted that, in those analyses, the studied glazing systems were considered disconnected from the rest of the building. By integrating the model proposed by Strobel *et al.* (2007) into the PowerDomus Building Energy Simulation program (Mendes *et al.*, 2003), the present study aims to analyze the modeling level needed to successfully evaluate the heat transfer through window glazing material in whole building simulation. In a first part, the two mathematical models employed here along with their main differences are presented. Then the description of the studied cases is given in a second section. The consequences of the simplest model's simplifications on the evaluation of the glazing surface temperature, the zone air temperatures and the energy demands are reported in a third part.

2. MATHEMATICAL MODELING

2.1. Preliminary Notes

The present mathematical models concern the determination of the so-called "center of glass" temperature, i.e., the temperature of the glazing itself. The window frame effect is then disregarded in the calculation of both the glazing temperature and zone heat gain. Moreover, the spectral dependency of the glazing optical coefficients (transmittance, reflectance and absorptance) is ignored here. Two window heat balance models are presented in this section: the simplified resistive model and the finite-volume based model. Both have been integrated into the Brazilian Building Energy Simulation program called PowerDomus (Mendes *et al.*, 2003).

2.2. Simplified Resistive Model

The simplified resistive model (Fig. 1) is similar to those integrated in most building energy simulation programs and consists of evaluating the glazing surface temperatures using a two-node (four-node) approach for single (double) glazing systems. As described in the EnergyPlus Engineering Reference book (EnergyPlus, 2007), the window heat balance in this model is based on several assumptions:

- the glass layers are thin enough that heat storage in the glass can be neglected; therefore, there are no heat capacity terms in the equations;
- the heat flux is normal to the glass faces and is one dimensional;
- the glass layers are opaque to infrared radiation;
- the glass faces are isothermal. This is generally a good assumption since glass conductivity is very high;
- the short-wave radiation absorbed in a glass layer can be apportioned equally to the two faces of the layer.

The heat balance for a double-glazing window can be written as:

$$\varepsilon_1 E_o - \varepsilon_1 \sigma \mathrm{T}_1^4 + k_1\left(T_2 - T_1\right) + h_o\left(T_o - T_1\right) + S_1 = 0 \tag{1}$$

$$k_1\left(T_1 - T_2\right) + h_1\left(T_3 - T_2\right) + \sigma \frac{\varepsilon_2 \varepsilon_3}{1-\left(1-\varepsilon_2\right)-\left(1-\varepsilon_3\right)}\left(\mathrm{T}_3^4 - \mathrm{T}_2^4\right) + S_2 = 0 \tag{2}$$

$$k_2\left(T_4 - T_3\right) + h_1\left(T_2 - T_3\right) + \sigma \frac{\varepsilon_2 \varepsilon_3}{1-\left(1-\varepsilon_2\right)-\left(1-\varepsilon_3\right)}\left(\mathrm{T}_2^4 - \mathrm{T}_3^4\right) + S_3 = 0 \tag{3}$$

$$\varepsilon_4 E_i - \varepsilon_4 \sigma \mathrm{T}_4^4 + k_2\left(T_3 - T_4\right) + h_i\left(T_i - T_4\right) + S_4 = 0 \tag{4}$$

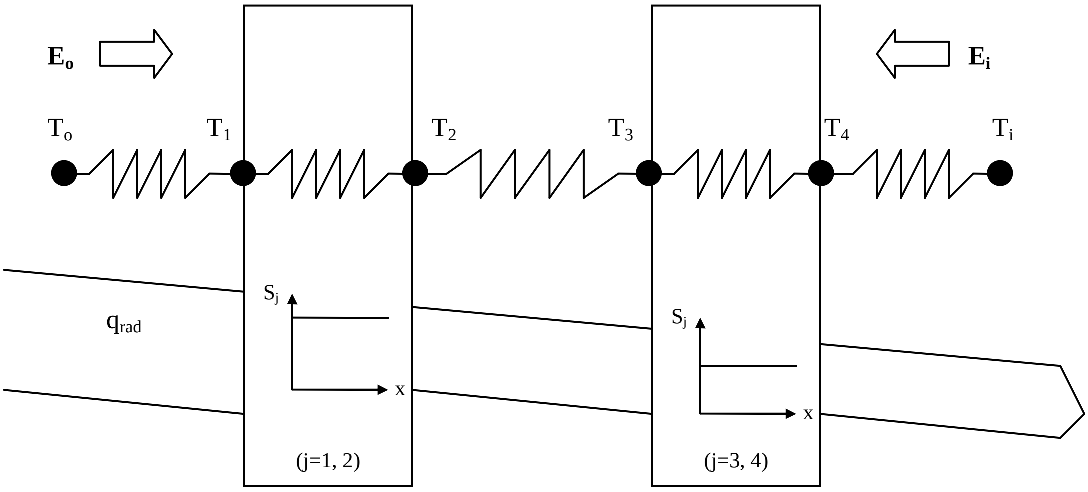

Figure 1. Simplified resistive model description.

Where *E* is the long-wave radiation incident on window ($W.m^{-2}$), *h* is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$), *k* is the thermal conductivity ($W.m^{-1}.K^{-1}$), *q* is the heat flux ($W.m^{-2}$), *S* is a source term ($W.m^{-2}$), *t* is the time (s), *T* is the temperature (K), α is the thermal diffusivity ($m^2.s^{-1}$), ε is the surface emissivity (-) and σ is the Stefan-Boltzmann constant ($W.m^{-2}.K^{-4}$). The subscripts *1*, *2*, *3* and *4* are related to the glazing surfaces, *o* is for outdoor and *i* is for indoor.

In Equation (1)-(4), S_i is the radiation (short -wave and long-wave from zone lights and equipment) absorbed by the i-th layer. Short-wave radiation (solar and short-wave from lights) is assumed to be absorbed uniformly along a glass layer, so that for the purposes of the heat balance calculation it is split equally between the two faces of each layer, i.e., $S_1= S_2$ and $S_3= S_4$ for the double-glazing system.

The “simplified” term has been added to emphasize the calculation of the absorption and transmission of solar radiation through the glazing system. The present model directly uses tabulated solar absorption and transmission coefficients obtained from the Window 5 program (Finlayson *et al.*, 1995). Each coefficient is given for radiation incident angle ranging from 0° to 90° with a 10° increment. Values at intermediate angle are linearly interpolated.

2.3. Finite-Volume Based Model

The finite-volume based model (Fig. 2) has been presented in Strobel *et al.* (2007). The main differences with the simplified resistive model are:

- the heat storage in the glass is taking into account by the resolution of the one-dimensional transient heat conduction within the glazing material;
- the solar radiation absorption is a function of the location inside the glazing material;
- the solar radiation absorption and transmission coefficients are evaluated according to the radiation incident angle (and not tabulated) using the calculations presented in Siegel and Howell (2001);
- the value of the convective heat transfer coefficient between the two glass layers of a double-glazing system can be imposed constant or calculated according to the gas temperature and properties, the spacing between the glass layers and the window height using the correlations of Wright (1996);
- the properties of the gas between the two glass layers of a double-glazing can be imposed constant or calculated according to the expressions described in Finlayson *et al.* (1993).

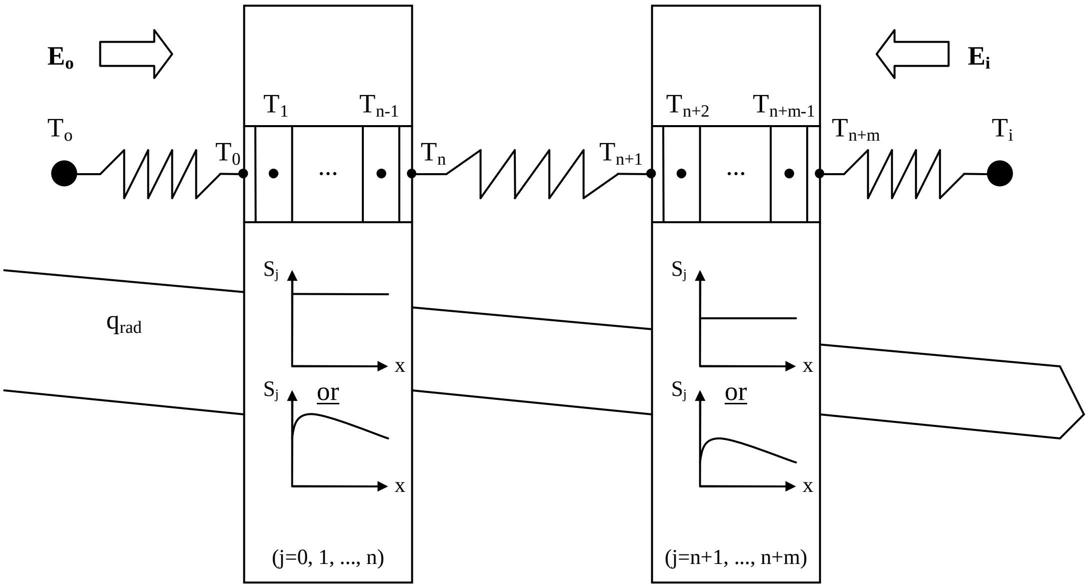

Figure 2. Finite-volume model description.

The general equation for the heat transfer across a glazing is given by Eq. (5):

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + S \tag{5}$$

The boundary conditions are similar to the ones described for the simplified resistive model, i.e., the radiative and convective heat fluxes are taking into account at the glass layers' surfaces. The governing partial differential Eq. (5) is discretized using a fully-implicit scheme and the equations system is solved by means of the Tri-Diagonal Matrix Algorithm (TDMA). The radiation absorption that takes into account the solar ray multiple reflections between the two surfaces of a single glazing and between the two glass layers of double-glazing system is introduced in the source term of Eq. (5). Two options are available for calculating the absorbed radiation (Fig. 2):

- the absorption can be considered uniformly distributed within the glazing material and is, as a consequence, very close to the previous model; or
- the absorption can be precisely evaluated using the algorithm presented by Strobel *et al.* (2007) that accounts for the exponential attenuation of the radiation energy intensity in the glazing material according to the electromagnetic theory of radiation energy propagation.

3. SIMULATION PROCEDURES

3.1. Building Structure

In order to verify and report the differences between the two glass-systems mathematical models, the BESTEST geometry presented by the International Energy Agency (IEA, 1995) has been chosen. Data provided by many building simulation programs – developed for the Building Energy Simulation Test (BESTEST) and Diagnostic Method report – have been used to define which are the most relevant situations to use a more complex model.

One BESTEST building structures have been chosen and are based on the single-zone model of the BESTEST methodology for the low-thermal mass (600FF) cases. Figure 3 shows the building model geometry, while Table 1 presents the building envelope material properties and Table 2 shows the window properties for the BESTEST case.

The 600FF geometry is made up of one room with 8.0 m X 6.0 m X 2.7 m of length, width and height, respectively. There are also two south-oriented 6.0 m² windows. The input signals applied on the building simulation tool are the Denver's weather variables, that is: outdoor temperature, outdoor relative humidity and diffuse and direct solar radiations. Also one forced ventilation rate of 0.5 air changes per hour and a 200 W internal hot gain (100% sensible : 60% radiative, 40% convective) have been applied to the zone. In the heating and cooling loads, temperatures of: i) heating if air temperature is less than 20°C and; ii) cooling if air temperature is higher than 27°C have been adopted.

Table 1. Materials for lightweight case (BESTEST 600FF).

Materials	k (W/m²)	ρ (kg/m³)	c_p (J/kg.K)	d (m)
Exterior Wall (inside to outside)				
Plasterboard	0.16	950	840	0.012
Fiberglass quilt	0.04	12	840	0.066
Wood siding	0.14	530	900	0.009
Floor (inside to outside)				
Timber flooring	0.14	650	1200	0.025
Insulation	0.04	10	1400	1.003
Roof (inside to outside)				
Plasterboard	0.16	950	840	0.0100
Fiberglass quilt	0.04	12	840	0.1118
Wood siding	0.14	530	900	0.0190

Table 2: Window properties.

Property	Value
Pane thickness (standard 1/8'' glass under the inch-pound ([IP] system)	3.048 mm
Air-gap thickness	12.7 mm
Index of refraction	1.526
Normal direct-beam transmittance through one pane in air	0.86156
Conductivity of glass	1.06 W/m.K
Conductance of each glass pane	333 W/m².K (R: 0.003 m².K/W)
Combined radiative and convective coefficient of air gap	6.297 W/m².K (R: 0.1588 m².K/W)
External convective heat transfer coefficient	24.0 W/m².K (R: 0.0416 m².K/W)
Internal convective heat transfer coefficient	3.0 W/m².K (R: 0.333 m².K/W)
Overall heat transfer coefficient (U) (Double glazing)	3.0 W/m².K (R: 0.333 m².K/W)
Overall heat transfer coefficient (U) (Single glazing)	2.6 W/m².K (R: 0.378 m².K/W)
Hemispherical infrared emittance of ordinary uncoated glass	0.84

Density of glass	2200 kg/m³
Specific heat of glass	750 J/kg.K
Double-pane solar heat gain coefficient (at normal incidence - SHGC)	0.787

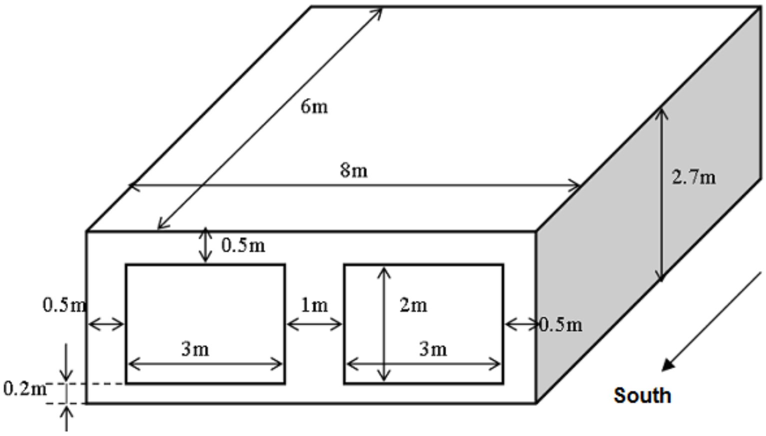

Figure 3: BESTEST dimensions (600FF).

3.2. Simulation Parameters

A two-year simulation period with objective of avoiding the effects caused by the initial conditions has been adopted. The results presented in this work have been obtained on the second year of simulation. A previous study to define the time step for the simulations has been performed and, according to the results, a 900 s time step has been chosen. The number of nodes needed in the finite-volume based model has also been selected by previous tests and, in Fig. 4, comparisons for the BESTEST 600FF simulations, where just the number of nodes has been changed, are presented. According to the results presented in Fig. 4, it is noticed that 10 nodes are enough to perform a simulation with a maximum error of 0.1 °C on the glass surface.

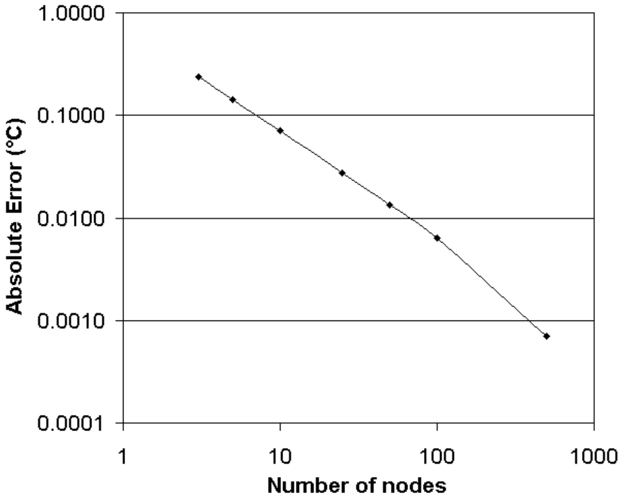

Figure 4: Absolute error as a fraction of the number of nodes.

4. RESULTS

This section presents comparisons between the simplified resistive and the finite-volume based models. In addition, comparisons to the results (temperature variations and heating and cooling loads) obtained by different softwares during the development of the International Energy Agency study (IEA, 1995) for the BESTEST 600FF and 600 cases have also been reported in this work.

First, a single glazing system applied to the BESTEST 600FF building structure (originally composed of double-glazed windows) has been simulated in order to verify the correct physical behaviors of the proposed models. After those validation procedures, an original case study based on BESTEST 600FF with a double glazing system of higher thermal inertia and solar absorption has been evaluated in order to emphasize the differences between the two building simulation models. All the results presented in this article regarding the zone air and glass internal surface temperatures are reported for the 4th of January (winter) and 27th of July (summer).

4.1. Single Glazing System

Figure 5 presents the variation of the glass internal surface temperature for the single glazing system. Both models give identical responses because of the high conductivity and small thickness of the glass. As a consequence, the variations of the zone air temperature obtained using the simplified resistive and the finite-volume based models are also identical (Fig. 6).

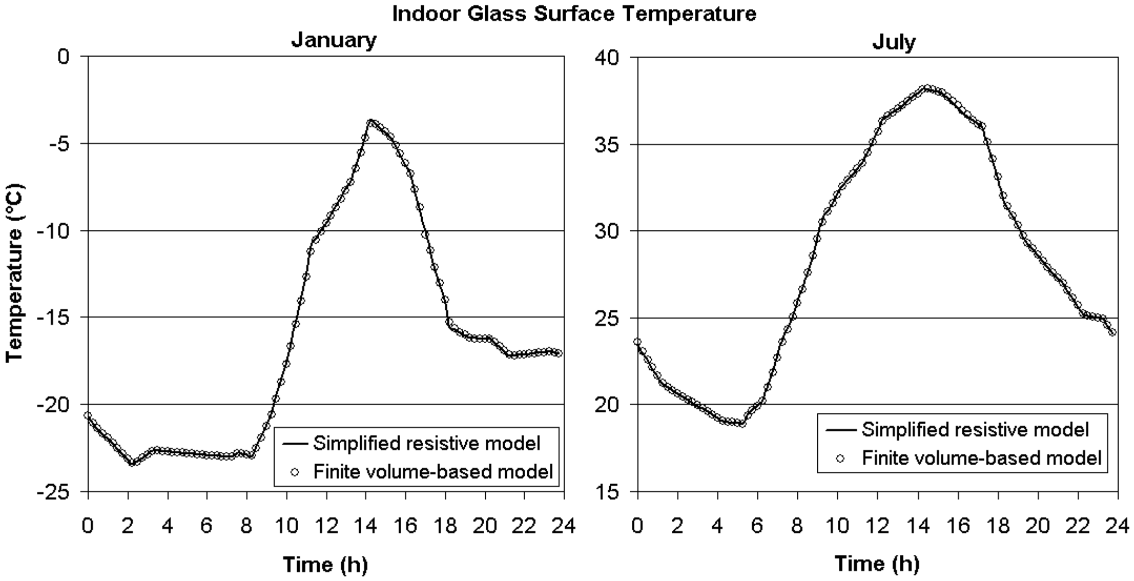

Figure 5: Glass internal surface temperature for the single glazing system configuration.

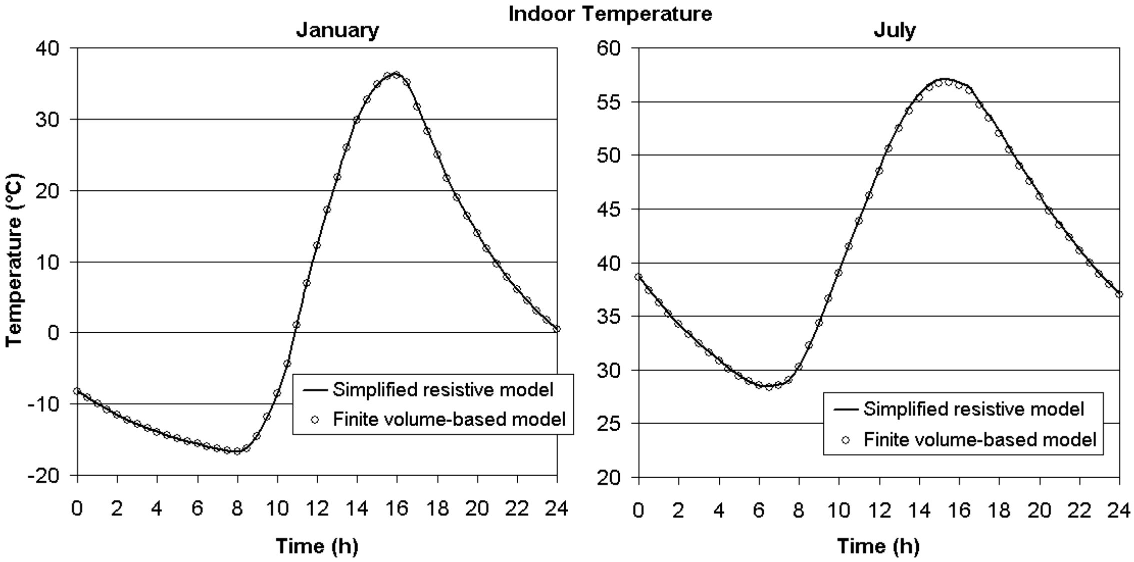

Figure 6: Zone air temperature for the single glazing system configuration.

4.2. Double glazing system of high inertia

The present case concerns the low inertia building (600FF case) with a double glazing system of high thermal inertia. The objective of this configuration is to evaluate the difference between the two models in an extreme case where most of the solar radiation is actually absorbed within the glass panels of the window and do not directly enter into the building. For the present case, the two options have been tested for the finite-volume based model: the absorption has been considered uniformly distributed within the glazing material (identified as "uniform") or the absorption has been precisely evaluated using the algorithm accounting for the exponential attenuation of the radiation energy intensity in the glazing material ("non-uniform").

Figure 7 presents the indoor glass surface temperature variations obtained with the three models. Firstly, there is almost no difference between the two ways of considering the solar absorption within the glazing material. Note that no effect of those two approaches has been observed for the previous configurations of conventional glazing systems. Secondly, the simplified resistive model predicts much lower temperature during the sunny hours with a maximum of about 4°C for the winter day. Figure 8 shows the effect on the indoor temperature that is much attenuated and almost inexistent for the summer day. Statistically, the difference between the two models is higher for this double glazing system of high inertia where mean indoor air temperature is 0.25°C higher for the finite-volume based model (Tab. 3). As a consequence, heating and cooling loads are respectively much lower and higher for this model (Tab. 4). In particular, compared to the results obtained with the simplified resistive model, the cooling energy and power peak increase of about 50% and 25%, respectively. The impact on the condensation risk is also notable: 39.5 hours of condensation has been calculated for the resistive model and only 19 hours for the second model.

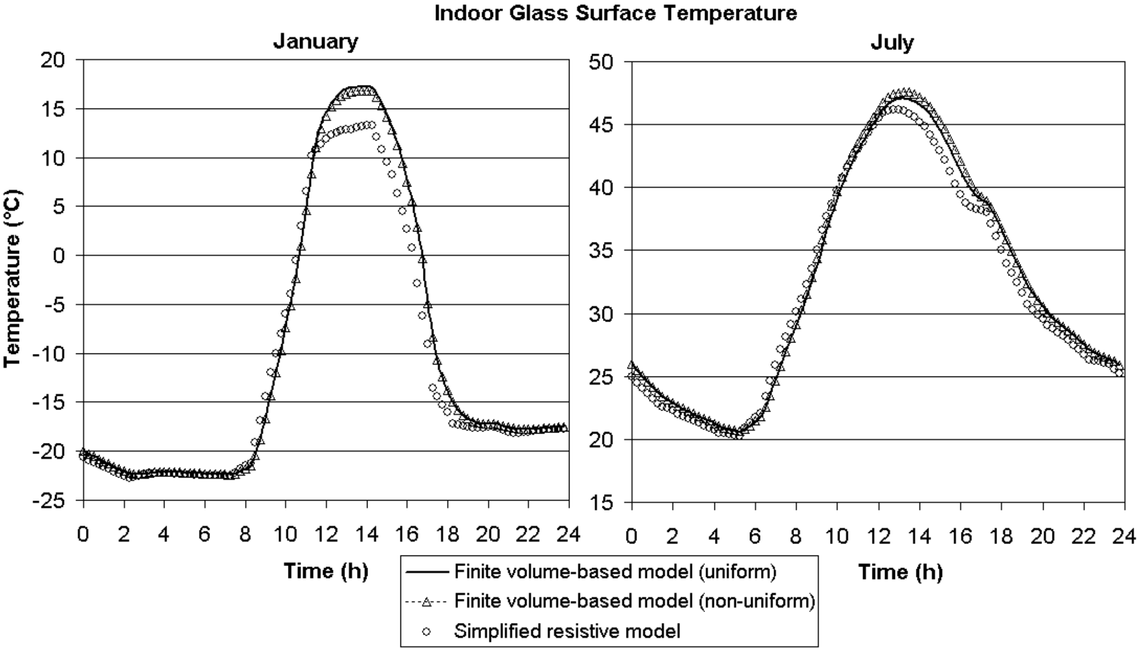

Figure 7: Glass internal surface temperature for the double glazing system configuration.

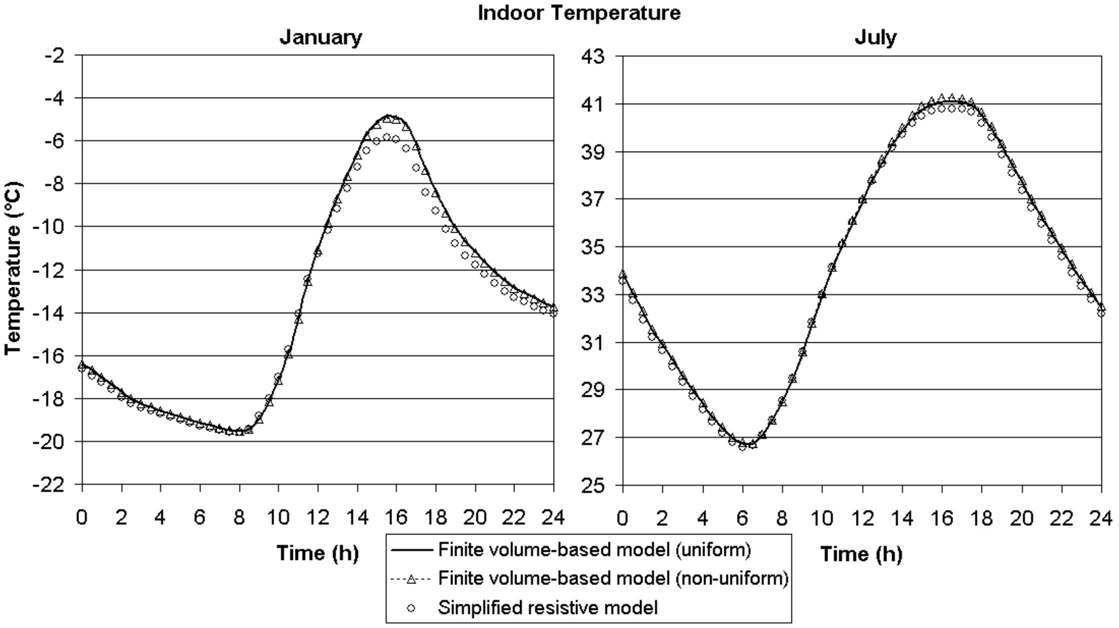

Figure 8: Zone air temperature for the double glazing system configuration.

Table 3: Zone air temperature comparisons for the double glazing system of high inertia.

	MODEL		
ZONE AIR TEMPERATURE	Simplified resistive	Finite-volume based (non-uniform)	Finite-volume based (uniform)
MINIMUM (°C)	-19.60	-19.52	-19.52
MAXIMUM (°C)	40.99	41.44	41.26
MEAN (°C)	16.30	16.57	16.54

Table 4: Heating and cooling loads comparisons.

	HEATING			COOLING		
MODEL	ENERGY (MWh)	PEAK (kW)	PEAK DATE – TIME	ENERGY (MWh)	PEAK (kW)	PEAK DATE – TIME
Simplified resistive	5.803	3.680	04/01 - 2:00	0.701	1.580	26/07 - 15:00
Finite-volume based	5.541	3.787	04/01 - 2:00	1.040	2.005	11/08 - 13:00

5. CONCLUSIONS

Due to the effects caused by glazing elements in the thermodynamical behavior of buildings, as internal gains/losses, the heat transfer calculation through glass surfaces is an important issue which has to be taken into account when the building hygrothermal and energy simulation is considered.

Comparisons between two glazing heat transfer models coupled to a standard building geometry have been presented in this work. No difference between the predictions obtained by the resistive model and the finite-volume based model has been observed in the case of single glazing windows. However, when a double glazing system is present, notable differences appear regarding the energy demand and condensation occurrence. In this case, the simplified resistive model is no more legitimate and the absorption of solar radiation within the glazing system has to be better described.

Although the present study has been focused on a limited number of building configurations, it has nevertheless put into relief some important limitations of the model that is commonly integrated in building energy simulation programs to calculate the heat flow through glazing systems. In particular, caution has to be exercised when studying energy demand and problems related to the glazing system surface temperature (e.g. condensation and thermal comfort) of buildings with a large percentage of their envelope made up of double-glazing systems.

6. ACKNOWLEDGEMENTS

The authors thank CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) of the Secretariat of Education of Brazil and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) of the Secretariat of Science and Technology of Brazil for support of this work.

7. REFERENCES

Askar, H., Probert, S.D. and Batty, W. J., 2001, “Windows for Buildings in Hot Arid Countries”, Applied Energy 70, pp. 77–101.

Bahaj, A.S., James, P.A.B. and Jentsch, M.F., 2008, “Potential of Emerging Glazing Technologies for Highly Glazed Buildings in Hot Arid Climates”, Energy and Buildings, 40, pp. 720–731.

Crawley, D.B., Lawrie, L.K., Pedersen, C.O., Winkelmann, F.C., Witte, M.J., Strand, R.K., Liesen, R.J., Buhl, W.F., Huang, Y.J., Henninger, R.H., Glazer, J., Fisher, D.E., Shirey, III D.B., Griffith, B.T., Ellis, P.G. and Gu., L., 2004, “EnergyPlus: an Update”, Proceedings of the SimBuild 2004 Conference, 4-6 August 2004, Boulder, Colorado.

EnergyPlus, 2007, “Engineering Reference book: The Reference to EnergyPlus Calculations”, November 6.

Finlayson, E., Arasteh, D., Huizenga, C., Rubin, M. and Reilly, M., 1993, “Window 4.0: Documentation of Calculation Procedures”, Lawrence Berkeley National Laboratory, report LBNL-33943.

Finlayson, E., Arasteh, D., Rubin, M., Sadlier J., Sullivan, R., Huizenga, C., Curcija, D. and Beall, M., 1995, “Advancements in Thermal and Optical Simulations of Fenestration Systems: The Development of WINDOW 5”, Proceedings of the VI Thermal Envelopes Conference, Clearwater Beach, FL.

IEA, 1995, “International Energy Agency Building Energy Simulation Test (BESTEST) and Diagnostic Method”, National Renewable Energy Laboratory (NREL).

Ismail, K.A.R. and Henríquez, J.R., 2003, “Modeling and Simulation of a Simple Glass Window”, Solar Energy Materials and Solar Cells, pp. 355-374.

Klein, S.A., Beckman, W.A., Mitchell, J.W., Duffie, J.A., Duffie, N.A., Freeman, T.L., Mitchell, J.C., Brau, J.E., Evans, B.L., Kummer, J.P., Urban, R.E., Fiksel, A., Thornton, J.W., Blair, N.J., Williams, P.M., Bradley, D.E., McDowell, T.P. and Kummert, M., 2004, “TRNSYS 16 – A TRaNsient System Simulation Program, User manual”, Solar Energy Laboratory, Madison: University of Wisconsin-Madison.

Loutzenhiser, P.G., Manz, H., Carl, S., Simmler, H. and Maxwell, G.M., 2008, “Empirical Validations of Solar Gain Models for a Glazing Unit with Exterior and Interior Blind Assemblies”, Energy and Buildings, 40, pp. 330–340.

Mendes, N., Oliveira, R.C.L.F. and Santos, G. H., 2003, “Domus 2.0: A Whole-Building Hygrothermal Simulation Program”, Proceedings of the 8th International Building Performance Simulation Association (IBPSA), vol. 1, Eindhoven – Netherlands.

Papaefthimiou, S., Syrrakou, E. and Yianoulis, P., 2009, “An Alternative Approach for the Energy and Environmental Rating of Advanced Glazing: An Electrochromic Window Case Study”, Energy and Buildings, 41, pp. 17-26.

Poirazis, H., Blomsterberg, A. and Wall, M., 2008, “Energy Simulations for Glazed Office Buildings in Sweden”, Energy and Buildings, 40, pp. 1161-1170.

Powles, R., Curcija, D. and Köhler, C., 2002, “Solar Absorption in Thick and Multilayered Glazings”, World Renewable Energy Congress VII, June 29-July 5, Cologne, Germany.

Strobel, C.S., Abadie, M.O. and Mendes, N. 2007, “Absorption of Solar Radiation in Thick and Multilayered Glazing”, Xth International Building Performance Simulation Association Conference and Exhibition (BS2007).

Siegel, R. and Howell, J., 2001, “Thermal Radiation Heat Transfer”, Taylor & Francis, 4th edition.

Tanaka, H., Okumiya, M., Tanaka, H., Yoon, G.Y. and Watanabe, K., 2009, “Thermal Characteristics of a Double-Glazed External Wall System with Roll Screen in Cooling Season”, Building and Environment, 44, pp. 1509-1516.

Urbikain, M.K. and Sala, J.M., 2009, “Analysis of Different Models to Estimate Energy Savings Related to Windows in Residential Buildings”, Energy and Buildings (In press).

Wright J.L., 1996, “A Correlation to Quantify Convective Heat Transfer between Vertical Window Glazings”, ASHRAE Transactions, Vol. 102 (1).

5. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.