ABSORPTION OF SOLAR RADIATION IN THICK AND MULTILAYERED GLAZING

Christian S. Strobel[1], Marc O. Abadie[1, 2] and Nathan Mendes[1]

[1]Thermal Systems Laboratory, Pontifical Catholic University of Paraná, Curitiba, Brazil
[2]LEPTAB, University of La Rochelle, La Rochelle, France

christian.s.strobel@gmail.com mabadie@univ-lr.fr nathan.mendes@pucpr.br

ABSTRACT

Given the major role played by windows with regard to energy losses and gains from buildings in respectively cold and hot climates, accurate prediction of the heat transfer through its glazing materials is of great importance in building energy simulation. In most of the building energy simulation programs, solar radiation absorption inside glazing layers is usually treated considering that all the radiation is uniformly absorbed in the glazing. The present assumption is obviously valid in the case of thin homogeneous glazing but, when dealing with thick glazing (commonly used in buildings), it poorly represents the complex non-uniform distribution of absorbed solar radiation. The present study aims to numerically investigate the error induced by such approximation in the case of thick and multilayered glazing. Results show that if the error remains negligible for glazings under steady-state solicitations, it becomes more important in particular for double glazings under transient conditions.

Keywords: Glazing; Heat transfer; Solar radiation; Absorption; Modeling; Building energy.

INTRODUCTION

Glass 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. A well executed project concerning the glazing areas and the accomplishment of a complete study about how the energy flows through these surfaces are of great importance to ensure low-energy consumption while maintaining comfortable indoor environment.

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 solicitations. Various simplifications regarding the treatment of heat transfer through glass panels are used in current building energy simulation programs. A resistance network of a small number of nodes is usually adopted and the heat capacity of the glazing is always neglected. For example, in TRNSYS (Klein et al. 2004) and EnergyPlus (Crawley et al. 2004), the heat transfer through glazings is performed using a 2-node model i.e. 1 node per glazing surfaces and half the absorbed solar radiation is imposed at each glazing node.

These simplifications are perfectly acceptable when dealing with glazings with thin thicknesses for which thermal inertia is negligible but when applied to thicker or multilayered glazings, such as the ones that are more and more commonly used in modern buildings; it may not represent the complex non-uniform distribution of absorbed solar radiation. Therefore, the temperature field within these thicker materials may differ from that obtained by current models. In particular, an approximated evaluation of the glazing indoor surface temperature can lead to errors on the prediction of the Solar Heat Gain Coefficient (SHGC) and condensation-related problems.

Alvarez et al. (1998) and more recently Powles et al. (2002) proposed a method for calculating the distribution of absorbed solar radiation inside thick and multilayered glazings in steady-state with or without a solar control film. The model is based on the one dimensional discretization of the heat transfer in the glazing material. Non-uniform solar absorption and multiple reflections are taken into account. Results obtained by Powles et al. (2002) showed that, for the case of thick single glazings, this simplified approach can induce an overestimation of both the interior surface temperature (+1°C) and SHGC (+0.01), that may be considered significant.

Ismail and Henriquez (2003) used the same approach and developed a two-dimensional transient-based model to study the heat transfer across a single glazing window. Results showed that SHGC slightly varies when the glazing is submitted to transient solicitations.

The present study aims to compare the glazing temperatures and SHGC obtained with current simplified models to those calculated with a one-dimensional transient-based model in the case of single and double glazings. In a first part, the model that is equivalent to those previously referenced, is presented. A particular care has been brought to the treatment of the solar absorption in the glazing material. Then, the simulation parameters and tools are described. Finally, results are presented and discussed in a last section.

MATHEMATICAL MODEL

Preliminary notes

The present mathematical model concerns the determination of the so-called "center of glass" temperature i.e. the temperature of the glazing alone. The window frame effect is then disregarded in the calculation of both the temperature and the SHGC. Two simplifications are made concerning the solar radiation. First, the spectral dependency of the glazing optical coefficients (transmittance, reflectance and absorptance) is ignored here. Second, the solar incidence angle is set to 0° (normal to the glazing surface).

General equation

The general equation for the heat transfer across a glazing is given by equation (1) where S includes the solar absorption described in the last sub-sections.

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + S \qquad (1)$$

Boundary conditions

The boundary condition for the outdoor glazing surface is:

$$q_{x=0} = -k\left.\frac{\partial T}{\partial x}\right|_{x=0} = h_{out}.\left(T_{out} - T_{x=0}\right) + \sum_{m=1}^{\infty} F_m.\varepsilon.\sigma.\left(T^4_{ngh,m} - T^4_{x=0}\right) \qquad (2)$$

Similarly, for the indoor glazing surface:

$$q_{x=L} = -k\left.\frac{\partial T}{\partial x}\right|_{x=L} = h_{ind}.\left(T_{ind} - T_{x=L}\right) + \sum_{m=1}^{\infty} F_m.\varepsilon.\sigma.\left(T^4_{ngh,m} - T^4_{x=L}\right) \qquad (3)$$

For the first glazing internal surface of a double pane system:

$$q_{x=n} = -k\left.\frac{\partial T}{\partial x}\right|_{x=n} = h_{int\,1}.\left(T_{x=L} - T_{n+1}\right) + \varepsilon.\sigma.\left(T^4_{n+1} - T^4_{x=L}\right) \qquad (4)$$

where "n+1" stands for the point in the middle of the air layer.

Finally, the second glazing internal surface of a double pane system:

$$q_{x=n+2} = -k\left.\frac{\partial T}{\partial x}\right|_{x=n+2} = h_{int\,2}.\left(T_{n+1} - T_{x=0}\right) + \varepsilon.\sigma.\left(T^4_{n+2} - T^4_{x=0}\right) \qquad (5)$$

Interglazing convective heat transfer coefficients have been calculated according to correlations developed by Wright (1996) for vertical windows and from Hollands et al. (1976) and ElSherbiny et al. (1982) for tilted windows.

Multiple reflections

According to Siegel and Howell (1992), it is possible to use the ray tracing method to calculate the reflection, transmission and absorption of heat in a glass system. If a unitary ray acts on a system (Figure 1), a fraction will be reflected, with intensity "ρ" and an amount of "(1-ρ)" enters inside the medium. Of this fraction that enters the material, "(1-ρ).τ" is transmitted for the other surface, and "(1-ρ).(1-τ)" is absorbed by the material. In the other surface, from the fraction "(1-ρ).τ" that arrives, a part is reflected again for the first surface, and a fraction "$(1-\rho)^2.\tau$" is transmitted for the inner ambient. This process repeats itself until the infinite, by the multiple reflections inside the glazing material, with shorter intensities at each reflection, until extinction. For a double system, the fraction transmitted by the first glass can be used as an initial parameter for the calculation of the second glass.

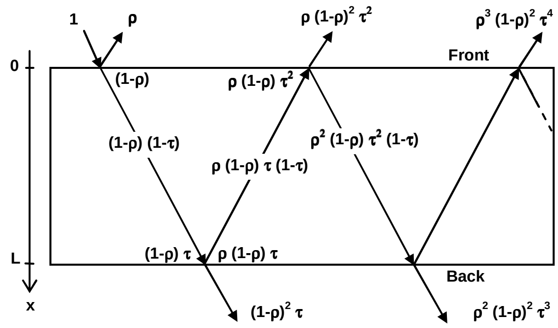

Figure 1 Multiple reflections inside a glazing material

Absorption of solar radiation considering multiple reflections

According to Siegel and Howell (1992), the intensity of the radiation energy is attenuated exponentially in the glazing material according to the electromagnetic theory of radiation energy propagation.

For a single glazing material, in the case of a solar ray going from the material front surface to the back one (positive x), the absorption along the distance x is given by:

$$A_{0\rightarrow x}(x) = 1 - \tau_1^{\frac{x}{L}} \qquad (6)$$

For a ray going in the opposite direction, the absorption from the back surface to the x location is:

$$A_{L\rightarrow x}(x) = 1 - \tau_1^{1-\frac{x}{L}} \tag{7}$$

Considering the multiple reflections that occur in a single glazing, the total absorption from the front surface to the x location is:

$$A_{front}(x) = \left(1 - \tau_1^{\frac{x}{L}}\right)\left[(1-\rho_1) + \rho_1^2\tau_1^2(1-\rho_1) + \rho_1^4\tau_1^4(1-\rho_1) + \ldots\right] \tag{8}$$

or

$$A_{front}(x) = \left(1 - \tau_1^{\frac{x}{L}}\right)\delta_1 \tag{9}$$

with

$$\delta_n = \frac{1-\rho_n}{1-\rho_n^2\tau_n^2} \tag{10}$$

The total absorption from the back surface to the x location is:

$$A_{back}(x) = \left(1 - \tau_1^{1-\frac{x}{L}}\right)\eta_1 \tag{11}$$

with:

$$\eta_n = \frac{\rho_n\tau_n(1-\rho_n)}{1-\rho_n^2\tau_n^2} \tag{12}$$

For a double glazing material, taking into account the multiple reflections inside and between the two glazing layers, the total absorption the total absorption from the front and back surfaces are given by equations (13) and (14) for the first panel and equations (15) and (16) for the second one.

$$A_{front1}(x) = \left(1 - \tau_1^{\frac{x}{L}}\right)(\delta_1 + R_2\varphi\eta_1) \tag{13}$$

$$A_{back1}(x) = \left(1 - \tau_1^{1-\frac{x}{L}}\right)(\eta_1 + R_2\varphi\delta_1) \tag{14}$$

$$A_{front2}(x) = \left(1 - \tau_1^{\frac{x}{L}}\right)\varphi\delta_2 \tag{15}$$

$$A_{back2}(x) = \left(1 - \tau_1^{1-\frac{x}{L}}\right)\varphi\eta_2 \tag{16}$$

where

$$\varphi = \frac{T_1}{1-R_1R_2} \tag{17}$$

Numerical solution

The governing partial differential equation (1) 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 is calculated at each node considering that the absorption at x equals the absorption that occurs in the region $[x^- = x - \Delta x/2;\ x^+ = x + \Delta x/2]$:

$$q_{abs}(x) = q_{rad}\left[A_{front}(x^+) - A_{front}(x^-) + A_{back}(x^-) - A_{back}(x^+)\right] \tag{18}$$

The radiation absorption is then introduced in the source term of equation (1).

SIMULATIONS

Glazing properties

Six glazings have been chosen from the International Glazing DataBase (IGDB, Anon A) in order to cover a wide range of glazing thicknesses and short-wave absorptions. Table 1 presents the single glazing properties.

Table 1 Single glazing properties

id	NFRC id	L (mm)	T	R
#01	102	3.0480	0.83385	0.06947
#02	103	5.7150	0.77068	0.06909
#03	100	3.1242	0.64591	0.07004
#04	101	5.7404	0.48560	0.22143
#05	402	7.9880	0.36652	0.07729
#06	420	5.6750	0.07459	0.06945

NFRC: US National Fenestration Rating Council; L: glazing thickness; T: transmittance; R: reflectance.

Thermal properties have been considered constant: ρ_{glz}=2200 kg.m^{-3}, cp_{glz} =750 J.kg^{-1}K^{-1}, k_{glz} =1.0 W.m^{-1}.K^{-1}. Front and back surface emissivity is 0.84. Due to the current developpement state of the present program, the front and back surface reflectances have been set equal to the front surface value. As a result, glazings #05 and #06 reflectances are slightly different from the IGDB values but these small modifications have negligible effect on the current analysis results.

Double glazings are made of two identical single glazings separated by a 12.7cm air layer (ρ_{air}=1.205 kg.m^{-3}, cp_{air} =1005 J.kg^{-1}K^{-1}, k_{air} =0.0257 W.m^{-1}.K^{-1}). The suffix “d” will be added to the single glazing identification number to distinguish the double glazings (#01d, #02d,…).

Steady-state simulations

Steady-state simulation environmental conditions are based on the NFRC 100 Summer conditions (2001).

The only difference is that the convective heat transfer coefficients have been set to constant values instead of using wind and/or temperature dependent values. Table 2 presents the environmental conditions considered in the present work.

Table 2 Steady-state simulation environmental conditions

	Outdoor conditions	**Indoor conditions**
Temperature	32°C	24°C
Mean radiant Temperature	32°C	24°C
Convective heat transfer coefficient	15 $W.m^{-2}.k^{-1}$	3 $W.m^{-2}.k^{-1}$
Solar irradiance	783 $W.m^{-2}$	-

Transient simulations

Transient simulation environmental conditions are based on the steady-state ones. The only difference lies in the 24hour periodic evolution of both outdoor air temperature and solar irradiance. Outdoor air temperature evolves harmonically versus time and presents a mean value of 32°C and a maximum value of 40°C at 5PM. Solar irradiance presents a maximum value of 783 $W.m^{-2}$ at noon (Figure 2).

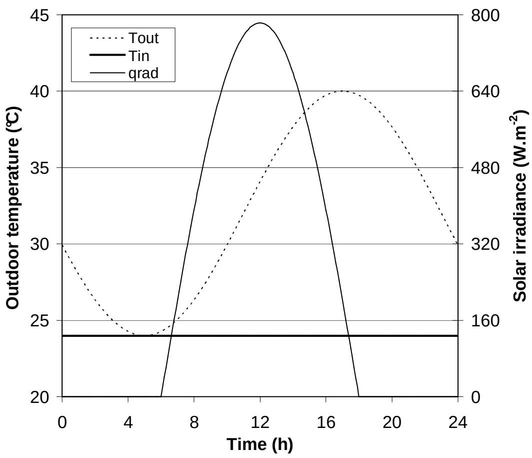

Figure 2 Outdoor air temperature and solar irradiance evolutions

Simulation programs

WINDOW version 5.2a (Anon B) has been used to calculate the glazing surface temperatures and the SHGC values under steady-state conditions.

Transient calculations have been performed with TRNSYS version 15 (Anon C). Glazing properties have been imported from Window 5.2a and used in Type56. Due to the STAR network model implemented in this component and to the impossibility of changing the surface emissivities of the room internal surface walls, long-wave radiations have been set to zero to allow the comparison with the present calculations. Simulation time step has been set to 0.1 hour.

The model presented in the previous section has been implemented in the C++ based program called VITREOUS-LST (Mazuroski, 2006 and Strobel, 2007) developed at the LST laboratory. Spatial discretization (1 volume/0.03mm inside the glazing material and 1 volume/0.015mm at the glazing surfaces) and time step (0.1 hour) have been set constants for the whole set of simulations.

RESULTS AND DISCUSSION

The present analysis aims to compare the temperature and SHGC predictions obtained by conventional calculations (WINDOW and TRNSYS) with those given by the proposed approach. In addition to the previously described treatment of the short-wave radiation absorption (referenced as “complete” in the next sections), the absorption will be also considered as uniformly distributed within the glazing material (“unif. dist.”) in order to evaluate the error induced by such approximation.

SHGC is defined as the fraction of the heat from the sun that enters through a window and is the sum of the glazing system transmittance and the fraction of solar radiation that enters the indoor environment by convection and long-wave exchanges.

As a consequence, two simulations have been performed with the present model to calculate the heat fluxes at the glazing indoor surface with and without solar radiation:

$$SHGC = T_{sys} + \frac{q_{ind}(q_{rad} \neq 0) - q_{ind}(q_{rad} = 0)}{q_{rad}} \quad (19)$$

Steady-state simulations

Figure 3 presents the single glazing temperature profiles obtained by WINDOW and the present model (glazing #06). As the solar absorption decrease according to the distance from the solar ray entering surface (x=0), a shift of the maximal temperature obtained with the complete model is observed in comparison to that calculated with the uniform distribution of the solar absorption. Consequently, there are an underestimate of about 0.25°C and an overestimate of about 0.5°C of the glazing outdoor and indoor surface temperatures, respectively, with the latter simplification and the conventional calculation. Figure 3 shows that the WINDOW calculation gives the same surface temperature than the present model using the uniformly distributed solar absorption.

Figure 4 presents the temperature profiles for the case of a double glazing made up of two glazings #06. The same trends are observed here.

Table 3 gives the Solar Heat Gain Coefficient values using the three approaches and the relative differences between the present model and WINDOW. The three calculations give very close estimates as the maximal difference is 1.37%.

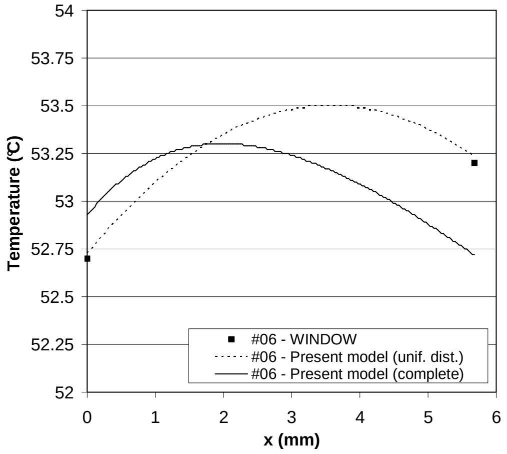

Figure 3 Single glazing temperature profiles

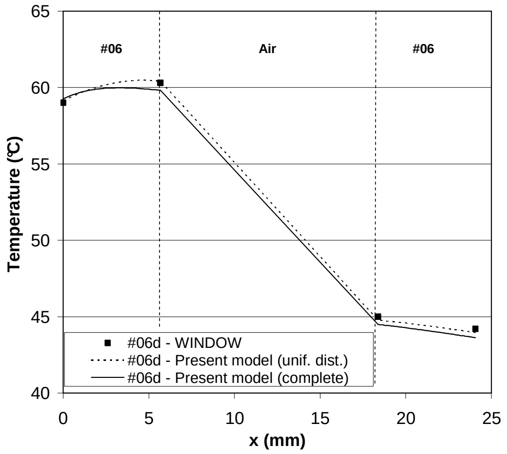

Figure 4 Double glazing temperature profiles

Table 3 Solar Heat Gain Coefficient (SHGC)

	WINDOW	Present model – unif. dist.		Present model – complete	
	SHGC	SHGC	Diff.	SHGC	Diff.
#01	0.860	0.8606	0.07%	0.8606	0.07%
#02	0.818	0.8185	0.07%	0.8185	0.07%
#03	0.731	0.7328	0.24%	0.7326	0.22%
#04	0.623	0.6252	0.35%	0.6243	0.21%
#05	0.542	0.5441	0.40%	0.5420	0.01%
#06	0.341	0.3448	1.11%	0.3385	-0.74%
#01d	0.763	0.7628	-0.02%	0.7628	-0.03%
#02d	0.703	0.7023	-0.10%	0.7022	-0.12%
#03d	0.586	0.5866	0.11%	0.5864	0.07%
#04d	0.455	0.4551	0.02%	0.4544	-0.13%
#05d	0.365	0.3669	0.53%	0.3653	-0.09%
#06d	0.192	0.1932	0.62%	0.1894	-1.37%

Transient simulations

As the same differences between the two calculations of the present model have been observed in the case of transient simulation, only the results obtained with the complete model are presented here.

Figure 5 presents the evolution of the outdoor and indoor surface temperatures in the case of the single glazings #01 and #06. TRNSYS and the present model give the same temperature variations for this case. Glazing outdoor and indoor temperatures remain almost equal and vary according to the solar absorptance (higher temperatures for the glazing #06 when solar radiation takes place) and the transient solicitations.

For double glazings (Figure 6), larger differences are observed especially for the indoor surface temperatures. Those differences seem to originate from the inertia of the glazing system as tests showed that, using very small values of inertia (product of the material density by the material heat capacity), results tend to approach those obtained with TRNSYS.

Figures 7 and 8 present the SHGC results. As obtained by Ismail and Henriquez (2003) for single glazings, SHGC slightly varies when the glazing is submitted to transient solicitations. The SHGC variation is found higher for double glazing for which using the conventional calculation gives larger errors.

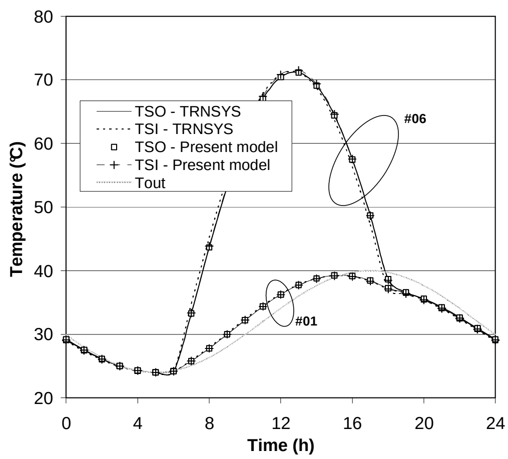

Figure 5 Single glazing outdoor and indoor surface temperatures

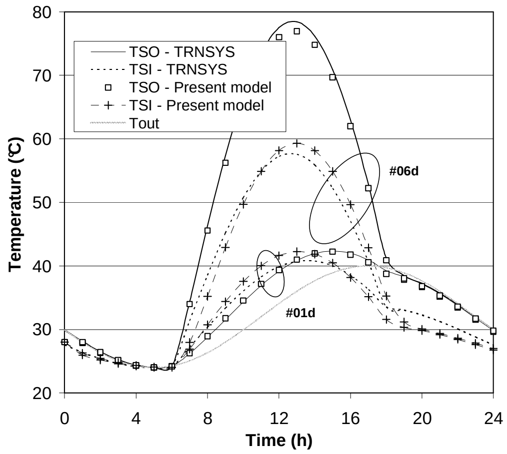

Figure 6 Double glazing outdoor and indoor surface temperatures

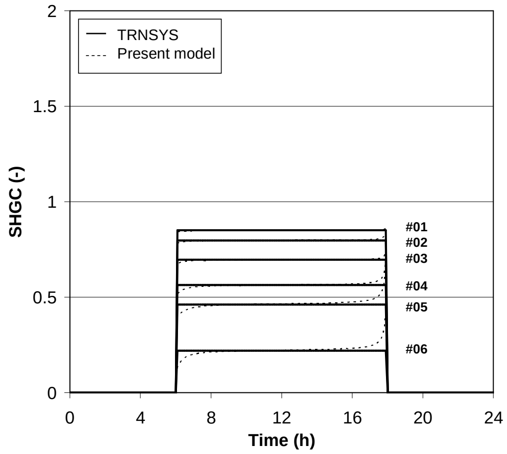

Figure 7 Single glazing SHGC

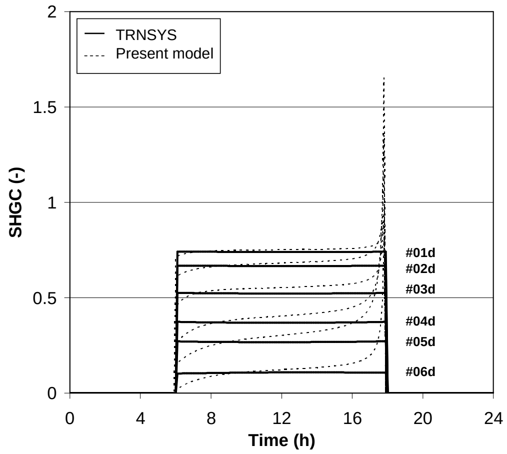

Figure 8 Double glazing SHGC

CONCLUSIONS

The present study aimed to understand the level of complexity required to numerically evaluate the effect of heat transfer through multilayered glazing systems on the building energy consumption.

From the present analysis results, it can be concluded that conventional calculation gives accurate predictions of the temperature field and SHGC in steady-state. In the case of transient solicitations, higher differences have been observed, particularly concerning the SHGC values, and thus the part of solar radiation that enters the room by convection and long-wave radiation exchanges.

The main perspective of this work concerns the integration of the presented model into the whole-building simulation tool PowerDomus (Mendes et al. 2003) in order to evaluate the relative importance of taking into account the solar radiation absorption into glazings in building energy simulation.

ACKNOWLEDGMENT

The authors thank the Brazilian Research Council (CNPq) of the Secretary for Science and Technology of Brazil for support of this work.

REFERENCES

Alvarez G., Jimenez DN. and Estrada CA. 1998. “Thermal performance of solar control coatings: a mathematical model and its experimental verification” J. Phys. D: Appl. Phys. 31, pp.2249–2257.

Anonymity A http://windows.lbl.gov/materials/igdb/

Anonymity B http://windows.lbl.gov/software/window/window.html

Anonymity C http://sel.me.wisc.edu/trnsys/

Crawley DB., Lawrie LK., Pedersen CO., Winkelmann FC., Witte MJ., Strand RK, Liesen RJ., Buhl WF., Huang YJ., Henninger RH., Glazer J., Fisher DE., Shirey III DB., Griffith BT., Ellis PG. and Gu. L. 2004. “EnergyPlus: An Update,” in Proceedings of the SimBuild 2004 Conference, 4-6 August 2004, Boulder, Colorado. IBPSA-USA.

ElSherbiny SM., Raithby GD. and Hollands KGT. 1982. “Heat Transfer by Natural Convection Across Vertical and Inclined Air Layers” Journal of Heat Transfer, Vol. 104, pp. 96-102.

Hollands KGT., Unny TE., Raithby GD. and Konicek L. 1976. “Free Convection Heat Transfer Across Inclined Air Layers” Journal of Heat Transfer, Vol. 98, pp. 189-193.

Ismail KAR. and Henriquez JR. 2003. “Modeling and simulation of a simple glass window” Solar Energy Materials and Solar Cells, pp. 355-374.

Klein SA., Beckman WA., Mitchell JW., Duffie JA., Duffie NA., 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.

Mazuroski W. 2006. "Desenvolvimento do Programa VITREOUS-LST para determinação da carga térmica através de superfícies vítreas" Relatório de Convenio PUCPR/ELETROBRÁS ECV-934/2003, Dezembro.

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

NFRC, National Fenestration Rating Council. 2001. NFRC 100: Procedure for Determining Fenestration Product U-Factors. Silver Spring, MD.

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.

Siegel R. and Howell J. 2001. "Thermal radiation heat transfer" Taylor & Francis, 4th Edition.

Strobel CS. 2007. "Análise da Transferência de Calor em Superfícies Vítreas" Master dissertation, Pontifical Catholic University of Parana (PUCPR), to be defended in 2007 (in Portuguese).

Wright JL. 1996. "A Correlation to Quantify Convective Heat Transfer between Vertical Window Glazings" ASHRAE Transactions, Vol. 102(1).

Nomenclature

A	absorptance	-
cp	heat capacity	$J.kg^{-1}.K^{-1}$
F	view factor	-
h	convective heat transfer coefficient	$W.m^{-2}.K^{-1}$
k	thermal conductivity	$W.m^{-1}.K^{-1}$
L	glazing thickness	m
q	thermal flux	$W.m^{-2}$
R_n	reflectance of glazing n	-
S	source term	$K.m^{-2}$
t	time	s
T	temperature	K
T_n	transmittance of glazing n	-
x	distance from glazing front surface	m
Greek symbols		
α	thermal diffusivity	$m^2.s^{-1}$
ε	surface emissivity	-
ρ_n	reflection coefficient of glazing n	-
σ	Boltzmann's constant	$W.m^{-2}.K^{-4}$
τ_n	transmission coefficient of glazing n	-
Subscripts		
abs	absorption	
air	air	
back	glazing back surface	
front	glazing front surface	
glz	glazing	
ind	indoor	
ngh	neighbor	
out	outdoor	
rad	radiation	
sys	glazing system	