EFFECT OF INTERNAL LONG WAVE RADIATION AND CONVECTION ON FENESTRATION SIMULATION

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ABSTRACT

This paper presents the results of the first part of a research project. The objective of the project is to solve accurately the heat balance on a single glass window in a moderate climate. This procedure will allow the designer to calculate the main parameters of a fenestration (surface, orientation, overhangs, etc.), minimising the energy consumption for a specific enclosure (including heating, air conditioning and lighting). The main problem which most of existent models present, when trying to make the heat balance for winter conditions in a moderate climate, is that internal convection and long wave radiation are not considered efficiently. For this case, some of the existent models can predict the heat losses with an error of about 50%.

The present study is mainly focused on problems related with the internal long wave radiation calculations, and secondly on the effect of internal convection coefficient on the heat balance. In the present paper, a detailed model to calculate internal radiation is proposed. A comparison between the results obtained using this model and those obtained with other current models is included. The importance of using the right internal convection coefficient on the heat balance of fenestration for this kind of application is also analysed.

The proposed model calculates the internal radiation taking into account the radiation angle factor between the window and the other internal surfaces and the actual temperature of each internal surface. To calculate the temperature of the internal surfaces, the actual long wave radiation balance and the right quantity of solar radiation absorbed by each internal wall is considered.

Nomenclature

A :	Area [m^2].
e :	Thickness of the glass [mm].
$F_{k,l}$:	Angle factor for radiation calculation.
h_{ci} :	Internal convective heat transfer coefficient [W/m^2°C].
h_{cr} :	Combined convection and radiation coefficient. [W/m^2°C].
h_{ri} :	Internal radiative heat transfer coefficient [W/m^2°C].
I :	Solar radiation incident in the window plane (including shading factor) [W/m^2].
q_{lw} :	Heat flow through the window by temperature difference [W/m^2].
q_{ce} :	External convection heat transfer [W/m^2].
q_{re} :	Net radiation heat flow in the external part of the glass [W/m^2].
q_{ri} :	Net radiation heat flow between the glass and internal walls of the room [W/m^2].
t :	Time [s].
T_{ext} :	External air temperature [K or °C].
T_{mrt} :	Mean radiant temperature [K or °C]
T_i :	Internal air temperature [K or °C]
T_w :	Window glass temperature [K or °C]
α :	Absorption coefficient
ρ :	Reflection coefficient [-] and density [kg/m^3].
τ :	Transmission coefficient

1.- INTRODUCTION

In a moderate climate with high level of radiation and not too low temperatures, the daily average heat balance of a fenestration, including solar radiation, and losses produced by the difference of temperature, may be positive, even in winter. If we also consider the consumption of lighting electricity, we can often save energy if we increase the size of the window. In this situation, the right design of a fenestration, including orientation, size and shading (internal and external), may be an excellent opportunity for saving energy in residential and commercial buildings.

For the right design of fenestration, it is necessary to have a good mathematical model. This model must take into account in detail: solar heat gains, losses by difference of temperature, and indoor daylight. There exist very accurate models to calculate solar heat gains [Duffie, J. and Beckman W. 1980] and indoor daylight [Ribero, R. 1988], but most models currently used to calculate heat losses due to temperature differences are not sufficiently precise.

For losses calculations, we find many models based in the U-value of a window [Robinson P. and Littler J. 1993, Curcija et al 1989, Klems J. H. 1989, Sullivan R. et al 1993]. We will see that this kind of models are proper for characterising a window, but not for calculating the heat balance, because they do not consider the influence of the building on the heat balance. Many efforts were made to improve the model of a window itself [Wright, J.L. and Sullivan, H.F. 1994], but not to try to connect the window with the building.

There are also detailed models for window simulations, but very often those models do not consider either the angle factor between surfaces (for long wave radiation), or in which surface the solar radiation is actually absorbed.

There are also, many other kinds of models, with many different characteristics [Alereza T. And Hossli R. I. 1979]. In most cases, the degree of detail of those models is placed between de U-values models and detailed models.

We propose to create a mathematical model that integrates solar transmission, indoor daylight and heat loss by temperature difference through the glass. The precision of the model must be sufficient to simulate accurately the heat balance of a window.

This paper is a first step in the development of this model. The specific objective is to study the influence of internal convective and radiative heat exchange in the heat balance of the window, and to determinate the degree of detail necessary to consider in the physical model of those phenomena.

2.- MATHEMATICAL MODEL

Since a long time ago, we know much more about the thermo-physical behaviour of a window than what we actually apply in current models, even in detailed ones. In the past, the reason to simplify the models was that computational capacity was too small. Another reason was to restrain quantity of data input.

Today, the computational capacity is much higher than what we had some years ago. Unfortunately, this capacity has been mainly used to create very powerful input and output interfaces, but not to improve the physical aspect of the models.

We propose to create a new model, of physical complexity in accordance with current computational capabilities. We do not want to impose restrictions on quantity of data input, because the alternative is laboratory test, whis is much more costly in time and money. Evidently, we do not expect that people use this model for the design of a building (too much data inputs). The application of this model is mainly in the field of research.

The model must allow, as a second step, the easily integration of the effect of internal shading devices and other details of physical problem.

The challenge is to integrate all current physical knowledge, without restriction of computational capability and amount of data input, in a model for accurate calculation of the heat balance of a window. In this paper, we show only the first step, as we explained in the introduction.

2.1.- Heat balance of a glass.

Figure 1 shows the heat balance of a single glass, and is expressed by the equation (1). In this equation, we suppose that internal and external temperatures of surfaces of the glass are the same.

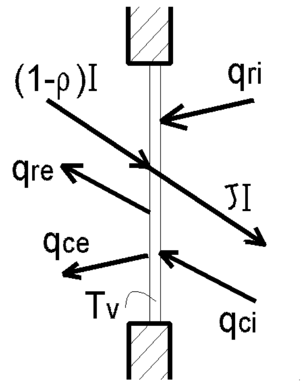

Figure 1. Heat balance of a glass

$$I(1-\rho^{\circ}) + q_{ri} + q_{ci} - I\tau - q_{re} - q_{ce} = \rho ce \frac{\partial T}{\partial t} \qquad (1)$$

$$or, \qquad I\alpha + q_{ri} + h_{ci}(T_i - T_W) - q_{re} - h_{ce}(T_W - T_{ext}) = \rho ce \frac{\partial T}{\partial t} \qquad (2)$$

If we have n internal surfaces, the net heat balance for the surface k (qrik) can be calculated by:

$$q_{ri,k} = \frac{\sigma T_k^4 - J_k}{(1-\varepsilon_k)/\varepsilon_k}$$

where

$$j_k = \varepsilon_k \sigma T_k^4 + (1-\varepsilon_k)\sum_{l=1}^{n} F_{k,l} J_l \qquad (3)$$

We have a system of n equations (J_1, J_2, . . J_n) which must be solved simultaneously.

For external long wave radiation, we can simplify the calculation if we suppose that we have only 2 surfaces; one surface is the window (suffix: w) and the other surface (suffix: 2) is a fictive surface that has a fictive temperature called mean radiant temperature ($T_{mrt,e}$), where:

$$T_{mrt,e}^4 = \sum_{l=1}^{n} T_l^4 F_{W,l}$$

and

$$q_{re} = \frac{\sigma(T_W^4 - T_{mrt,e}^4)}{\frac{1}{\varepsilon_W} + \frac{A_W(1-\varepsilon_2)}{A_2\varepsilon_2}} \qquad (4)$$

In this case, we have (n-1) real surfaces expressed by one fictive surface (2).
If we suppose that $A_w << A_2$,then

$$q_{re} = \sigma\varepsilon_W (T_W^4 - T_{mrt,e}^4) \qquad (5)$$

We can also suppose that $T_{mrt,e} = T_{ext}$, then we can write:

$$q_{re} = \sigma\varepsilon_W (T_W^4 - T_{ext}^4) \qquad (6)$$

$T_{mrt,e} = T_{ext}$ is a good assumption for a cloudy sky. In other conditions, is better to consider the fictive temperature of the sky in $T_{mrt,e}$. In this study, we use the simplest formulation, because it does not influence the conclusions. But, in the future, it is necessary to ameliorate this part of the model.

The equation 6 can be linearized, and q_{re} can be expressed by:

$$q_{re} = \varepsilon_W \sigma(T_W^4 - T_{ext}^4) \approx h_{re}(T_W - T_{ext}) \qquad (7)$$

where

$$h_{re} = 4\sigma\varepsilon((T_W + T_{ext})/2)^3 \qquad (8)$$

In most cases (when $[T_w\text{-}T_{ext}]<15°C$), the error produced by this simplification is lower than 0.1%; in extreme conditions for this kind of application (when $[T_w\text{-}T_{ext}]$ 50°C), the error is about 0.6%.

We can combine external convection with long wave external radiation, and we obtain:

$$q_{ce} + q_{re} = h_{cre}(T_W - T_{ext}) \quad with \quad h_{cre} = h_{ce} + h_{re} \qquad (9)$$

Using precedent equations, we can rewrite the equation of balance. In this equation, we have neglected the variation of internal energy of the glass.

$$I\alpha + q_{ri} + h_{ci}(T_i - T_W) - h_{cre}(T_W - T_{ext}) = 0 \qquad (10)$$

where q_{ri} is calculated by the system of equation (3).

Equation (10) must be solved using a numerical procedure to find T_w . Having T_w, we can calculate the heat loss for the window (q_{lw}) using equation (11):

$$q_{lW} = h_{cre}(T_W - T_{ext}) \qquad (11)$$

Equations (3), (10) and (11) are used in the present model. The following equations show other simplifications currently used in other models. We will use the next simplifications to determinate the level of the error induced when we use those simplifications.

2.1.1.- Simplifications to the model

Internal radiation can be expressed by an equation similar to equation (4). In this case, the surface 2 is a fictive surface taking into account all internal surfaces ($T_{mrt,i}$). If we suppose that A_w<<A_2 (in most cases $A_w/A_2 < 0.1$) then we have:

$$q_{ri} = \sigma \varepsilon_W (T_{mrt,i}^4 - T_W^4) \qquad (12)$$

Equation (12) can be linearized too, and we find:

$$q_{ri} = h_{ri}(T_{mrt,i} - T_W) \quad where \quad h_{ri} = 4\sigma\varepsilon_W((T_W + T_{mrt,i})/2)^3 \qquad (13)$$

Evidently, the use of mean radiant temperature and linearized radiation concept are not new. In this paper, we study those concepts because we want to know which is the level of error when this formulation is used.

Using equation (10) and (13), we avoid a numerical method to find T_w, and we can calculate T_w directly by the equation (14).

$$T_W = \frac{I\alpha + h_{ri}T_{mrt,i} + h_{ci}T_i + h_{cre}T_{ext}}{h_{ri} + h_{ci} + h_{cre}} \qquad (14)$$

In this case, h_{ri} and h_{re} depend on T_w. Usually, with only 1 iteration it is possible to find a very good approximation of T_w. Another way, is to use a fixed h_{ri} and h_{re}, based on standard temperatures.

Another approximation used is to impose: $T_{mrt,i}$ T_i. Using $h_{rci} = h_{ri} + h_{ci}$, and imposing also =o, it is possible to calculate directly q_{lw}, without calculating T_w, using the well known equation:

$$q_{lW} = U(T_i - T_{ext}) \quad where, \quad U = \frac{1}{h_{cri} + h_{cre}} \qquad (15)$$

We will see later that the use of the film coefficient (convection + radiation) is not a good solution for this application, because the assumption $T_{mrt,i}$ T_i is not true, ant the error could be big. The use of a film coefficient where $T_{mrt,i}$ T_i does not produce many error, but it is not interesting because is not a real simplification of the problem.

Table 1 shows a summary of the models considered.

Table 1. Summary of the models considered.

Name of the model	Equations	Comments
Model A	(3), (10) and (11)	Most detailed model presented in this paper.
Model B1	(10), (11) and (12)	Calculation of internal radiation using a T_{mrt} calculated with angle factors.
Model B2	(10), (11) and (12)	Calculation of internal radiation using a T_{mrt} prorated by areas of each surface.
Model C	(11), (13) and (14)	Internal radiation linearized.
Model D	(15)	Model using U total concept.

2.2.- Secondary components of the model

To use the Model A, we must know accurately the internal surfaces temperatures. The present model, solves numerically the unidimensional conduction equation for each wall.

The internal long wave radiation between the walls is calculated using the same procedure as used for the window, i.e. solving numerically the system of equations (3). Internal convective heat transfer coefficient is calculated using the Alamdari and Hammond model [Dascalaki et al. 1994].

Considering the sun position, the present model computes the percentage of direct solar radiation, passing through the window and effectively absorbed by each internal wall. The distribution of diffuse solar radiation in internal walls is calculated using the angle factor between the window and each internal wall. In a first step, it is not considered the internal reflection of incident solar radiation, i.e. it is supposed =1 (only for solar radiation and not for long wave radiation).

3.- DATA INPUT FOR SIMULATIONS

Using the model presented previously, it is presented in this section the simulation of several types of rooms and the calculation for different typical conditions.

3.1.- Room geometry.

Figure 2 shows the geometry of the room considered in the calculation. It is the typical office in a building. All the simulations were performed using almost the same geometry. The only parameter modified of this geometry was the size of the window. We used a small window of 0.8 m^2 or a big one of 5.7 m^2.

This room has only one external wall (where the window is placed). Other walls are internals ones.

3.2.- Nature of construction considered in simulations.

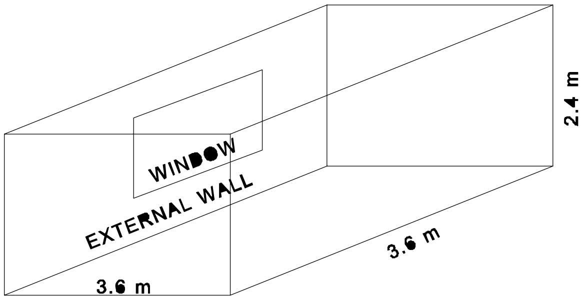

Figure 2. Geometry of the room considered in simulations

We consider 6 kinds of constructions (typical of Chile):

- Common brick (20 cm).
- Timber wood without isolation and wooden floor.
- Timber wood without isolation and concrete floor.
- Timber wood with 5 cm. of expanded polystyrene and floor of wood.
- Concrete (30 cm) and tiled floor.
- Concrete (30 cm) and floor composed of 2.5 cm of wood and 1 cm of woolen carpet.

3.3.- Boundary conditions

Boundary conditions for the external wall are meteorological conditions measured in Concepción city (-36° latitude, Chile). For our analysis, we consider results of one day simulation; but before obtaining the result, it is repeated several times the simulations within the same day. This procedure permits of approach to the actual initial conditions.

We consider two different days for the simulation. One day is a mean winter day, and the other one is a typical cloud free winter day. Both days are obtained from real meteorological data for Concepción. Main parameters of the days considered are summarized in table 2.

Table 2. Summary of meteorological conditions considered.

	mean day	free cloud day
Mean temperature of the day	8.9 °C	9.0 °C
Maximal temperature of the day	13.2 °C	15.4 °C
Minimal temperature of the day	4.6 °C	3.5 °C
Total daily solar radiation over an horizontal surface	8000 kJ/m^2	11200 kJ/m^2

The temperature of other rooms, having a common wall with the room, is considered fixed. We use alternatively 21 C and 8 C for different simulations.

3.4.- Heating control

The room is considered to have an ideal heating control, which maintains the inside temperature at 21°C, but air conditioning is not present. That means that when, due to solar gains, the temperature of the room rises over 21°C, the heating is turned off, and the program calculates the balance temperature (over 21°C) for each time step.

3.5.- Other parameters considered

Other parameters considered on simulations and values assigned are:
External wall orientation (North. West)
Internal convection coefficient (Alamdary model. 50% of reduction from Alamdary model. Fixed = 3.0 W/m^2°C. Fixed = 4.0 W/m^2°C)
Internal distribution of solar radiation passing through the window (Calculated. Fixed 1/5 for each wall)

We performed the calculations using all of the models individualized in table 1 (Model A, B1, B2, C and D).

4.- RESULTS

Before analysing the results of the model, we will analyse the effect of the error of $T_{mrt,i}$ and h_{ci} on q_{lw}, using Model C. We found that for an error of 1°C on $T_{mrt,i}$, the error on q_{lw} is 1.7% when the external temperature is -30°C, and 5.7% when the external temperature is 10°C (near the mean winter temperature for the climate considered). So, the right consideration of internal long wave radiation is much more important for template climates than for cold climates. For the h_{ci} coefficient (using Model C) we found that an error of 1 [W/m^2°C] in h_{ci}, produces an error of 10% on the q_{lw}.

The next paragraphs show some results of simulations. They only represent conditions indicated in part 3.

4.1.- Effect of internal convective heat transfer coefficient.

The results of simulations, shows that only due to difference of temperature between air and surfaces, h_{ci} varies from 0.08 to 4.1. Ranges of daily mean values and hourly mean values of hci are shown in Figure 3 for different surfaces. We can see that if it is not considered the temperature difference between air and surfaces, it is only possible to have an h_{ci} fixed, and therefore the error may be high.

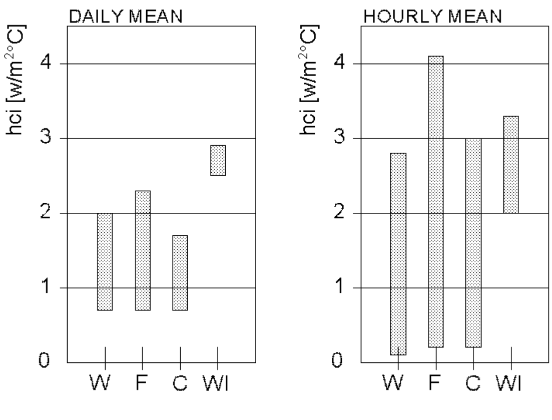

Figure 3. hci for different surfaces obtained in simulations.

W: means Walls, F means Floor, C means Ceiling and WI means Window.

The calculation shows that a 50% of error on h_{ci} (which is frequently possible considering the Figure 3), the error on q_{lw} varies from 6 to 15% (for different cases simulated). Errors on h_{ci} could be bigger than 50%. There are some special cases (for example when an internal shading device is present), in which the uncertainty on h_{ci} for the window could be 100% or bigger.

4.2.- Influence of the internal radiation and internal surfaces temperatures on the heat balance of a window.

If it is considered that the mean value for h_{ci} is about 2 [W/m^2°C], and that the h_{ri} value is about 5 [W/m^2°C], it is possible to conclude that h_{ri} is preponderant in the heat balance of the window.

The temperature of the surfaces, is the main parameter affecting the calculation of internal heat radiation for a window. Obviously, if it is not used a well representative value of the temperature, the error on internal radiation heat transfer could be very high.

There are several parameters which have an influence on inside surfaces temperature. The influence of some of them on q_{lw} is analysed. In next results, the parameters of windows are not modified, and the variation on q_{lw} is only due to the variation on internal surfaces temperature and its effect on internal radiation exchange.

The temperature of the air in the other side of internal walls has the main influence on the internal temperature of the wall. Comparing the mean daily temperature of internal surfaces for a room where the air temperature of the other side of the internal wall is 21°C (heated space) with a room where the air temperature of the other side of internal wall is 8°C (not heated space), it is found a difference of about 6°C. This difference of temperature produce a difference in q_{lw} of about 35% and a difference of about 50% on net heat balance of a window. Therefore, a model in which it is not considered if the adjacent space is heated or not (or a window model disconnected of the building), could produce an error, only for this concept, of about 50% in the heat balance of a window.

The nature of construction is another factor influencing the internal surfaces temperature. Simulations performed show that we can find a difference of about 4°C, on daily mean value of internal surfaces temperature for 2 different types of construction. This variation of temperature produces a variation on q_{lw} of about 25%. This value is obtained when we use a little window. For larger size of windows, the difference is yet bigger, but results of simulations are more difficult to analyse, because for some periods of the day, the internal temperature rises over 25°C and this is not a realistic condition in winter.

If we compare a concrete room having a tiled floor, with another concrete room having a floor with a carpet, daily average value of q_{lw} does not change very much. We only find a significative difference for hourly values. Those hourly differences produce a maximal difference of about 7% for small windows and about 10% for big ones.

The precedent analyses show the error if some parameters of the building are not considered in the simulation. The next analyses, show the error, if those parameters are considered, but with some simplifications in the internal long wave radiation model.

4.3.- Analyses of error using some simplifications for the long wave radiation model.

When we use Model B1 instead of Model A, the error on daily mean value of q_{lw} is smaller than 1% (2% maximum for hourly mean values), if emissivities of surfaces (for long wave radiation) are higher than 0.9. In cases where there exist one or more surfaces with emissivities lower than 0.9 we recommend to use the Model A.

If a linerlized model is used (Model C), maximal differences on q_{lw} with respect to Model B1 are about 0.2%.

The error produced by calculating a $T_{mrt,i}$ as mean temperature of internal walls (averaged by areas) (Model B2), instead of using an angle factor (Model B1), is about 7% of q_{lw}.

The error produced by considering a uniform absorption on internal surfaces of the solar radiation passing through the window (averaged by area), compared with appropriate calculation, is not higher than 2% of q_{lw} for all the simulations performed.

The error on q_{lw} produced by a model that consider only a fixed U-value for the window (U=6.8 [W/m^2°C]) (Model D) varies from 0.1% to 65% for different simulations performed.

Those errors are daily mean values. The behaviour of hourly error is erratic. For some cases the hourly error is uniformly shared on the day, and for other cases there are many differences of the error from a certain hour to another. Figure 4, shows an example of distribution of q_{lw} during a day, using 3 different models.

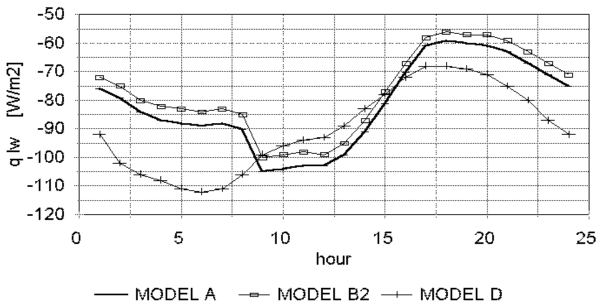

Figure 4. Distribution of qlw during a day.

5.- CONCLUSIONS

The same window can have a very different behaviour, depending on the specific room where it is placed. The heat losses (q_{lw} i.e., U-value) can change very much from one room to another. Therefore, standard U-Value must be used only for comparison between windows and not for calculating the heat losses.

The heat balance of a window must be done with a quite accurate model. Current simplified models are not recommended for this kind of application, because the error is too high and it is almost impossible to conclude anything.

An accurate model must consider in detail, the internal convection and radiation. In this paper, it is proposed to use the Model A. The Model C must give an acceptable result too for most of the practical applications. Internal convection factor h_{ci}, must be calculated using the best model available.

This paper was focused on the proper utilization of q_{ri} and h_{ci} , but we must take into account that other parameters, as shading factor, external convection, external long wave radiation with the sky, solar radiation on windows plane, etc.; are also very important for the heat balance of a window.

Preliminary results show that, in some cases, it is possible to reduce the heating load increasing the area of some well orientated windows. This conclusion is a motivation to create a very accurate model that allows optimization of the main parameters of windows.

The complexity of the model is not a problem today. We have at our disposal a sufficient computational capability to increase many times the complexity of currently used model.

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