

INVESTIGATING GLAZING SYSTEM SIMULATED RESULTS WITH REAL MEASUREMENTS

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ABSTRACT

Over the past decades there has been a great deal of research related to simulation programs that calculate glazing thermal performance.

In this study, several glazing systems were designed using VISION 3 (University of Waterloo, 1992) and WINDOW-6 (Lawrence Berkeley National Laboratory, 2010). The systems were fabricated and experimentally tested in-situ for a summer month.

It was found that in most cases the predicted results of the glass temperature matched those measured, though slight discrepancies were observed during periods of high solar radiation, particularly for more complex systems and systems with shading devices.

INTRODUCTION

Predicting the heat gain or heat loss from a fenestration (glass façade) system is ultimately dependent upon the calculation of the glass surface temperature. In other words, after the physical properties of glass (conductivity, absorption, reflection, and transmittance) are accounted for with respect to the environmental conditions (solar radiation, wind and external/internal air temperatures) we can determine the glass' surface temperature. Once the temperature is calculated, it is possible to calculate the amount of heat transfer from, or to, the glazing by conduction, convection and radiation (Duffie and Beckman, 2005).

In theory, this should be quite straight forward, however, glass computational heat transfer is dependent upon steady state algorithms (Ismail and Henriquez, 2003), which work best under constant ambient conditions. The argument for applying a steady-state model originally stems from the assumption that glazing materials have minimal resistance to thermal conduction and have little thermal mass or heat capacitance.

However, with the advent of advanced double and triple glazing as well as laminated thicknesses, insulated glass (IG) units with inert gasses and selective surface materials for low emissivity or high solar reflectivity it could be argued that glazing systems have changed dramatically (Freire et al, 2011). As such, there is a need to assess if the assumptions associated with steady state analysis

hold true and determine if computational models based on this assumption are still valid.

Glass Performance Identifiers

In order to appreciate glazing simulation package outputs it is necessary to understand what these actually are and how they are defined. The 'instantaneous' transfer of heat to and from a glazing system is represented by three components as illustrated in Figure 1 (Luther, 1995).

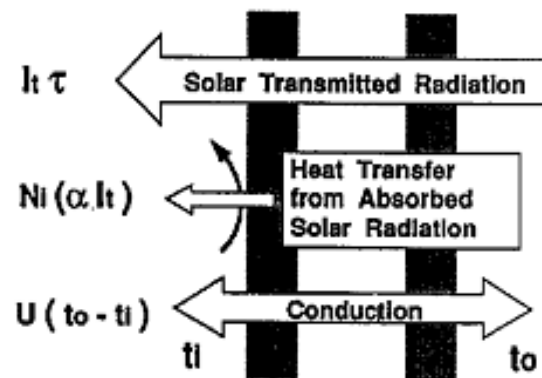


Figure 1 Components of the instantaneous heat gain through glazing

The overall transfer of heat can then be described by Equation 1:

$$q_A = I_t \tau + N_i (\alpha I_t) + U (t_o - t_i) \quad (1)$$

where:

q_A = the total inward heat gain through the glass (W/m^2)

I_t = incident solar radiation available on the exterior glass (W/m^2)

τ = the fraction of I_t which is directly transmitted through the glass

N_i = inward-flowing fraction of absorbed solar radiation (0.267 is the standard for DSA glass)

α = fraction of I_t which is absorbed within the glass

U = total thermal conductance of the glazing unit ($\text{W/m}^2\text{K}$)

t_o = the exterior (ambient) air temperature (K)

t_i = the interior air temperature (K)

The coefficients of the first and second terms on the right hand side of equation 1, $(I_t \tau + N_i(\alpha I_t))$, represents the Solar Heat Gain Coefficient (SHGC) of the glass. This is the transfer of heat from solar irradiated glass. The last term on the right hand side $(U(t_o - t_i))$ represents conductive heat transfer through the glass considering air temperature differences between the interior and exterior, only. Therefore if the interior and exterior air temperatures (to both sides of the glazing unit) are equal the conductive term reduces to zero allowing only the heat gains due to solar radiation to be observed (see Figure 1).

The U-value is the overall heat transfer coefficient (W/m^2K) of the glazing unit and includes the conduction resistance the internal and external convection resistance. For IG (insulated glass) units this includes the layers of glass and the cavities' (air or gases) thermal resistance.

The SHGC consists of two components; the transmitted solar (visible) and the inward-flowing (thermal/infrared) fraction. The transmitted portion can be easily measured with a solar pyranometer on either side of the glass. However, the inward-flowing fraction is dependent on the emissivity of the glass and so cannot be as readily measured.

Finally, the Shading Coefficient, indirectly part of Figure 1, is a ratio of the Solar Heat Gain Coefficient (SHGC) of a specific glazing unit to that of a standard DSA glass (a clear architectural glass 3mm thick). In other words, the SHGC of a DSA glass equals unity (1.0). Usually all other tested glazing systems are less than unity when compared to a DSA glass. Therefore, low SC's are an indication of the glazing systems capability to reduce incident solar heat gain transfer into a building.

PROBLEM DESCRIPTION

The rationale for undertaking this study lies in a poorly performing façade of an east facing commercial office building in a refurbished wool-store (Figure 2). The office consists of a three-metre floor-to-ceiling single glazed façade with a selective mirror-faced external coating and a heat absorbing glass. The occupants sitting near this façade often complained of extreme thermal discomfort during periods of high solar radiation and hot weather.

As such, the building occupants were interested in investigating the existing façade system and possible solutions to the problem using in-situ measurements of the facade performance together with external weather and solar parameters.



Figure 2 Glazed facade of office building

In light of the problem, three alternatives were proposed to help remedy the issue:

- A shading screen fabricated from a protruded 3-D micro-screen, situated on an external frame 50mm from the existing glass facade.
- An argon filled IG unit consisting of a clear glass and a low-e glass mounted on the interior of the existing facade. This solution provides a triple glazed façade with the low-e surface on the cavity side of the interior glass.
- An argon filled IG unit with the middle glass replaced by a heat absorbing grey glass and again forming a tripled glazed system.

SIMULATION DESCRIPTION

To determine the effects of modifying the facade it was decided to utilise two readily available glazing analysis programs:

- VISION 3.0 developed at the Advanced Glazing System Laboratory at the University of Waterloo in Canada (1992) was used to predict the U-Value, SHGC and SC for the proposed systems. Additionally it was used to calculate the glass surface temperatures, absorbed radiation, transmitted radiation, the radiative and convective component of heat flux as well as the transmitted visible/solar ratio.
- WINDOW 6 a package developed at Lawrence Berkeley National Laboratory (2010) for analyzing window thermal performance in accordance with standard NRFC procedures was also utilised in predicting the transient glass surface temperatures in the facade system.

Original Glazing System

The original glazing system consisted of a single layer of tinted glass, the transmittance (τ) and reflectance (ρ) of which are shown in Table 1, for the visible, solar and long-wave spectrums. It is interesting to note that the original glazing system has a high emissivity value on its inner surface. This would suggest that the incident radiation absorbed by the glass would be radiatively transferred to office.

Table 1
Optical properties of single glazed system

Glazing System	Visible		Solar		Longwave Reflectivity	
	$\tau\%$	$\rho\%$	$\tau\%$	$\rho\%$	Outside %	Inside %
	29	17	21	16	16	35

Figure 3 provides a summary of the VISION 3.0 predicted heat gains through the window (for the internal and external temperatures and radiation shown). From this, it can be seen that approximately 20% of the incident radiation (147 W/m^2) is transmitted into the building, corresponding to the solar transmittance.

However more importantly, it shows that the glass absorbs over 60% of the incident solar radiation. This leads to a significant increase in the glass temperature encouraging high rates of convective (C) heat transfer (66.3 W/m^2). Further, the relatively high emissivity of the inner surface results in a large radiative (R) heat transfer rate into the building (77 W/m^2).

What this modelling shows is that original system has a high SHGC and SC. As such heat gains by the building will be high during high radiation times and during colder periods the building will suffer heat losses due to a high U-Value and high emissivity.

In turn if we consider this over a range of conditions (varying radiation, temperature and wind speed) using WINDOW 6, as shown in Figure 4, it can be seen that even at low radiation levels the glass' outside surface temperature may be significantly above the ambient temperature.

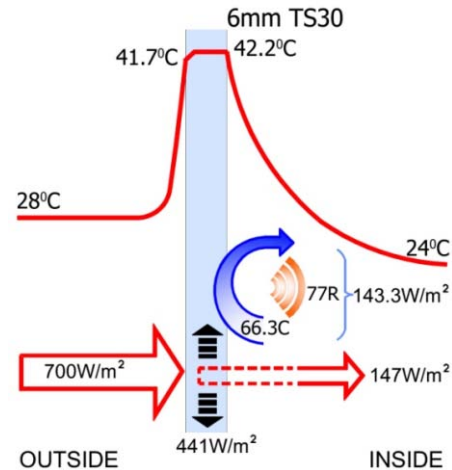


Figure 3 Heat transfer in single glazed system

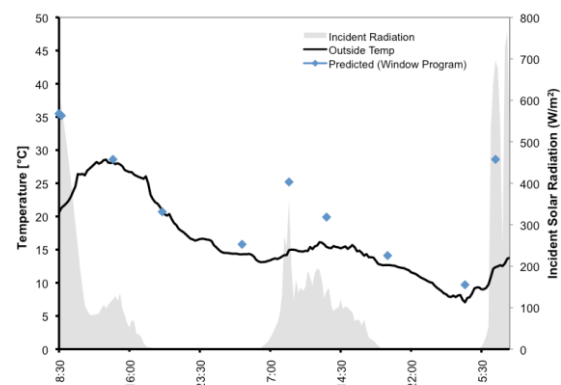


Figure 4 Predicted transient temperature of original single glazed system

Shaded Glazing System

The first proposed solution to overheating of the glazed facade was to provide a shading screen to the exterior of the glass facade. For the shaded glazing system the glass optical properties are the same as for the original glazing system, as the screen as added to the exterior of this. However, for the simulations, it was assumed that the screen would result in an 85% decrease the incident solar radiation reaching the glass.

Under this assumption, Figure 5 shows that by blocking a significant portion of the radiation from reaching the glazing that the glass temperature is substantially reduced from that of the original glazing system. In turn, the total heat gain is about significantly less than the original glass and the inside glass surface temperature nearly 15°C cooler.

The net result of the screen is that the shading screen should lead to improvements in the SHGC and SC. However, the U-Value of the system is still relatively high, as the screen offers no real thermal resistance.

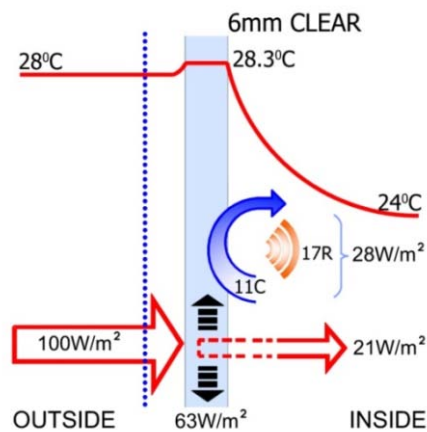


Figure 5 Heat transfer in shaded single glazed system

Clear Triple Glazed System

The second solution that was explored was a retrofit triple glazing unit. In this system, the original glazing was maintained and a double glazed unit, with a clear glass pane forming the middle pane of the triple glazed unit, was fitted behind this on the interior of the building. As such, this new system had varying glass properties between the three layers where the new middle and interior layers had high values of visible and solar transmittance and low values of visible and solar reflectance as shown in Table 2.

Due to the use of a low-e coating on the outside of the interior layer of glass the surface has a high longwave reflection compared to the rest of the high emissivity surfaces.

Table 2

Optical properties of clear glass triple glazed system

Glazing System	Visible		Solar		Longwave Reflection	
	$\tau\%$	$\rho\%$	$\tau\%$	$\rho\%$	Out %	In %
Clear Triple Glazed						
Tinted Glass:	29	17	21	16	16	35
Clear Glass:	87	7	77	7	16	16
Low-E Glass:	82	10	66	22/10	84	16

Figure 6 illustrates the clear triple glazed systems, with this triple glazed system it can be seen that a high amount of the incident radiation is absorbed in the outside layer of the glass. This means that the interior surfaces absorb very little radiation and therefore the inside glass temperature is much lower than the original system. In this system about 10% of the incident radiation is still transmitted, but because of the lower temperature of the internal pane, heat gain due to convection and radiation into the room are significantly less. On this basis the overall system should perform better than the original system.

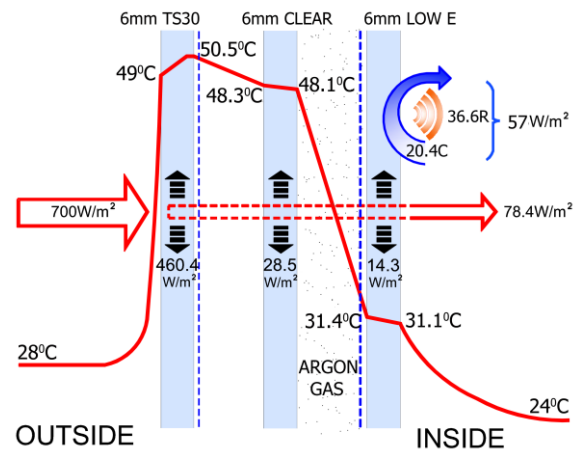


Figure 6 Heat transfer in clear triple glazed system

Moreover, the clear triple glazing should have a much lower U-Value, SHGC and SC than the original glazing system meaning that it is reducing heat gain when ambient temperatures are hot and heat loss when ambient temperatures are cold.

Grey Triple Glazed System

The third solution that was explored was another retrofit triple glazing unit. Again, in this system a double-glazed unit, with a grey glass pane forming the middle pane of the triple glazed unit, was fitted behind the original glazing on the interior of the building. Table 3 shows the glass properties for the three layers, where the grey middle layer has low visible and solar transmittance compared to the clear glass in the previous system. The interior glass however was still a clear low-e glass, meaning high longwave reflectance on the outside of the interior glass.

Table 3

Optical properties of grey glass tripled glazed system

Glazing System	Visible		Solar		Longwave Reflection	
	$\tau\%$	$\rho\%$	$\tau\%$	$\rho\%$	Out %	In %
Grey Triple Glazed						
Tinted Glass:	29	17	21	16	16	35
Grey Glass:	32	10	29	8	16	16
Low-E Glass:	82	10	66	22/10	84	16

Figure 7 illustrates the grey triple glazed system simulation results. In this system the middle grey glass layer absorbs a significant fraction of the remaining radiation through the outside layer. This results in a low absorption on the inside layer as a result of the low amount of transmitted radiation (<5%). However, the absorption by the grey glass leads it to having a higher inside temperature than the clear triple glazed system and so a high rate of

radiant heat transfer to the low-e pane. This leads to the inner pane having a higher temperature thereby resulting in a higher convective and radiant heat gain from the inside pane to the office space.

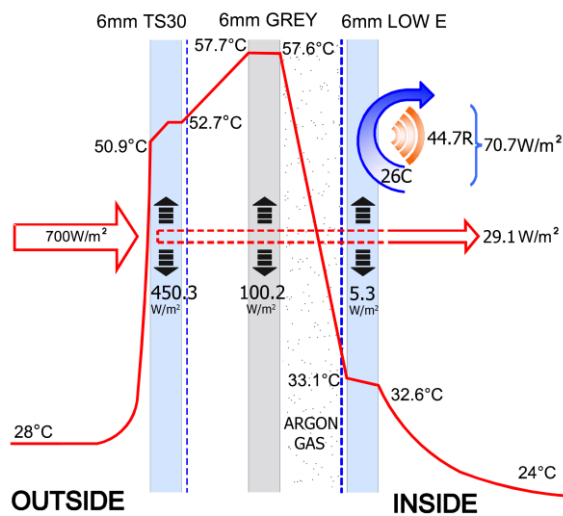


Figure 7 Heat transfer in grey glass triple glazed system

In summary, this type of triple glazing should have lower values of SHGC and SC than the clear IG unit described previously but a higher U-Value due to the radiant properties of the grey layer of glass allowing more outward heat loss.

EXPERIMENTAL SET-UP

In order to further explore the findings from the model it was decided to conduct an in-situ experimental assessment of the three alternative glazing systems in conjunction with the original system.

A weather station was assembled on the roof of a building adjacent to the office. This station consisted of a pyranometer measuring global radiation on a horizontal plane, a HMP35C Temperature/Relative Humidity Probe and a cup anemometer to determine wind speed. This data was logged at 15-minute intervals using a CR10X Campbell Scientific data logger.

Additionally a pyranometer, was mounted on the facade of the building to measure the solar radiation incident on the windows. An array of calibrated ($\pm 0.3K$) light gauge T-type thermocouples, prepared for solar exposure as suggested by Liu (1988) were used to measure the temperatures ($\pm 0.3K$) at various locations within the glazing systems, as shown in Figure 8. Further radiant asymmetry sensors were placed approximately 500mm from the inside glazing to measure the radiant heat gain or loss from the windows.

Additionally a 1221 Bruel & Kjaer Comfort Meter was used to measure the interior glass surface temperature, dry and wet bulb temperature, mean

radiant temperature, absolute humidity, air velocity and the radiant asymmetry within the office.

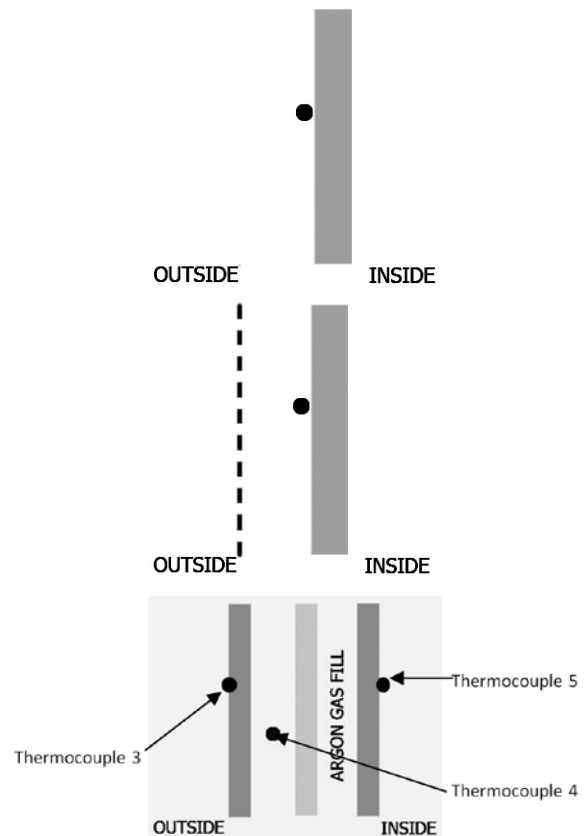


Figure 8 Location of temperature measurements on original system, shaded system, triple glazed system (top to bottom)

RESULTS AND MODEL VALIDATION

Having undertaken instantaneous design calculations and experimental measurements of the performance of the different glazing systems, it was decided to explore the effectiveness of the steady state modelling tools under transient conditions.

Therefore, the experimentally measured incident solar radiation, ambient temperature, wind speed and internal air temperature for a range of conditions were input into WINDOW 6. Figure 9 and 10 shows that there was good correlation between the modelled and measured temperatures on the inside and outside of the original glazing system.

The largest variation between the results typically comes about when there was high incident radiation for the outside of the original glazing system, and so maximum error from the solar exposed thermocouple junctions (circled). However, under most conditions the results deviate by less than 5% variation between the predicted and measured.



Figure 9 Predicted v Measured Glass Temperatures Outside Surface of Original Glazing System

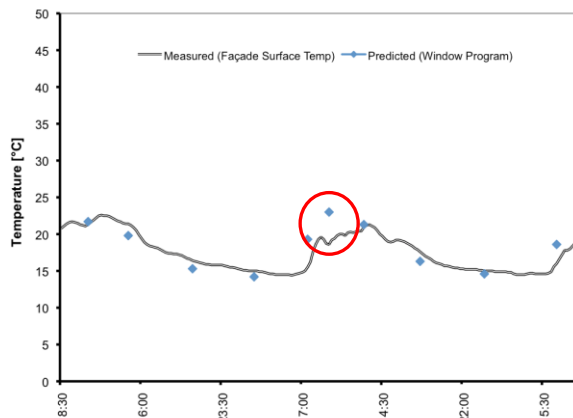


Figure 10 Predicted v Measured Glass Temperatures Inside Surface of Original Glazing System

Similarly, Figure 11 shows good correlation of the inside glass surface temperature of the clear triple glazed system, for most conditions. This suggests that even for multilayered glazing systems, steady state models are able to achieve a relatively satisfactory correlation with reality ($R^2 \sim 0.73$).

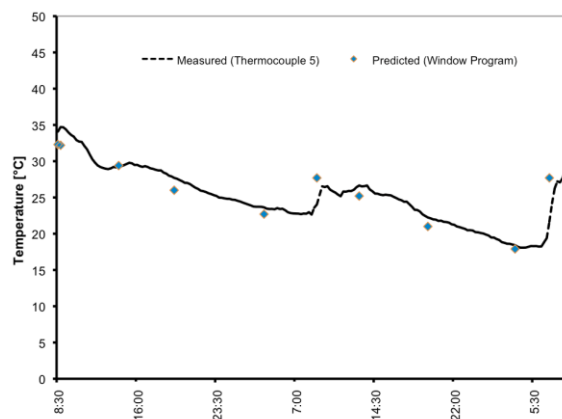


Figure 11 Predicted v Measured Glass Temperatures Inside Surface of Clear Triple Glazing

Now, for most conditions Figure 12 shows good correlation of the outside glass surface temperature of the shaded glazing system. However, the measured results suggest that the shading was blocking more radiation than the woven shade model in WINDOW 6 predicted.

The reason for this may be due to the optical characteristics of the shade screen examined here, which is three dimensional as opposed to the simple two-dimensional structure in the WINDOW model. This complex structure could lead to significant variation in the transmittance through the screen over a wide range of incidence angles.

In turn this leads to poor prediction of the radiation transmitted by the screen and hence the glazing temperature. It should however be noted that the shading models used in WINDOW 6 are for research purposes as they are still awaiting validation (Lawrence Berkeley National Laboratory, 2011).

The variance between the model and measured is particularly pronounced (circled in Figure 12) when the beam component of the radiation is large (typically high radiation). This is a result of the geometric properties of the screen leading to significant filtering of the incident radiation. Without having the transmittance variation with incident angle properties incorporated into the models, it is essentially impossible to achieve good correlation under high beam radiation situations and this needs further consideration in the development of the WINDOW shading database.

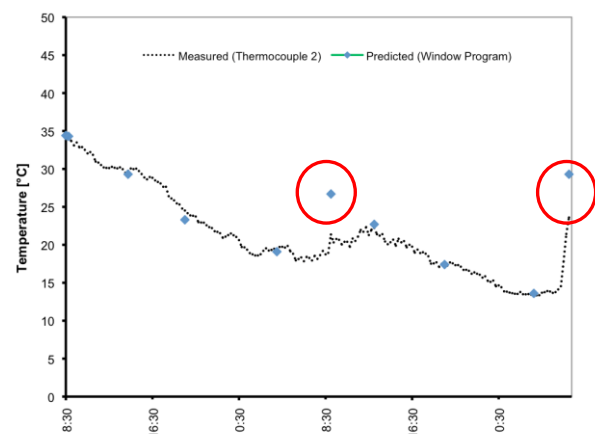


Figure 12 Predicted v Measured Glass Temperatures Outside Glass Surface of Shaded Glazing System

CONCLUSION

The work here is the beginning of an exploration as to how glass facades perform in situ. The interest is in understanding heat transfer in a range of systems; from simple single glazed systems to complex glazing systems with novel shading elements and how and by what mechanisms they transfer heat. More importantly, there is a desire to explore whether these can be determined through modelling. In this regard, measurement and instrumentation techniques are a first step in revealing the modes of heat transfer.

This study illustrated the results of glazing thermal performance from calculation and in measurement. It focused on the verification of measured results with that of simulation. The study found that while it is relatively easy to calculate the total heat transfer

through a glazing system, there is a need to break this down into its components of transmittance, radiation and convection.

Moreover, though the simulation models do provide a relatively good prediction of glazing temperatures for common glazing arrangements. There is significant disparity when more complex shading systems are incorporated into facades. In particular complex shading systems (screens) that block solar exposure are significantly dependent on optical property information, with respect to angle of incidence, that has yet to be incorporated into the standard models.

In achieving this, further work should be undertaken to ensure that the use of shading elements in glazing models that are subsequently incorporated into larger building energy models do not lead to over estimation of heat gain as well as heat loss.

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REFERENCES

- Duffie, J.A. and Beckman, W.A., 2006, "Solar engineering of thermal processes", Wiley, New York
- Freire, R.Z., Mazuroski, W., Abadie, M.O. and Mendes, N., 2011, "Capacitive effect on heat transfer through building glazing systems", *Applied Energy* (In Press) doi:10.1016/j.apenergy.2011.04.006
- Ismail, K.A.R and Henriquez, J.R., 2003, "Modeling and simulation of a simple glass window", *Solar Energy Materials and Solar Cells*, 80, 355-374
- Luther M.B., 1995, *A Dynamic Evaluation of Glazing Thermal Performance*, A dissertation in Architecture at the University of Michigan, UMI Ann Arbor Michigan
- Lawrence Berkeley National Laboratory, 2010, <http://windows.lbl.gov/software/window/window.html>
- Lawrence Berkeley National Laboratory, 2011, <http://windows.lbl.gov/software/window/6/index.html> [cited 11/8/2011]
- Liu, S.T., 1988, "Temperature measurement of glass subjected to solar radiation", *ASHRAE Transactions*, 94 (2), 1359-1369
- University of Waterloo, 1992, *VISION 3.0, Glazing System Thermal Analysis*, Advanced Glazing System Laboratory, University of Waterloo, Waterloo