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Analysis of the Solar Radiation Distribution and Passive Thermal Response of an Attached Solarium/Greenhouse

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ABSTRACT

This paper presents a detailed model for the distribution of solar radiation and the transient thermal response of a solarium/greenhouse. The objective is to optimize the geometrical configuration to obtain the highest air temperature inside the solarium for the coldest period in Montreal (latitude of 45 N). In this study, a combination of ray tracing and radiosity methods are used to calculate the solar radiation absorbed by interior surfaces. Then a detailed transient thermal analysis using heat balance method is performed to simulate the passive thermal response of the solarium/greenhouse. Solar radiation absorbed by interior surfaces and inside air temperatures for various roof tilt angles and interior surfaces absorptances are presented. Although a solarium design with a roof slope of 65° does not always absorb the maximum solar radiation, this configuration experiences the highest minimum and maximum indoor air temperatures.

1. INTRODUCTION

The addition of a solarium/greenhouse attached to a house is a promising design option that can be implemented in both retrofit and new buildings to provide additional high quality space with abundant solar radiation levels. Such a space may improve the appearance of the building and reduce the heating requirements of a house (Mihalakakou, 2000). However, an improper design may raise the energy consumption of the building (Bryn & Schiefloe, 1996) or lead to frequent overheating and high temperatures that are not acceptable either for people or plants growth.

It was found (Kumar *et al.*, 1994) that for the same glass area, the south glass oriented at the optimum angle for a given latitude gives better thermal comfort compared to a vertical south glass or a combination of vertical and tilted glass. This is caused by the decreasing solar radiation transmittance of glazings as the angle of incidence increases. Therefore, more solar radiation will be transmitted with a glazing tilted so that the solar angle of incidence at noon is closer to normal than for vertical glass.

In temperate climates, greenhouses are used to grow vegetables in winter. However, many of them are used year round, even if there is no need for extra heat in summer. Therefore, a greenhouse should be designed to maximize solar radiation penetration in winter but to limit it in summer when the sun and heat are abundant. To maximize annual solar radiation collection, a solar collector should be facing the equator with a tilt angle close to its latitude. However, for a greenhouse, solar radiation is more needed in winter than in summer, therefore the tilt angle of the roof should be higher than the latitude to increase the transmittance when the sun is low and decrease it when the sun is high.

Temperature fluctuations inside a glazed space rise with increasing glazing area (Kumar *et al.*, 1994). In addition, only 30%-90% of the transmitted radiation is retained in a highly glazed space (Wall, 1995). Therefore, it is not necessary nor desirable to have glazing on all sides. Having an opaque and insulated north wall will retain more radiation inside the space and reduce heat losses. Besides glazing area, temperature fluctuations are also influenced by the presence of thermal mass: temperature fluctuations decrease with the addition of thermal mass (Kumar *et al.*, 1994). Consequently, the insulated north wall becomes a privileged location for thermal mass.

Gupta and al. (2003) analyzed the effect of different greenhouse shapes on the weighted solar fraction of the north partition wall. Their results showed that the weighted solar fraction was higher for an even span shape than for uneven shape at latitudes of 13°-34°. Although of some interest, the weighted solar fraction of the north wall is not the most appropriate variable to optimize: solar radiation incident on the floor is as useful as the radiation incident on the wall,

contributing to photosynthesis when absorbed by plants and thermal load levelling when absorbed by the floor.

Wall (1997) showed that simulation programs reveal important differences in the calculation of solar gains of glazed spaces. Simpler simulation programs that do not calculate accurately the solar radiation distribution overestimate significantly the absorbed solar radiation. This work emphasizes the importance of using a detailed method for the calculation of solar radiation distribution of highly glazed space.

It was shown (Wall, 1995) that for a rectangular room with double glazing on the south, east, west and roof façades and on 20% of the north wall, the percentage of transmitted radiation retained in a sunspace varies between 20%-65%, depending of the absorptivity of the opaque surfaces. However, these calculations were conducted with monthly average values of solar radiation and transmittance of glazing at normal incidence, therefore the influence of incidence angle on transmittance is not captured.

Glazing area, along with its thermal conductance and solar transmittance are the key parameters that determine net solar heat gains and heat losses for a solarium. The goal of this study is to analyze the solar radiation distribution and the thermal response of a solarium/greenhouse in order to determine the optimum geometrical configuration. The main parameters evaluated in this study are the roof tilt angle of the solarium and the absorptance of its interior surfaces.

2. MATHEMATICAL MODEL

2.1 Transmission of Solar Radiation

The solar radiation transmitted through the atmosphere is simulated using the Hottel clear sky model (1976). An empirical correlation developed by Liu and Jordan (1960) is used to estimate the diffuse atmospheric transmittance. The solar radiation incident on a surface is calculated with equations (7)-(9) presented in the appendix.

The glazing considered in this study is a double glazing with a 13 mm air gap (no coatings are considered). The solar radiation transmitted though glazings is calculated from fundamental physical principles like Snell's law and Fresnel's equations for unpolarized light. At every time step (6 mn), the radiative properties of the glazing are calculated as a function of the angle of incidence. The equations used to calculate the transmittance and absorptance of the glazing are given in the appendix. The diffuse transmittance of the glazing is assumed to be equal to the beam transmittance at an angle of incidence of 60° (Duffie & Beckman, 2006).

2.2 Solar Radiation Distribution

The solar radiation distributed inside the solarium is simulated by combining ray tracing and radiosity methods. Firstly, the transmitted beam solar radiation is distributed on interior surfaces using ray tracing techniques by calculating the area of a window illuminating directly the surface. The transmitted beam radiation illuminating a portion of a surface is assumed to be uniformly distributed on that surface; likewise, each surface is assumed to be at uniform temperature. The reflected component after direct solar radiation is incident at a surface is treated as diffuse and is distributed with a radiosity method, along with the transmitted diffuse solar radiation.

To find the portion of a window which is illuminating directly a surface, the coordinates of that surface need to be projected onto the window plane along the sun ray employing a homogenous coordinate method. The window area illuminating the surface is then equal to the overlapping area between the window and the image of the surface in the window plane. A method to calculate the homogenous coordinates and the area of overlapping convex polygons is given in Walton (1979).

The procedure developed by Athienitis (1985, 1991) for determining the solar radiation absorbed by interior surfaces of the room is followed. The total beam radiation $S_{b,i}$ absorbed by a surface *i* is given by

$$S_{b,i} = \alpha_i G_b f_{w,i} + A_i \sum_j \frac{F_{ij}^d \rho_j G_b f_{w,j}}{A_j}$$
(1)

where α_i and A_i are the absorptance and area of surface i, $f_{w,i}$ is the part of the window area illuminating directly surface i, F_{ij}^d is a transfer factor and ρ_j is the reflectance of surface j. G_b and G_d are the transmitted beam and diffuse solar radiation respectively. The transfer factor F_{ij}^d is the fraction of diffuse solar radiation emitted by surface j which is absorbed by surface i. Note that the first term of equation (1) represents the beam radiation absorbed directly by surface *i* while the second term represents the beam radiation absorbed as diffuse radiation after many reflections. The diffuse solar radiation $S_{d,i}$ transmitted through the window (*w*) and absorbed by surface *i* is calculated with

$$S_{d,i} = A_i G_d F_{i,w}^d \tag{2}$$

2.3 Calculation of heat transfer coefficient

Radiative heat transfer between surfaces is characterized by the linearized radiation coefficient (Duffie & Beckman, 2006), which is given by

$$h_r = \frac{\sigma \left(T_2^2 + T_1^2\right) (T_2 + T_1)}{\frac{1 - \epsilon_1}{\epsilon_1} + \frac{1}{F_{12}} + \frac{(1 - \epsilon_2)A_1}{\epsilon_2 A_2}}$$
(3)

where σ is the Stefan-Boltzmann constant, T_i , ϵ_i and A_i are the temperature, emissivity and area of surface *i* respectively. Radiative properties of surfaces are assumed to be independent of wavelength (gray surfaces). Correlations developed by Khalifa and Marshall (1990) for the calculation of the convective heat transfer coefficient on interior building surfaces are employed. For a vertical glazing (with no radiator under the window), a vertical wall and a horizontal surface (facing upward), the convective heat transfer coefficient may be estimated with

- Vertical glazing $h_c = 7.61 (\Delta T)^{0.06}$ (4a)
- Vertical wall $h_c = 2.03 (\Delta T)^{0.14}$ (4b)Horizontal surface $h_c = 2.27 (\Delta T)^{0.24}$ (4c)

where ΔT is the temperature difference between the surface and the air. The convective coefficient due to wind effect on buildings is calculated by using the recommended equation given in Duffie and Beckman (2006, p. 166)

2.4 Configuration of the Greenhouse/Solarium and Input Parameters

The passive thermal response of the solarium/greenhouse is simulated from basic equations characterizing conductive, radiative and convective heat transfer. Numerical simulations are based on a transient lumped parameters heat transfer model; this model enables accurate simulation of transient effects induced by thermal mass. A finite difference thermal network formulation is used to solve equations at each node *i*:

$$T_{i,t+1} = \frac{\Delta t}{C} \left(q_i + \sum_j (T_{j,t} - T_{i,t}) U_{ij} \right) + T_{i,t}$$
(5)

where j represents all nodes connected to i, Δt is the time step, C is the capacitance, q_i is a heat source at node i and U_{ij} is the overall conductance between nodes *i* and *j* (W/K). The greenhouse is equipped with an Earth to Air Heat Exchanger made of two rows of pipes buried in a two meters deep soil thermal storage. The air is circulating continuously in the pipes at an air speed of 1m/s. Each row is made of six pipes with a diameter of 10 cm distributed along the length of the greenhouse. The thermal storage is divided into five lumped capacitances and the pipes into four control volumes. The transient effect of the back wall, which consists of 20 cm of concrete, is also modelled. The temperature in the house is assumed to be constant at 20°.

The greenhouse is heavily insulated with insulation of the side walls and foundations set to $6 \text{ m}^2\text{K/W}$ and to $4 \text{ m}^2\text{K/W}$ for the bottom of the thermal storage. A thermal screen with a U value of $3 \text{ W/(m}^2\text{K})$ is drawn on all glazings when there is no solar radiation. The outside temperature is modelled by a sinusodal function with a mean of -10° and an amplitude of 5° , maximum at 3 pm and minimum at 3 am. The infiltration rate is assumed to be equal to 0.5 air changes per hour. Thermal simulations are performed for several clear days until steady-state condition is reached.

3. RESULTS AND DISCUSSION

Figures 1 and 2 depict an attached solarium with a roof tilt angle of 45° and 65° respectively. For Montreal, the highest heating load occurs typically in January. The process design should be oriented toward the objective to optimize greenhouse performance for that period. Consequently, the following simulations are conducted for January 15th. At that moment, 65° is the optimal slope to maximize solar radiation transmission for a latitude of 45° . Figures 3 and 4 show the distribution of solar radiation for a greenhouse with a roof tilt angle of 45° and 65° respectively for an absorptance of the interior opaque surfaces α of 0.7.



Figure 1: Attached solarium with a roof tilt angle of 45°.



Figure 3: Absorbed and transmitted solar radiation for an attached solarium with a roof angle of 45° on January 15th.



Figure 2: Attached solarium with a roof tilt angle of 65°.



Figure 4: Absorbed and transmitted solar radiation for an attached solarium with a roof angle of 65° on January 15th.

For a constant floor area, increasing the roof tilt angle reduces the total glazed area from 67.3 m^2 for a roof tilt angle of 45 (Figure 1) to 63.2 m^2 for a roof tilt angle of 65 (Figure 2). This could lead to a reduction of total transmitted radiation. However, since 65° is the optimal slope for January 15th, the transmitted radiation per unit of glazed area is enhanced. Many variables can be analyzed to qualify the performance of sunspaces regarding their solar radiation collection. Because glazed surfaces are driving heat losses, their use should be limited; this is why the absorbed radiation per unit of glazed area is an interesting indicator linking the solar radiation collection and the thermal performance of a sunspace. Moreover, the solar collection property S is often employed to characterize the performance of glazed space (Wall, 1995, Bryn & Schiefloe, 1996). It is defined as the ratio of the absorbed solar radiation to the radiation transmitted through the glazings

$$S = \frac{\text{absorbed solar radiation}}{\text{transmitted solar radiation}}$$
(6)

This variable depends highly on the positioning on the glazed versus opaque surfaces and their view factors. A low solar collection property may indicate that too many surfaces are glazed so that a lot of the incoming radiation is retransmitted outside.

3.1 Effect of Absorptance and Roof Tilt Angle on Solar Radiation Collection

Figures 5, 7 and 9 show the total solar radiation absorbed by the interior surfaces of the solarium and transmitted to the house for a roof tilt angle varying between 25° and 65°. Because light transmission from the solarium to the house is beneficial, it was included in the total absorbed radiation. All interior opaque surfaces have the same absorptance which varies between 0.5-0.9. For absorptances of 0.5 and 0.7, a solarium with a slope of 35° absorbs the maximum radiation while a slope of 65° absorbs significantly less. This is caused by two reasons: first, less radiation is



Figure 5: Total radiation absorbed by interior surfaces - α =0.5.



Figure 7: Total radiation absorbed by interior surfaces - α =0.7.



Figure 9: Total radiation absorbed by interior surfaces - α =0.9.



Figure 6: Total radiation absorbed by interior surfaces per unit of glazed area - α =0.5.



Figure 8: Total radiation absorbed by interior surfaces per unit of glazed area - α =0.7.



Figure 10: Total radiation absorbed by interior surfaces per unit of glazed area - $\alpha{=}0.9.$



International High Performance Buildings Conference at Purdue, July 12-15, 2010

transmitted with increasing roof angle because of a reduction in glazing area; second, more radiation is reaching the back wall with increasing tilt angle while the view factor between the back wall and the roof is simultaneously increasing therefore more light reflected by the back wall is lost through the glazed roof. However, the absorbed solar radiation is maximal for a slope of 65° for an absorptance of 0.9.

The total absorbed solar radiation per unit of glazed area is presented in Figures 6, 8 and 10. For all absorptances, the tilt angle of 25° absorbs the less radiation per unit area, followed by the tilt angle of 35° . At high absorptance (0.7-0.9), the absorbed radiation per unit area increases with increasing roof tilt angle.

As can be seen from Figures 11, 13 and 15, for tilt angles of 25° and 35° , the solar collection property is lower early and late in the day. This is because at that time, for these tilt angles, a portion of the glazed roof is illuminating the glazed south façade, increasing the loss of radiation to outside. At low absorptances (0.5 - 0.7), the solar collection property at noon for a roof tilt angle of 65° is significantly lower than for the other tilt angles. However, for an absorptance of 0.9, a roof slope of 65° surpasses the solar collection property of all the other tilt angles.

A reduction of glazing area reduces heat losses by conduction but may also reduce the solar heat gains. A thermal analysis should be performed in combination with the calculation of the solar radiation distribution into the greenhouse to determine the optimum design. Ultimately, the design of an attached solarium should have as objective to optimize its thermal behavior in order to reduce the heating requirements of the house while allowing acceptable indoor conditions for people and plants growth during the daytime.

3.2 Thermal Analysis

Air temperature inside the greenhouse is presented in Figures 12, 14 and 16. The temperature drop/rise at sunrise/sunset is caused by the thermal screen which was removed during the day. It can be seen that a greenhouse with a roof slope of 65° experiences a higher air temperature for all absorptances. Such a roof angle was not always giving the best performance in terms of solar radiation collection, especially for low absorptances. Therefore, these results show that a thermal analysis has to be done in addition to the analysis of the solar radiation distribution (i.e. there is no unique variable quantifying solar radiation collection properties to be optimized to ensure optimum thermal performance). A reduction of glazing area of 16% (from 75.3 m² for a slope of 25° to 63.2 m² for a slope of 65°) increases the minimum air temperature between 3°C to 4°C for absorptances between 0.5 - 0.9. By increasing the absorptance from 0.5 to 0.9, the minimum temperature can be raised by 4°C - 5°C and the maximum temperature can be raised by 6°C - 8°C for all roof tilt angles. The minimum air temperature at night is lower for the solarium with the maximum glazed area and is higher for the solarium with the minimum glazed area.

4. CONCLUSION

The solar radiation distribution and the passive thermal response of various solarium/greenhouse configurations were analyzed in this study. The effects of roof tilt angle of a solarium between 25° and 65° and the absorptance of the interior opaque surfaces varying between 0.5 - 0.9 on solar radiation collection and thermal behavior of the solarium are presented.

It was found that for absorptances between 0.5 - 0.7, a solarium with a roof tilt angle of 25° absorbs the maximum solar radiation while the minimum absorbed radiation is for a tilt angle of 65° . However, at a high absorptance of 0.9, a solarium configuration with a slope of 65° outperforms the other configurations and absorbs the maximum solar radiation. For absorptances comprised between 0.7 to 0.9, a solarium with a roof tilt angle of 65° absorbs the maximum solar radiation per unit of glazed area. For all absorptances, the solarium configuration with the lowest roof tilt angle of 25° absorbs significantly less solar radiation per unit of glazed area than for other configurations. For absorptances between 0.5 - 0.7, a roof tilt angle of 65° results in low solar energy absorptions. However, it outperforms the other configurations for a room interior surface absorptance of 0.9.

Thermal simulations demonstrate that the solarium design with a roof slope of 65° is optimal for Montreal for January which is the critical design period. For absorptances between 0.5-0.9, this solarium design experiences the highest interior air temperature when passively heated during a clear cold day in January. This study demonstrated the importance of analyzing the thermal response of a sunspace in combination with the solar radiation distribution in order to determine the best geometrical configuration of an attached solarium. The next step in the design of an optimization methodology under development is to optimize the thermal storage in conjunction with the operating strategies and active control of solar gains with motorized blinds.

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ACKNOWLEDGEMENT

The first author is thankful to Natural Sciences and Engineering Research Council of Canada (NSERC) for a Canada Graduate Scholarship and to Concordia University for a High-Caliber Ph.D Student Scholarship. In addition, the support from the NSERC Solar Building Research Network (SBRN) is gratefully acknowledged.

APPENDIX: CALCULATIONS OF TRANSMITTED SOLAR RADIATION

For a clear sky, the direct radiation incoming on a surface with an incidence angle θ is computed as the product of the extraterrestrial radiation I_{on} with the atmospheric beam transmittance τ_b and the cosine of the incidence angle:

$$I_b = I_{on} \tau_b \cos(\theta) \tag{7}$$

The sky diffuse solar radiation I_{ds} and ground diffuse solar radiation I_{dq} incident on a surface are given by

$$I_{ds} = I_{on} \tau_d \sin(\alpha) F_{i,s} \tag{8}$$

$$I_{dg} = I_{on} \left(\tau_d + \tau_b \right) \sin(\alpha) \rho F_{i,g} \tag{9}$$

where τ_d is the atmospheric diffuse transmittance, α is the solar altitude and $F_{i,j}$ is the view factor between surfaces *i* and *j*.

For a double glazed window with two identical panes, the effective transmittance (τ_{2g}) as well as the absorbance of the exterior $(\alpha_{2g,o})$ and interior $(\alpha_{2g,i})$ glazing are calculated as follows:

$$\tau_{2g} = \frac{\tau^2}{1 - \rho^2} \tag{10a}$$

$$\alpha_{2g,o} = \alpha (1 + \tau \rho (1 - \rho^2)) \tag{10b}$$

$$\alpha_{2g,i} = \alpha \tau \left(1 - \rho^2 \right) \tag{10c}$$

where τ , α and ρ are respectively the solar transmittance, absorptance and reflectance for a single pane of glass, as a function of the solar angle of incidence θ .