Modeling and Study of the Impacts of Electrically Heated Windows on the Energy Needs of Buildings

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Abstract: - In areas where heating requirements are significant, an innovative solution exists to counter the physical discomforts caused by windows – electrically heated windows. At first sight, installing heated windows would somehow appear not to make sense from an energy standpoint since the initial perception is to think about the energy consumed by a heated window as being dissipated towards the outdoors. In order to examine the effects of an electrically heated window on a building's energy needs, a model was developed and validated. The model is applicable to both conventional and heated windows. Compared to standard double-glazed windows, the model reveals that using heated windows actually reduces the space heating and cooling loads. It also increases the thermal comfort in a building's perimeter zone by preventing cold temperatures on the indoor side of the window from occurring. On the other hand, compared to energy-efficient double pane windows, the results demonstrate a slight increase in the space heating load but a decrease in the needs for air conditioning. Furthermore, in cold climates and from an energy standpoint only, the results demonstrate that it is more advantageous to install a heated window on the north and east (or west) walls of a building as opposed to the south because, among other things, the solar heat gain coefficient (SHGC) of a heated window is lower than that of windows normally used in the building sector.

Key Words: - Electrically heated window, heated glass, comfort, perimeter heating, energy efficiency, thermal loss

1 Introduction

In areas where heating requirements are significant, managing the thermal comfort in the perimeter zone of buildings can be a concern. A building's windows are generally the main culprits. In the wintertime, the cold surface temperature of the windows result in physical discomforts by creating, on one hand, cold drafts and, on the other, a chilly sensation by radiation – not to mention condensation and frost problems on the windows during cold periods. The impacts of windows on a building's comfort level and energy consumption are comprehensively examined in references [1, 2, 3].

High performance windows improve the thermal comfort near the windows. However, in climates where the outdoor temperature is often below -20°C, so-called high performance windows are not sufficient to prevent the negative effects of cold surfaces. For instance, when the outdoor temperature is -18°C, the indoor surface temperature of the glass is in the vicinity of 6°C for a standard double pane window (clear glass + air + clear glass) and in the vicinity of 11°C for an energy-efficient double pane window (clear glass + argon + low-e glass).

To alleviate the discomforts, the usual reaction is to increase the thermostat setpoint, to the detriment of the building's overall energy consumption. In other respects, perimeter heating systems like baseboards or hot air systems are often installed under or near the windows to create a "thermal curtain". These types of systems sometimes result in physical discomfort by creating overheated areas in addition to being sometimes noisy. Managing a building's thermal comfort near the windows by traditional means such as these without addressing the problem at the source is indeed solving the issue in a roundabout way.

From an energy perspective, the ideal solution is to approach the problem at the source. A solution to stop the unpleasant chill caused by windows consists in installing electrically heated windows. A heated window is composed of a conventional double pane window of which the inner pane can be heated by an electrical current. This is not a new technology per se. Heated windows have been used for several years in the refrigeration and transportation industries to prevent frost and condensation. They have also been used in residential and commercial buildings as a heat source and to maintain an appropriate comfort level near the windows.

To date, there is very little documentation on the impacts of heated windows on a building's energy consumption. The efficiency of electrically heated windows has been evaluated in [4] but their annual impact on a building's energy needs was not addressed.

Based on the advantages that could be gained through the installation of electrically heated windows, a research program was launched and conducted by Hydro-Québec's Research Institute. Within this context, a model was developed to predict the thermal performance of conventional and heated windows. This model was used to estimate the impact of the windows on a building's energy needs.

2 Description of the Electrically Heated Window Technology

A typical electrically heated window is double-glazed (see Figure 1) and is very similar to a conventional energy-efficient double pane window. The main difference lies in an additional low-emissivity film on surface # 3 of the heated window. This tin oxide coating acts as a resistor when an electrical current is circulated, allowing to heat surface # 4 to the desired temperature. Electricity is supplied to the tin oxide film by 2 electrodes located on the perimeter of the glass. In order to reduce thermal losses through the window, a second low-emissivity film is applied to surface # 2. This coating however is not powered. In addition and again to reduce thermal losses, the space between the two glass panes is filled with a neutral gas, either argon or krypton.

The temperature of the heated window is monitored by a temperature sensor installed on surface # 4 of the glass. A thermostat modulates the electricity supplied to the window in order to maintain the surface temperature at the desired level.

Common practice is to maintain the heated window temperature in the vicinity of the indoor temperature, e.g. between 20 and 22°C. Typically, a power density of between 90 and 150 W/m^2_{window} is sufficient to maintain a surface temperature that is comfortable when it is very cold outside (-25°C).

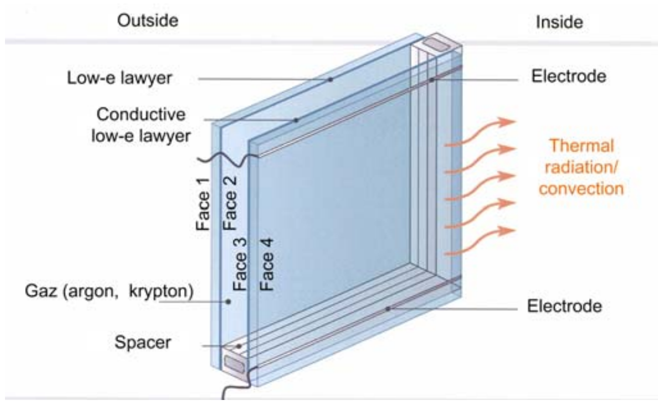

Figure 1: Diagram of a Heated Window

3 Simulation Model

3.1 Description of the Model

The simulation window model that was developed is based on ISO Standard 15099 calculations [5], a standardized method to predict the thermal performance of windows. More specifically, the model computes the thermal performances at the center of the glass. This part of the glass, contrary to its perimeter (edge-of-glass), is not affected by the thermal bridges caused by the spacer and the window frame.

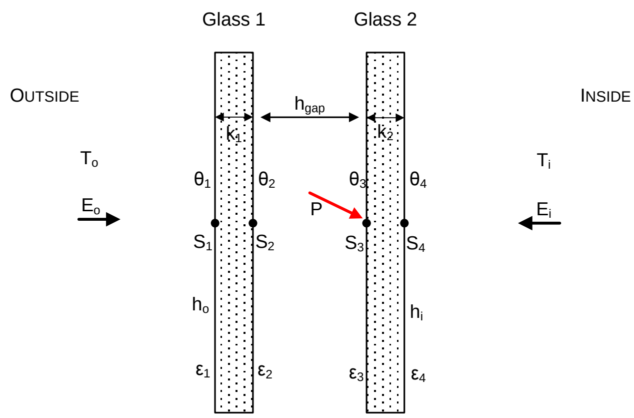

Figure 2: Variables used to determine the thermal balance

The model conducts an energy balance on each of the glass surfaces of the window. Figure 2 shows the variables included in the equation used to determine this thermal balance. The thermal balance for each of the glass surfaces is expressed in the following equations:

$$E_o\varepsilon_1 - \varepsilon_1\sigma\theta_1^4 + k_1(\theta_2 - \theta_1) + h_o(T_o - \theta_1) + S_1 = 0 \quad (1)$$

$$k_1(\theta_1 - \theta_2) + h_{gap}(\theta_3 - \theta_2) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}(\theta_3^4 - \theta_2^4) + S_2 = 0 \quad (2)$$

$$k_2(\theta_4 - \theta_3) + h_{gap}(\theta_2 - \theta_3) + \sigma\frac{\varepsilon_2\varepsilon_3}{1-(1-\varepsilon_2)(1-\varepsilon_3)}(\theta_2^4 - \theta_3^4) + S_3 + P_3 = 0 \quad (3)$$

$$E_i\varepsilon_4 - \varepsilon_4\sigma\theta_4^4 + k_2(\theta_3 - \theta_4) + h_i(T_i - \theta_4) + S_4 = 0 \quad (4)$$

where

T_o is the outdoor temperature (K);
T_i is the indoor temperature (K);
$\theta_1 \ldots \theta_4$ are the surface temperatures of the glass panes (K);
E_o, E_i are the thermal radiative fluxes from the outside (E_o) and from the inside (E_i) (W/m^2);
h_o, h_i are the convection coefficients on the external and internal surfaces (W/m^2/K);
h_{gap} is the convection coefficient between the two glass panes (W/m^2/K);
k_1, k_2 are the thermal conductivities of the glass panes (W/m^2/K);
$S_1 \ldots S_4$ are the solar fluxes absorbed by the surfaces (W/m^2/K);
$\varepsilon_1 \ldots \varepsilon_4$ are the emissivities of each of the surfaces;
P is the electrical power injected to surface # 3 of the heated window (W/m^2);

In equation 3, P represents the electrical power fed to the heated window. In the case of a conventional non-heated window, the term P is set to zero.

The indoor and outdoor thermal radiative fluxes (E) are expressed as follows:

$$E = \sigma * T^4 \quad (5)$$

where σ is the Stefan-Boltzmann constant. For the outdoor sourcing radiation, the T value in equation # 5 is a function of climatic parameters, such as the cloud covering, the dry bulb temperature and the dew point [6]. In the case of the radiation provided by the building's interior walls, the T value in equation # 5 is considered to be the same as the indoor temperature of the room.

The solar radiation absorbed by the glass layer is assumed to be uniformly distributed within the thickness of the glass, so it can be apportioned equally to the two glass surfaces. The solar radiation (S) is expressed as follows:

$$S_1 = S_2 = 0.5 * (I_b * \cos\varphi * \alpha_1(\varphi) + I_d * \alpha_{d,1}) \quad (6a)$$
$$S_3 = S_4 = 0.5 * (I_b * \cos\varphi * \alpha_2(\varphi) + I_d * \alpha_{d,2}) \quad (6b)$$

where

I_b is the beam solar irradiance on the exterior surface of the window (W/m^2);

φ is the incident angle of the direct radiation on the window;
$\alpha_j(\varphi)$ is the absorbance of the jth glass for the incident angle φ;
I_d is the diffuse solar radiation on the window coming from the sky and ground (W/m^2);
$\alpha_{d,j}$ is the diffuse solar absorbance of the jth glass. This value is independent of the solar radiation's incident angle.

The convection coefficients at the glazing cavity (h_{gap}), on the internal side (h_i) and on the external side (h_o) are directly derived from ISO Standard 15099.

The θ_1, θ_2, θ_3, θ_4, and P variables are the unknown factors that must be determined to solve equations # 1 to 4 in the thermal balance process. In the case of a non-heated window, the term P is set to zero and the equations are solved to establish the temperatures θ_1, θ_2, θ_3, θ_4 prevailing on the glass surfaces according to climatic conditions. In the case of an electrically heated window, the operating conditions of the window are determined in two steps. Firstly, the equations are solved by setting P to zero, in order to determine the temperatures prevailing on the glass surfaces based on climatic conditions. If the θ_4 value is higher than the desired temperature on surface # 4 of the heated window, P is set at zero and the θ_1, θ_2, θ_3, θ_4 values are those that are applicable. On the other hand, if the θ_4 value is lower than the desired temperature on surface # 4 of the heated window, the θ_4 temperature is imposed and the equation is solved once again to determine the θ_1, θ_2, θ_3 temperatures and the P value of the heated window, which allows to maintain the θ_4 temperature at the desired value.

In the context of this study, the thermal balance equations for the window were solved with the EES software [7]. This software is a mathematical tool designed to solve large sets of non-linear equations and it allows to easily interchange unknown variables.

3.2 Validating the Model

The model was validated in two steps. Firstly, the results of the model were compared with simulations using the WINDOW™ 5.2a software developed by LBNL [8]. This is a well-established software that can be used as a standard to predict the energy performance of windows. Among the results obtained, the software allows to predict the θ_1, θ_2, θ_3, θ_4 temperatures on the surface of each of the panes of a window. However, it cannot simulate the energy input of an electrically heated window. The validation of the model conducted with the WINDOW™ software therefore addresses conventional non-heated windows and inactive "heated" windows only.

Three types of windows were simulated (Figure 3) for validation purposes.

Window 1: standard double pane
Window 2: energy-efficient double pane
Window 3: electrically heated window

It should be noted that Window 3 had all the features of a heated window. However, for validation purposes, the *P* value of this window was set to 0. Two series of simulations were conducted to compare the results of the model (see Table 1). In the first simulation, the solar gains were set to 0 and only the outdoor temperature was modified. In the second, the simulation was conducted based on different combinations of solar gains and outdoor temperatures. Since WINDOW™ only allows to specify direct solar radiation at a normal angle, the model was slightly modified to take this feature into consideration. Also, the internal and external convective coefficients (h_i, h_o) prescribed by WINDOW™ were imposed directly in the model.

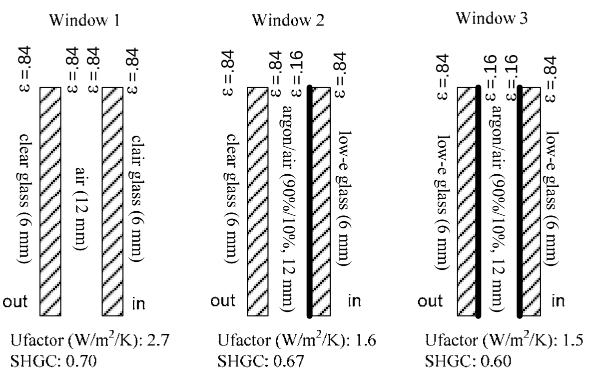

Figure 3: Description of the windows

In other respects, all the optical parameters of the windows (ε, α) incorporated in the model were those specified by WINDOW™ for the corresponding type of glass.

Table 1: Parameters for the validation with WINDOW™

	Series 1 T_i=20°C	**Series 2** T_i=20°C
1	I_b=0 W/m^2 T_o = -15°C	I_b=350 W/ m^2 T_o = -15°C
2	I_b=0 W/ m^2 T_o = -20°C	I_b=700 W/ m^2 T_o = -15°C
3	I_b=0 W/ m^2 T_o = -25°C	I_b=350 W/ m^2 T_o = -25°C
4	I_b=0 W/ m^2 T_o = -30°C	I_b=700 W/ m^2 T_o = -25°C

Figures 4 and 5 show the results of the comparison. They provide the surface temperature θ_4 (expressed in °C) obtained with the model and with WINDOW™. As demonstrated in the two figures, the model predicted surface temperatures that are almost identical to those predicted by WINDOW™ with or without solar radiation. The same exercise was conducted comparing the surface temperatures θ_1 and the conclusions were the same.

This comparison with WINDOW™ demonstrates that the developed model accurately predicts the center of glass performance of passive windows and that there are, at the very least, no flaws in the model.

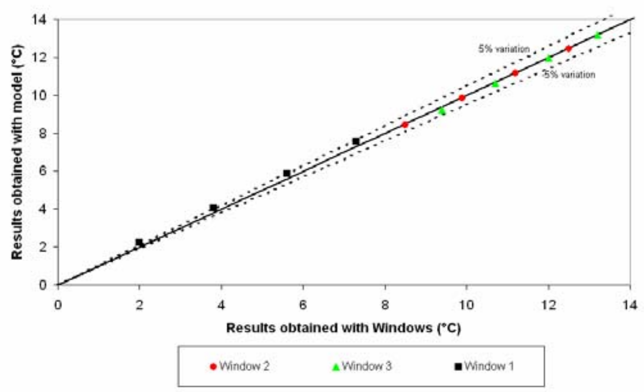

Figure 4: Surface temperature θ_4 obtained with WINDOW™ and with the model (first series of simulations)

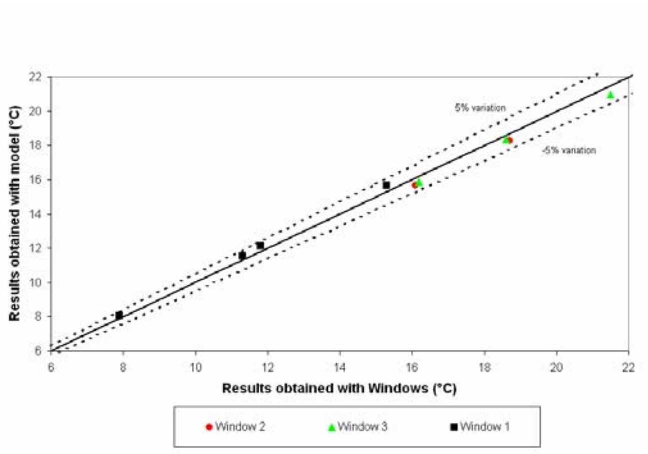

Figure 5: Surface temperature θ_4 obtained with WINDOW™ and with the model (second series of simulations)

In a second phase of validation, the model was compared with experimental results obtained on an electrically heated window based on tests conducted at Hydro-Québec's Research Institute in a dual-climate chamber. In this chamber, the heated window separated a warm room from a cold one. The heated window that was tested had the same characteristics as Window 3 mentioned in Figure 3 and measured approximately 81 cm by 107 cm. The surface temperatures θ_1 and θ_4 as well as the electrical power consumed by the heated window were measured during the tests. In the course of the tests in the dual-climate chamber, the T_o temperature on the cold side of the window was slowly ramped. In addition, the electrical power P of the heated window was kept constant while the temperature θ_4 was free to fluctuate.

For two separate tests, Figures 6 and 7 allow to compare the measured and calculated surface temperatures θ_4 of the heated window. These figures correspond to tests where the power density of the heated window was set to 245 W/m^2. The air temperature T_o and T_i of each test are shown on Figures 6 and 7. In order to simulate the heated window, the only inputs to the model consisted in the air temperatures on the warm (T_i) and cold (T_o) sides and the power density of the heated window (P). As shown on these two figures, the model allows to accurately predict the surface temperature of the heated window. In both tests, the absolute mean deviation between the simulation process and the experimental process was approximately 0.9°C over the entire duration of the tests. The simulations have a tendency to overpredict the experimental temperatures. Generally speaking, the deviation is more significant when the temperature of the air on the cold side is lower. The deviation may be explained by the uncertainty of the estimation of the internal and external convective coefficients. Also, the difference could be attributed to the fact that the model simulated the center of the glass only and that it did not take the edge effects into consideration. These edge effects increase as the outdoor temperature decreases. In the case of large windows, the edge effects are less significant because the surface area of the center of the glass is larger in accordance with the window's perimeter. In the case of smaller windows, the edge effects can be more significant, especially when the window frame is of poor quality and acts as a thermal bridge.

With the exception of edge effects, the results of the validation demonstrate that the developed model is a reliable tool for predicting the energy performance of both conventional and electrically heated windows.

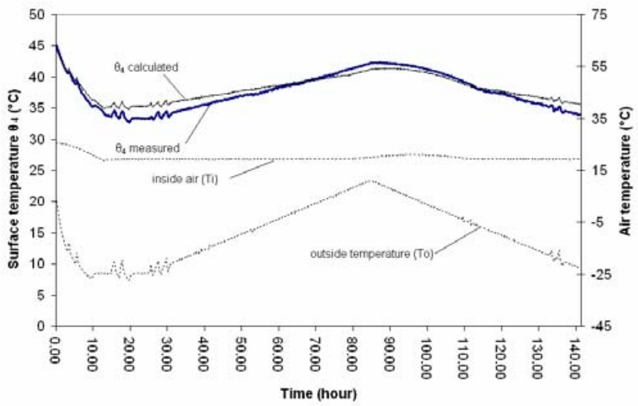

Figure 6: Comparison of the surface temperatures θ_4 calculated and measured during a test on an electrically heated window (Test 1, P=245 W/m^2)

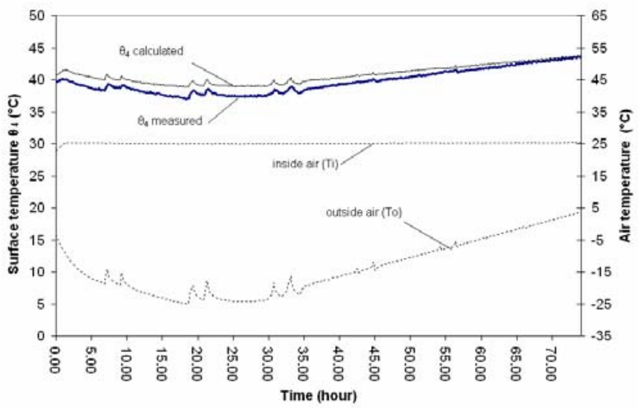

Figure 7: Comparison of the surface temperatures θ_4 calculated and measured during a test on an electrically heated window (Test 2, P=245 W/m^2)

4 Impacts on the Energy Needs of Buildings

4.1 Simulation Parameters

The thermal load incurred by a window is due, on one hand, to the solar radiation (Q_{trans}) that is transmitted through the window and, on the other hand, to the convection/radiation exchanges (Q_4) that occur between the inner surface (#4) of the window and the indoor space. Therefore, the total thermal load Q (W/m^2) incurred by a window is expressed as follows:

$$Q = Q_{trans} + Q_4 \tag{7}$$

$$Q = (I_b * \cos\varphi * \tau(\varphi) + I_d * \tau_d) + (h_o * (\theta_4 - T_i) + \varepsilon_4 * \sigma * \theta_4^2 - \varepsilon_4 * E_i) \tag{8}$$

where

$\tau(\varphi)$ is the window's transmittance according to the sun's incident angle;

τ_d is the window's transmittance for the diffuse solar radiation generated outdoors.

In a first approach, overlooking the heat storage phenomenon that occurs in a room, the Q value obtained in equation 8 represents the heating and cooling loads that must be fulfilled by a building's HVAC system to maintain an indoor temperature at the desired T_i value. In the case of an electrically heated window, the P value of the window must be added to the Q value, in order to take into account all the loads incurred by the window.

To evaluate the impact of heated windows on the energy needs for heating and air conditioning in buildings located in cold climates, an annual weather chart for the Montreal (Canada) area was used. The weather data is provided by the CWEC files (Canadian Weather for Energy Calculation), which gives hourly weather observations representing an artificial one-year period. For information purposes, there are 4,500 heating degree-days in the Montreal area (T_o<18°C).

The simulations were performed with 3 types of windows, the same 3 that are described in Figure 3. The optical properties of these windows, ε, α_d, $\alpha(\varphi)$, τ_d, $\tau(\varphi)$, were as specified by the WINDOW™ software. For the purposes of the study, the heating season was established as being from October 1st to May 1st. During this period, air conditioning systems are always shut down but heating systems and heated windows can be used only if the outdoor temperature is below the balance point temperature, set at 12°C. The cooling season occurs from May 1st to October 1st and, during this period, heating systems and heated windows are deactivated, whereas air conditioning is used when required, if the outdoor temperature is higher than 24°C.

Table 2 shows the simulation parameters that were used to evaluate the energy impact of electrically heated windows on a building's energy needs. In the case of heated windows, the temperature on the surface θ_4 of the glass was set to 20°C during the heating season. It should be noted that, during the heating season, the ambient temperature (T_i) in a room equipped with electrically heated windows is set to 20°C instead of 21°C in a room with unheated windows. This difference in room temperatures is an assumption based on the fact that heated windows improve the thermal comfort in a room's perimeter by reducing or eliminating the radiation exchange between the human body and the indoor glass, which in turn can result in a decrease in ambient temperature, in accordance with the thermal comfort equations [9].

Table 2: Simulation Parameters

	Heating Season		Cooling Season	
	T_i °C	θ_4 °C	T_i °C	θ_4 °C
Window 1	21	-	24	-
Window 2	21	-	24	-
Window 3	20	20	24	-

4.2 Results

For the heating and cooling seasons, Table 3 provides the following information for three orientations and for the three types of windows: 1) energy transfer (ΣQ_4) by convection/radiation between surface # 4 and the indoor space; 2) energy gains (ΣQ_{trans}) due to the solar radiation transmitted through the glass; 3) electrical energy consumed (ΣP) by the electrically heated window; 4) net impact (ΣQ) of the window on the heating or cooling load of the building.

In the case of the heating season, a positive value in Table 3 represents a thermal loss that must be compensated by the heating system, whereas a negative value represents a heat gain that reduces the heating load. Conversely, in the case of the cooling season, a positive value represents a solar gain that must be counterbalanced by the air conditioning system.

Table 3: Energy needs associated with the windows

	Heating season				Cooling season			
	Heat transfer (ΣQ_4)	Solar gain (ΣQ_{trans})	Electric cons. of heated window (ΣP)	Heating load	Heat transfer (ΣQ_4)	Solar gain (ΣQ_{trans})	Electric cons. of heated window (ΣP)	Cooling load
	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh/m²
Window facing north								
Window 1	282	-93	0	189	9	42	0	51
Window 2	159	-80	0	79	12	37	0	48
Window 3	-1	-73	181	107	10	33	0	44
Window facing east								
Window 1	267	-154	0	113	10	47	0	56
Window 2	141	-133	0	8	13	40	0	53
Window 3	-9	-121	170	40	11	37	0	48
Window facing south								
Window 1	239	-312	0	-73	13	57	0	69
Window 2	101	-269	0	-168	16	49	0	65
Window 3	-34	-244	154	-123	14	45	0	59

The results in the table show that the thermal losses Q_4 during the heating season are significantly reduced with a heated window, in comparison with a conventional window. This means that electrically heated windows prevent thermal losses in buildings through the windows and, as a result, that the traditional heating systems normally installed near the windows of a room's perimeter can either be totally eliminated or sized down.

The thermal losses Q_4 through a heated window are low essentially because the difference in the temperature between surface # 4 and the ambient air is low, which is not the case for non-heated windows that are generally colder than the ambient air during the heating season. However, to maintain surface # 4 warm, the heated window consumes electricity during the heating season. But when the reference window is a standard double pane window (Window 1), this electricity consumed by the heated window remains lower than the reduced energy losses through the window. On average and for windows facing any direction, the results in Table 3 show that the electrical consumption of a heated window is approximately 110 kWh/m^2 lower than the reduction in thermal losses it provides over the heating season. On the other hand, when the reference window is an energy-efficient double pane window (Window 2), the electricity consumed by a heated window is higher than the reduced thermal transfers by close to 20 kWh/m^2.

Table 3 also shows that the solar radiation transmitted through windows during the heating season and contributing to the heating of the room is lower in the case of a heated window compared to the other two windows. This can essentially be explained by the different optical properties of the windows. The heated window is coated with two low-emissivity films (surfaces # 2 and 3) and its solar heat gain coefficient (SHGC) is lower than the other windows (see Figure 3). During the heating season, this is a disadvantage for the heated window, especially if it is facing south. However, when the windows are facing towards the north or east, this disadvantage is less significant.

During the cooling season, the low SHGC of a heated window becomes an advantage because it helps to reduce the cooling load by decreasing the solar gains.

Using Window 1 and Window 2 as reference windows, Table 4 shows the net impact of heated windows on the energy needs for heating and air conditioning. The values in this table are directly drawn from Table 3. In this table, a negative value means that the heated window reduces the energy needs as compared to the reference window, whereas a positive value means that the heated window increases the energy needs as compared to the reference window.

Table 4: Net impact of heated windows on heating and cooling loads

Reference window	Orientation	Impact on heating load (kWh/m²)	Impact on cooling load (kWh/m²)
Window 1	North	-83	-8
	East	-73	-8
	South	-50	-10
Window 2	North	28	-5
	East	32	-5
	South	45	-6

This table demonstrates the following:

- Compared to a standard double pane window, an electrically heated window saves heating and air conditioning energy, regardless of the direction it is facing.
- Compared to an energy-efficient double pane window, an electrically heated window increases the heating load, but reduces the cooling load, again regardless of the direction it is facing.
- From an energy standpoint, it is more advantageous to install a heated window facing north and east (or west, assuming it is equivalent to

east) rather than facing south. This is mainly due to the reduction in solar gains transmitted through the window during the heating season.

These observations are conditional upon the operating conditions of the heated windows. More specifically, the results depend upon the surface temperature θ_4 maintained on the heated window. For instance, if the setpoint temperature θ_4 is lowered to about 18°C (instead of 20°C), the results show that a heated window has a negligible impact on the heating loads as compared to an energy-efficient double window.

5 Conclusion

The heated window technology offers many advantages including comfort near the windows, no accumulation of condensation or frost, noiseless heating in perimeter zones, no maintenance and the fact that heated windows do not take up any space. These advantages are the main criteria that would motivate one to install heated windows in a building. However, there is a misconception that the technology increases a building's energy consumption, whereas, in fact, our study's calculations demonstrate that installing electrically heated windows on a building's perimeter does not necessarily incur an increase in the energy consumed. Indeed, compared to standard double pane windows, the results show that using heated windows reduces the energy needs whereas, compared to energy-efficient double pane windows, the results show that heated windows incur a slight increase in energy consumption. Moreover, from an energy standpoint only, the results show that it is more advantageous to install heated windows on the north and east (or west) sides of buildings rather than facing south.

The reader must bear in mind that these conclusions are solely based on the energy balance occurring on the windows. These conclusions do not cover the different side effects associated with the use of heated windows that are also susceptible of having an impact on a building's energy consumption. For example, heated windows can allow to totally eliminate or size down perimeter heating in buildings. In this regard, it has previously been demonstrated that simply sizing down the conventional perimeter heating can result in savings of 10 to 15% on the energy needs for heating [1]. Heated windows also have an impact on the thermal comfort in a room. Indeed, the comfort equations show that the ambient temperature of a room with heated windows can be maintained at a lower level and still remain operationally adequate. In this regard, a lower setpoint temperature reduces the overall energy losses that occur through the whole thermal envelope of a building by infiltration, ventilation and conduction during the heating season.

The side effects associated with the installation of electrically heated windows must be taken into consideration for a comprehensive evaluation of their real impact on energy needs. To further study the impact of heated windows on the energy needs of buildings, it would therefore be useful to incorporate the window model presented in this study into a simulation model that includes more of the dynamics of a building.

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