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Exergetic Review on Thermal Performance of Window Systems

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Abstract

According to an advancement of exergy research in relations to thermal comfort and built environment for the last fifteen years, the availability of "warm" or "cool" radiant exergy emitted by the interior surfaces of building envelope systems is crucially important in providing building occupants with adaptive opportunity for thermal comfort both in summer and in winter. This paper demonstrates some numerical examples showing how the thermal performance of window systems affects the availability of "warm" and "cool" radiant exergies. In winter, thermal insulation of window systems together with appropriate internal solar control brings about ten to twenty times larger "warm" radiant exergy, while in summer external shading of window systems reduces "warm" radiant-exergy emission towards the indoor environment by more than 80% comparing to internal shading device, and allows the built environmental space to be filled with "cool" radiant exergy emitted by other interior surfaces of building envelopes.

Keywords: Warm and cool exergies, long-wavelength radiation, solar radiation, shading devices, emission

1 Introduction

The evaluation of indoor thermal environment in relations to thermal comfort of building occupants and also the estimation of the amount of fossil fuels for running space heating and cooling systems are usually made with the concept of energy, that is the first law of thermodynamics. They allow us to learn much, but it is not sufficient because of providing us with nothing about what we should learn from the second law of thermodynamics.

Over the last fifteen years or so, concerned building scientists, architects, and engineers have gradually recognized the importance of low-temperature heating and high-temperature cooling systems, which should be successful with a full use of advanced passive-system technology together with reformed and hence advanced active-system technology.

The performance of such systems and also their resultant built environment can be well evaluated with the concept of "exergy", which is derived from both, the first and the second laws of thermodynamics, together with the concept of environmental temperature for a system in focus. This is, I think, probably very much associated with the adaptive physio-psychological characteristics of human being(Shukuya, 2013).

In this paper, the exergetic characteristics of window systems as part of building envelope systems are demonstrated and thereby reviewed in order to confirm what is required in the pursuit of low-exergy system solutions, with which adaptive opportunity for thermal comfort should be more easily available.

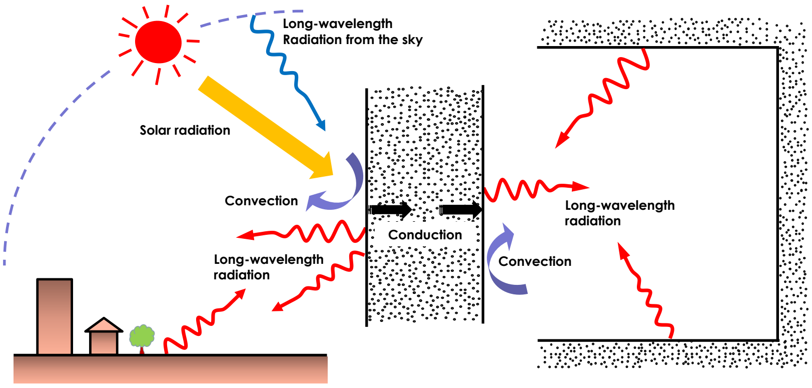


Figure 1. Thermal exergy transfer within an external wall by long-wavelength radiation, convection, and conduction. Solar exergy transfer is by short-wavelength radiation.

2 Warm and cool exergy transfer within the built environment

As schematically presented in **Figure 1.**, solar radiation, that is a kind of short-wavelength radiation, absorbed by the wall surface may cause the rise of surface temperature and thereby as its consequence the wall surface may emit thermal exergy by long-wavelength radiation. All of the adjacent surfaces of other building walls, the sky, and the pavement surface may also emit thermal exergy by radiation whose portion is absorbed by the wall surfaces. The same phenomenon apply to the room space surrounded by interior surfaces of wall, ceiling and floor.

Wind blowing along the exterior side of the wall sweeps away some amount of thermal exergy by convection. Along the interior surface of the wall, there is usually not such movement of air as strong as wind outdoors, but there is always a subtle movement of air upwards or downwards due to buoyancy caused by temperature difference between the interior surfaces of walls and room air in their respective vicinities.

Such thermal exergy transfer by radiation and convection outdoors and indoors influences on the variation of external and internal surface temperatures, but the conduction of thermal exergy inside wall and windows does also influence on the variation of external and internal surface temperatures.

In short, there are always three types of thermal exergy transfer: thermal radiation; convection; and conduction. Understanding of their exergetic characteristics is essential in order to plan, design, and realize low-exergy systems for human thermal health and comfort to be sought in the built environment.

2.1 Exergy balance equation

As we all know by our everyday experience, the absorption of solar radiation by materials yields “warmth”. One example is that we feel “warmth” or “hotness” in particular if we wear a dark-coloured shirt or sweater, when we are outdoors under a sunny condition. Another example is that you feel “warmth” by touching a part of floor or wall surface, on which solar radiation transmitting through the nearby windows is incident. In these cases, a portion of solar exergy is necessarily absorbed, consumed, and thereby “warm” exergy is generated.

We can set up an exergy balance equation for a system that absorbs solar radiation. Let us focus on the innermost layer of a window system, as shown in **Figure 2.**, as a thermodynamic system. We assume that the layer is infinitely thin so that we neglect

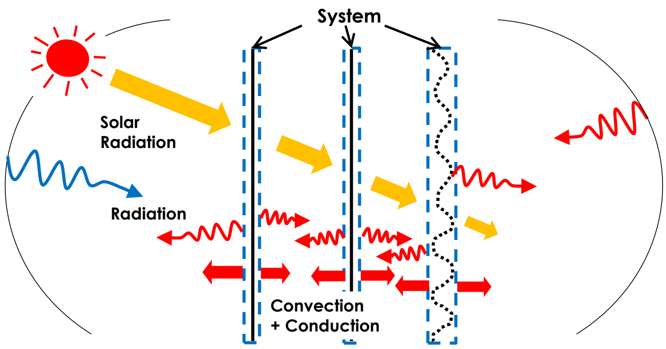


Figure 2. Window system consisting of three layers. Each of the layers can be regarded as a thermodynamic system. Whether a system assumed is opaque, transparent, or translucent, some amount of solar exergy is absorbed, consumed, and thereby thermal exergy is transferred to the surrounding space either by the emission of long-wavelength radiation, by conduction, or by convection. The system also absorbs thermal radiant exergy coming from surrounding surfaces.

the heat capacity. Then, the exergy balance equation can be set up in general as follows, assuming that thermal exergy transfer by convection and conduction are from the system to the surrounding space.

[Solar exergy absorbed] + [Thermal radiant exergy absorbed]

- [Exergy consumed within the system]

= [Thermal radiant exergy emitted]

+ [Thermal exergy transferred by convection to the surrounding]

+ [Thermal exergy transferred by conduction to the surrounding] (1)

2.2 Warm and cool radiant-exergy emission

Thermal radiant exergy emission rate from a surface, whose temperature is T_{isw} in the unit of Kelvin can be expressed by the following equation.

$$x_r = \varepsilon h_b \frac{(T_{isw} - T_o)^2}{T_{isw} + T_o}, \tag{2}$$

where ε is the surface emittance, h_b is radiative heat-transfer coefficient of blackbody [W/(m^2·K)], and T_o is the environmental temperature in Kelvin. Due to the fact that $0 < \varepsilon$, $0 < h_b$, $0 < T_{isw} + T_o$, and $0 < (T_{isw} - T_o)^2$, the radiant exergy is necessarily larger than zero except a case that the surface temperature equals the environmental temperature. For the cases of $T_o < T_{isw}$, there is "warm" radiant exergy emission and for the cases of $T_{isw} < T_o$, there is "cool" radiant exergy emission.

In eq.(1), its first term of right-hand side is exactly calculated by eq.(2). The second term of left-hand side of eq.(1) is also calculated by eq.(2), but in this case T_{isw} is replaced with the surrounding surface temperature, T_{rm} , and then the surface emittance being equal to absorptance is further multiplied to thermal radiant exergy given by eq.(2).

2.3 Warm and cool exergy transfer by convection

Let us focus on the boundary layer between the innermost layer and room air, as shown in **Figure 3**. We assume a case that room air temperature, T_{ia} , is higher than that of the innermost layer, T_{isw}. For this boundary layer, we can derive the following exergy balance equation.

$$x_{cv\_ia} - x_c = x_{cv\_isw}, \tag{3}$$

where x_{cv_ia} is the rate of exergy transferred from room air to the boundary layer [W/m^2], x_c is the exergy-consumption rate within the boundary layer [W/m^2], and x_{cv_isw} is the rate of exergy transferred into the innermost layer [W/m^2]. These three terms are expressed as follows.

$$x_{cv\_ia} = h_{cv}(T_{ia} - T_{isw})\left(1 - \frac{T_o}{T_{ia}}\right), \tag{4}$$

$$x_c = s_{gcv} \cdot T_o, \tag{5}$$

$$x_{cv\_isw} = h_{cv}(T_{ia} - T_{isw})\left(1 - \frac{T_o}{T_{isw}}\right), \tag{6}$$

where h_{cv} is convective heat-transfer coefficient [W/(m^{2}K)] and s_{gcv} is the entropy generation rate[W/(K·m^2) = Ons/(s·m^2)].

Taking a look at both eqs.(4) and (6), the rate of exergy flow by convection can be either positive or negative depending on the relationships between three temperature values of T_o, T_{isw}, and T_{ia}. Because of three variables, there are six combinations, which are different in whether a given exergy value implies “warm” or “cool” and also in whether it implies “outgoing” or “incoming”.

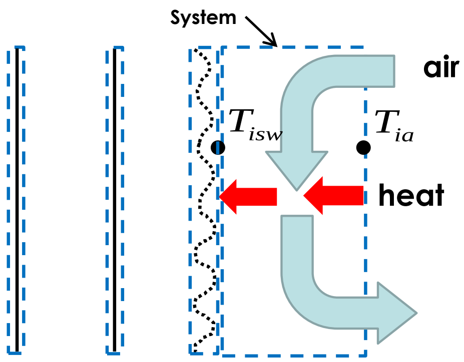


Figure 3. Heat transfer due to convection of room air taking place within the boundary layer adjacent to the innermost layer of a window system.

Table 1. Convective warm or cool exergy represented by eq.(4) flowing into the system of boundary layer near the innermost layer of window system

	Temperature	$a = T_{ia} - T_{isw}$	$b = 1 - \frac{T_o}{T_{ia}}$	$a \cdot b$	Warm/ Cool	In/ Out
I	$T_o \le T_{isw} < T_{ia}$	+	+	+	Warm	In
II	$T_o < T_{ia} \le T_{isw}$	–	+	–	Warm	Out
III	$T_{isw} < T_o \le T_{ia}$	+	+	+	Warm	In
IV	$T_{ia} \le T_o < T_{isw}$	–	–	+	Cool	In
V	$T_{isw} \le T_{ia} < T_o$	+	–	–	Cool	Out
VI	$T_{ia} < T_{isw} \le T_o$	–	–	+	Cool	In

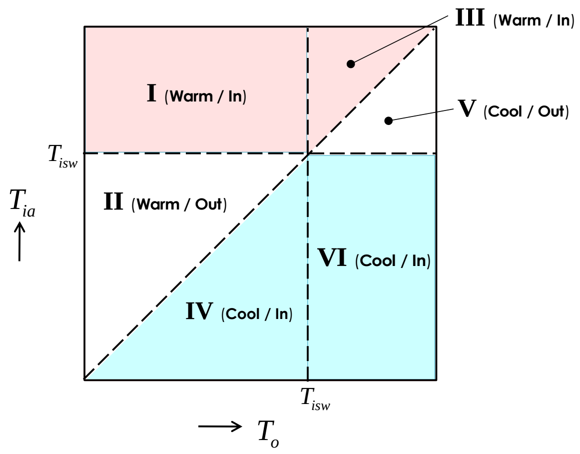


Table 1. shows these six combinations for the exergy flow of x_{cv_ia} given by eq.(4). In Table 1, the sign of Carnot factor denoted by b determines whether x_{cv_ia} is "warm" or "cool" exergy: positive is "warm" exergy and negative "cool" exergy. The other factor denoted by a is the difference in temperature between two surfaces and the sign of the product, $a \cdot b$, determines "inflow" or "outflow": positive is inflow and negative outflow; that is, the former is towards the innermost layer of window system and the latter towards room space. The diagram attached to Table 1 shows respective six ranges determined by the combination of three temperatures, T_o, T_{isw}, and T_{ia}.

The same discussion as above applies to convective exergy-transfer calculation to be made by eq.(6) and also to conductive exergy-transfer calculation.

2.4 Exergy consumption due to solar radiant and thermal radiant exergies

The third term of left-hand side of eq.(1), [Exergy consumed within the system], in the case of innermost layer consists of two parts: one due to the absorption of solar exergy and the other due to that of thermal radiant exergy given from the opposite interior surfaces of room space.

Focusing on the former, solar exergy absorption and consumption, we can set up the following exergy balance equation.

$$a_s \cdot x_{TV} - x_{c\_sol} = x_{th}, \tag{7}$$

where

$$x_{TV} = I_{TV} - s_{TV} \cdot T_o, \tag{8}$$

$$x_{th} = \left(1 - \frac{T_o}{T_{isw}}\right) a_s \cdot I_{TV} , \tag{9}$$

where a_s is the solar absorptance of the layer; x_{TV} is the sum of direct- and diffuse-solar exergy rates incident on the surface of the layer; x_{c_sol} is the rate of solar-exergy consumption within the layer; x_{th} is the thermal exergy produced by the absorption of solar exergy, which turns out to flow out from the system either by long-wavelength radiation, by convection, or by conduction; I_{TV} and s_{TV} are the total of solar energy and entropy incident on the system, respectively; T_{isw} and T_o are the layer temperature and the environmental temperature, respectively, both in the unit of Kelvin.

Substituting eqs.(8) and (9) into eq.(7), the rate of solar exergy consumption, x_{c_sol}, can be expressed as follows.

$$x_{c\_sol} = a_s \left(\frac{I_{TV}}{T_{isw}} - s_{TV}\right) \cdot T_o \tag{10}$$

Since the rate of exergy consumption is expressed as the product of the rate of entropy generation and the environmental temperature, the term multiplied by T_o is the rate of entropy generation. This is the product of solar absorptance and the difference between the outflow of thermal entropy from the system, that is either going into the adjacent layer or the surrounding space indoors, and the solar entropy to be absorbed by the system, that is the inflow of entropy to the system. The layer temperature, T_{isw}, is definitely much lower than the thermodynamic-solar temperature, which is about 4300 K, so that the entropy is necessarily generated by the absorption of solar radiation.

What has been described so far above can be exactly applied to other two layers shown in Figure 2., a transparent glass sheet as a part of double glazed window or to a system of a translucent shading device, which may be positioned either in the outdoor or indoor side of the window.

Substitution of the exact formulae for exergy transfer by radiation in the form of eq.(2), and convection and conduction in the form of eq.(4) or (6) and a little bit of algebraic operation of the resultant equation yields the following formula to give the exergy consumption rate at the interior surface of the innermost layer, x_{c_thrad} in the unit of W/m^2, which is exactly due to the absorption of thermal radiant exergy by the innermost layer.

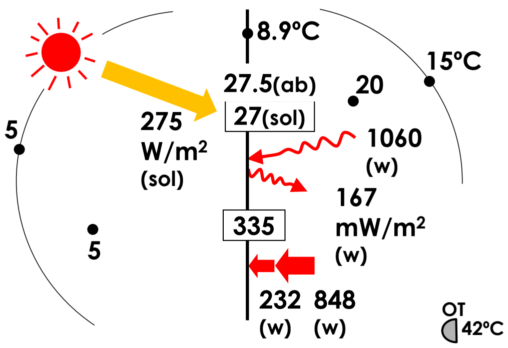
$$x_{c\_thrad} = \varepsilon T_{isw}^3 \left\{ \frac{1}{3} + \left(\frac{T_{rm}}{T_{isw}} \right)^3 \left(\frac{T_{rm}}{T_{isw}} - \frac{4}{3} \right) \right\} T_o \ , \qquad (11)$$

where T_{rm} is the mean radiant temperature of other walls surrounding the innermost layer, which is in the unit of Kelvin.

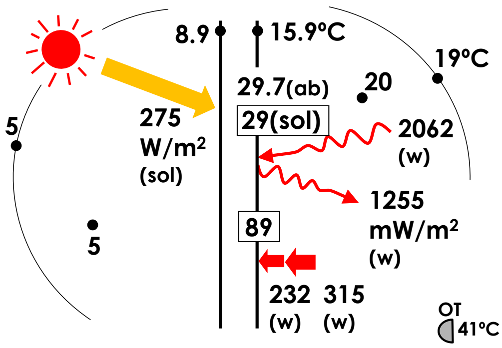
3 Numerical Examples

Figure 4. shows three cases of solar-exergy absorption and consumption together with thermal radiant exergy emission from and consumption at the innermost layer of the window and thermal exergy transferred by convection through the boundary air layer between the innermost layer of the window and the room air under a winter condition. Three cases of windows assumed are a) a single glass-paned window, b) a double-glazed window, and c) a double-glazed window having an internal shading device.

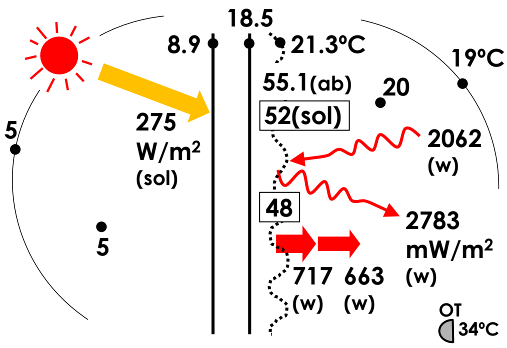
In order to calculate the numerical values of thermal exergy, we need to have the temperature of glass sheets and shading device. This was done by solving the



a) single-glazed window



b) double-glazed window



c) double glazed window with interior shading

Figure 4. Solar exergy absorption and consumption together with thermal radiant exergy emission, consumption, and thermal exergy transferred by convection at the innermost layers of three windows in winter. The innermost layer of the third case is internal shading device having its solar transmittance of 0.5 and absorptance of 0.3. The values in the upper squares are solar exergy consumption rate and those just above are solar exergy absorbed. The values in respective lower squares are thermal radiant exergy consumption rate. Those values denoted by "w" in bracket below them are "warm" radiant exergy flow rate.

respective sets of energy balance equations with respect to the temperatures of glass sheets and shading device, assuming the heat-transfer coefficients and the optical properties of glass sheets and shading device. The glass sheets, assumed for the exergy calculation shown in Figure 4., are ordinary clear glass having the thickness of 5mm, whose solar transmittance and absorptance are 0.8 and 0.1. The internal shading device is assumed to have the solar transmittance and absorptance of 0.5 and 0.3. The values of heat-transfer coefficients around the shading device were taken from a database compiled by Shukuya(1993).

The total of solar exergy incident on the exterior surface of each of these windows is 275W/m^2. In the case of the single-paned glass window, 27.5W/m^2 is absorbed and its 99%, that is 27 W/m^2, is consumed. The rate of “warm” radiant exergy emission from the interior surface of the single glazed window, 167mW/m^2, is very small compared to those in the cases of the other two windows, 1255 or 2783mW/m^2, since the temperature of the glass sheet in the case of the single glazed window is very low. This also results in the thermal radiant exergy consumption rate in case a) being the largest, 335mW/m^2, among the three cases. In other words, making the thermal radiant exergy consumption rate smaller by insulating the whole of window system results in making thermal radiant exergy emission larger. That is what can be seen in cases b) and c).

Three temperature values shown at the lower right corner of each drawing shows the equivalent operative temperature including the effect of solar radiation, which is equivalent to the black-surface temperature of a thick board of extremely low thermal conductivity. Among the three values of equivalent operative temperature, that in the case of the single-glazed window is the highest. This suggests that much of the incident solar radiation is transmitted through the window and results in raising the surface temperature of the floor or other internal walls.

The inside layer of the double-glazed window emits “warm” radiant exergy at a much larger rate, 7.5 times larger than the single glass paned window does. The intenral shading device in the third case, does not necessarily decrease solar-exergy gain for passive solar heating with window openings. Instead, it becomes rather an effective radiant heating panel to emit “warm” radiant exergy towards the indoor space. The “warm” radiant exergy emitted from the internal shading device is 1.35 times larger than the transparent layer of glass sheet of the double-glazed window.

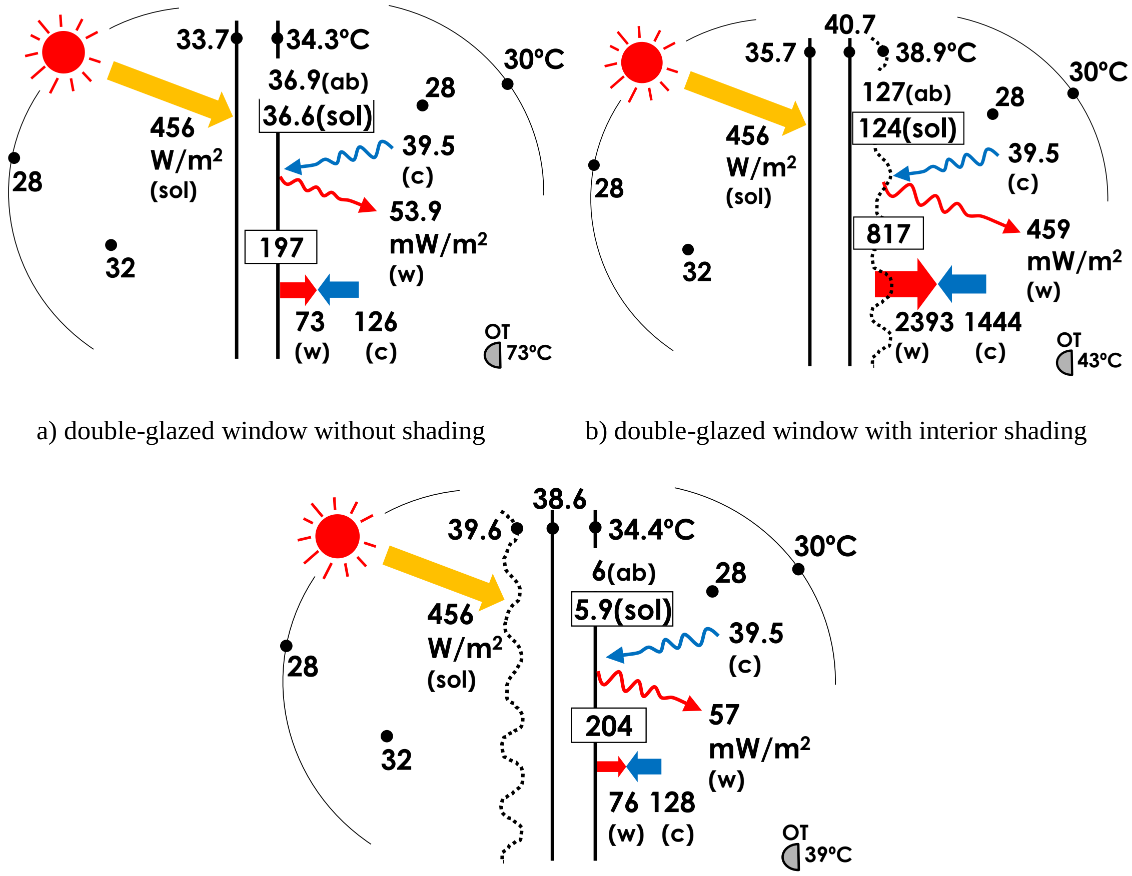
The largest solar-exergy consumption rate among the three cases is 52W/m^2 at the interior shading device due to its solar absorptance higher than that of clear glass sheets. A larger exergy consumption rate within the system brings about a higher temperature of the system.

The operative temperature in the third case is the lowest among the three cases due to the internal shading device. In the other two cases, the amount of transmitted solar exergy is much larger than the third case, but it is consumed totally anyway at the floor surface and the internal wall surfaces.

With the internal shading device, “warm” exergy transferred by convection is not from the room space toward the window, but from the shading device into the room space; this helps increase the amount of warm exergy contained by room air.

The results of exergy calculation described above for winter conditions confirms that the installation of well-insulated glass windows provides the occupants with a larger emission of “warm” radiant exergy, which would lower the human-body exergy consumption rate as pointed out by Isawa and Shukuya(2013).

Figure 5. demonstrates three cases of solar-exergy absorption and consumption together with thermal radiant exergy emission from and consumption at the innermost layer of the window and thermal exergy transferd by convection through the boundary air layerunder a summer condition. Three cases are a) the inside glass layer of a double-glazed window without shading device, b) the interior shading device placed



a) double-glazed window without shading

b) double-glazed window with interior shading

c) double-glazed window with exterior shading

Figure 5. Solar exergy absorption and consumption together with thermal radiant exergy absorption, emission, consumption and thermal exergy transferred by convection at the innermost layers of three windows in summer. The innermost layer of the second case and the outermost layer of the third case are shading device having its solar transmittance of 0.15 and the solar absorptance of 0.4. The values in the upper squares are solar exergy consumption and those just above are solar exergy absorbed. The values in respective squares are thermal radiant exergy consumption rate. Those values denoted by either “w” or “c” in bracket below them are either “warm” or “cool” radiant exergy flow rate.

in the indoor side of a double-glazed window, and c) the inside glass layer of a double glazed window with exterior shading device.

The solar transmittance and absorptance of the shading device are assumed to be 0.15 and 0.4, respectively, in both the second and third cases. We here assumed a rather severe summer condition: the outdoor air temperature reaching 32°C togehter with the total of solar exergy incident on the vertical surface outside the three windows being 456W/m^2. Outdoor average radiant temperature was assumed to be 28°C, that is such a condition of sky temperature and ground temperature being 20°C and 36°C, respectively.

Without either interior or exterior shading device, "warm" radiant exergy emitted from the innermost layer of the window is the smallest among the three cases, but this results in the highest operative temperature of 73°C, which is 30 to 34°C higher than the operative temperature of the other two windows with shading devices. This means that the floor surface or interior wall surface temperatures are increased by solar-exergy consumption there and hence make the "warm" radiant exergy emission rate large.

The internal shading device causes a large rate of "warm" radiant exergy emission, since its temperature is increased up to 38.9°C due to a large rate of solar absorption and consumption. "Warm" exergy transferred from the surface of the internal shading device towards the room space is very large, while at the same time "cool" exergy transfer from the room air towards the internal shading device is also very large. This is because the convective heat-transfer coefficient tend to be large due to a large temperature difference between the room air and the interior shading device. A large rate of "warm" radiant exergy emission together with that of "warm" exergy transfer by convection results in a lot of "cool" exergy requirement and thereby necessitates a mechanical cooling system that requires a lot of exergy consumption to produce and supply "cool" exergy into the room space.

In case c) with exterior shading device, such a large rate of "warm" radiant exergy emission as that in the case with interior shading device occurs at the exterior shading device and most of the "warm" exergy generated is transferred outdoors by convection and radiation. The temperature of the innermost glass sheet in the third case, 34.4°C, is 4.5°C lower than that of the interior shading device in the second case, 38.9°C. This results in a much smaller rate of "warm" radiant exergy emission in the case of exterior shading device. That is 57mW/m^2, only 12% of the case of the interior shading device. This is also due to smaller thermal exergy consumption rate in the third case, only one-fourth of the second case.

Installation of the exterior shading device also decreases the "warm" exergy transfer by convection from the innermost surface of the glass sheet towards the room air and thereby results in a small "cool" exergy loss by convection from the room air. The rate of "cool" exergy from the room air into the boundary layer is 1444W/m^2 in the case of the internal shading device, while on the other hand, it is 128W/m^2, only 9% of the former.

4 Conclusion

This paper has demonstrated a state-of-the-art method of calculating exergy emission by thermal radiation, solar exergy absorption and consumption, and also exergy transfer by convection within window systems.

Numerical examples of solar-thermal exergy balance within the innermost layer of three window configurations both in winter and in summer reveal the following two major points:

1) In winter, appropriate thermal insulation of window systems to be provided mainly by passive-heating measures is important in increasing the emission rate of “warm” radiant exergy from the interior surface of windows;

2) In summer, installation of exterior shading devices is important in decreasing “warm” radiant exergy from the interior surface of windows, while at the same time in increasing the availability of “cool” raidant exergy within room space.

These measures are thus confirmed to be crucial in the pursuit of low-exergy system solutions, which must well contribute to allowing building occupants to have more adaptive opportunity for thermal comfort.

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