POLITECNICO DI MILANO

Heat Transfer Through Windows

Ref: Heating and cooling loads in Buildings by Y. A. Cengel

Energy and Environmental Technologies for Building Systems

Piacenza Campus

B. Najafi

Heat Transfer through windows

❖Even in the absence of solar radiation and air infiltration, heat transfer through the windows is more complicated than it appears to be.

❖ This is because the structure and properties of the frame are quite different than the glazing. As a result, heat transfer through the frame and the edge section of the glazing adjacent to the frame is two-dimensional.

❖Therefore, it is customary to consider the window in three regions when analyzing heat transfer through it:

✓(1) the center-of-glass

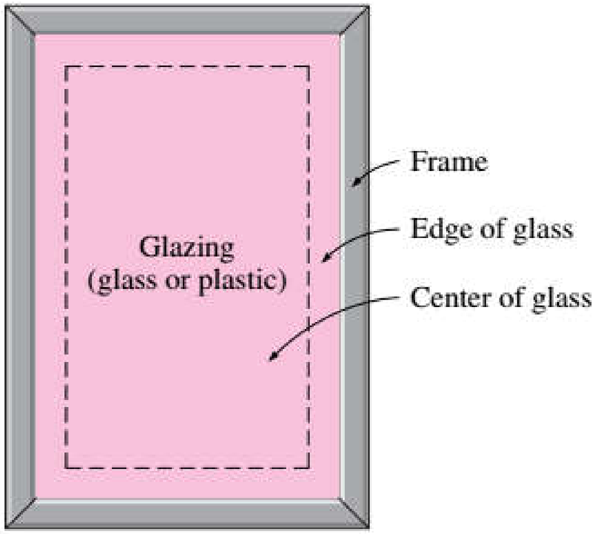
✓(2) the edge-of-glass,

✓(3) the frame regions

❖ Then the total rate of heat transfer through the window is determined by adding the heat transfer through each region as

$$\begin{aligned}\dot{Q}_{\text{window}} &= \dot{Q}_{\text{center}} + \dot{Q}_{\text{edge}} + \dot{Q}_{\text{frame}} \\ &= U_{\text{window}} A_{\text{window}} (T_{\text{indoors}} - T_{\text{outdoors}})\end{aligned}$$

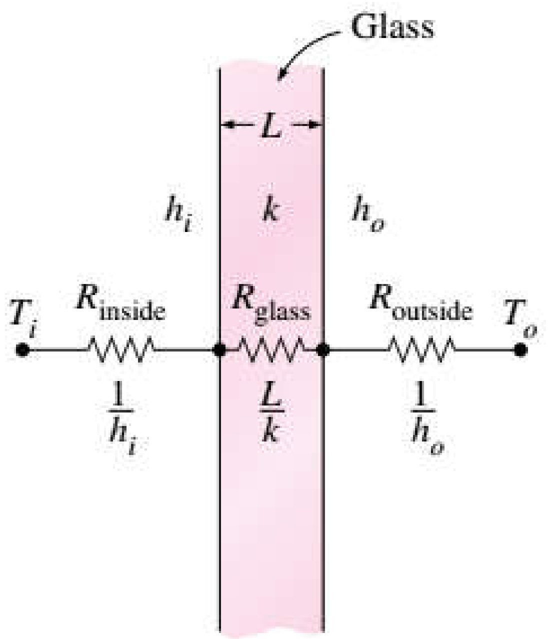
$$U_{\text{window}} = (U_{\text{center}} A_{\text{center}} + U_{\text{edge}} A_{\text{edge}} + U_{\text{frame}} A_{\text{frame}})/A_{\text{window}}$$



❖Also, the inverse of the U-factor is the R-value, which is the unit thermal resistance of the window (thermal resistance for a unit area).

❖Consider steady one-dimensional heat transfer through a single-pane glass of thickness L and thermal conductivity k. The thermal resistance network of this problem consists of surface resistances on the inner and outer surfaces and the conduction resistance of the glass in series, as shown in the figure, and the total resistance on a unit area basis can be expressed as:

$$R_{total} = R_{inside} + R_{glass} + R_{outside} = \frac{1}{h_i} + \frac{L_{glass}}{k_{glass}} + \frac{1}{h_o}$$

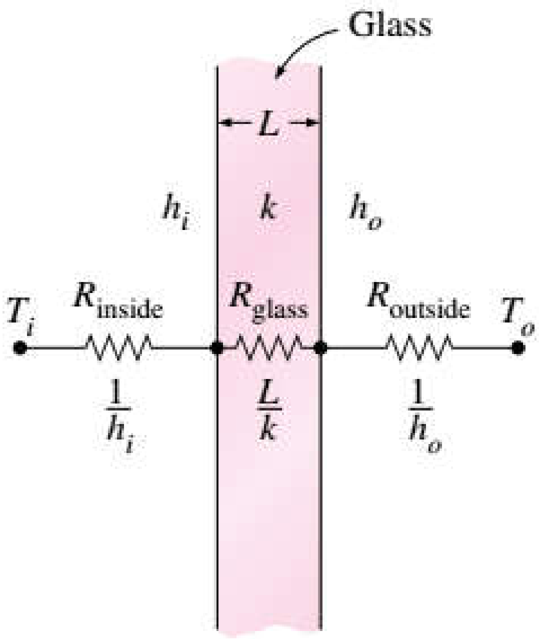


Heat Transfer through windows

❖Using common values of 3 mm for the thickness and 0.92 W/m°C for the thermal conductivity of the glass and the winter design values of 8.29 and 34.0 W/m2 °C for the inner and outer surface heat transfer coefficients, the thermal resistance of the glass is determined to be:

$$R_{\text{total}} = R_{\text{inside}} + R_{\text{glass}} + R_{\text{outside}} = \frac{1}{h_i} + \frac{L_{\text{glass}}}{k_{\text{glass}}} + \frac{1}{h_o}$$

$$R_{\text{total}} = \frac{1}{8.29\,\text{W/m}^2\cdot{}^\circ\text{C}} + \frac{0.003\,\text{m}}{0.92\,\text{W/m}\cdot{}^\circ\text{C}} + \frac{1}{34.0\,\text{W/m}^2\cdot{}^\circ\text{C}}$$
$$= 0.121 + 0.003 + 0.029 = 0.153\,\text{m}^2\cdot{}^\circ\text{C/W}$$



❖Note that the ratio of the glass resistance to the total resistance is:

$$\frac{R_{\text{glass}}}{R_{\text{total}}} = \frac{0.003\,\text{m}^2\cdot{}^\circ\text{C/W}}{0.153\,\text{m}^2\cdot{}^\circ\text{C/W}} = 2.0\%$$

❖That is, the glass layer itself contributes about 2 percent of the total thermal resistance of the window, which is negligible. The situation would not be much different if we used acrylic, whose thermal conductivity is 0.19 W/m °C, instead of glass.

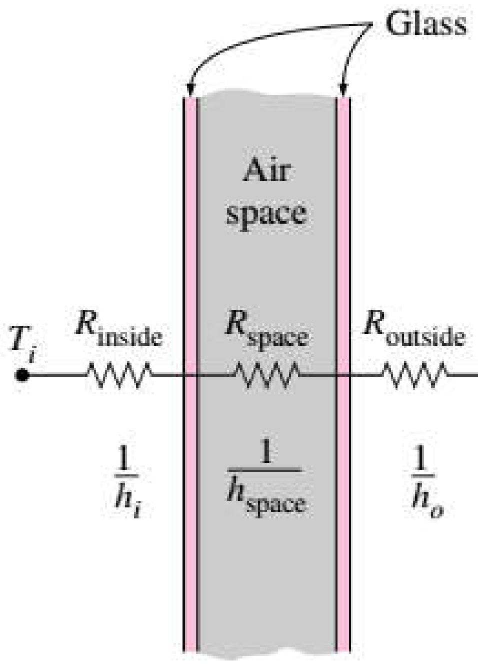
❖Therefore, we cannot reduce the heat transfer through the window effectively by simply increasing the thickness of the glass. But we can reduce it by trapping still air between two layers of glass. The result is a **double-pane window**, which has become the norm in window construction.

❖The thermal conductivity of air at room temperature is k_{air} =0.025 W/m ºC, which is one-thirtieth that of glass. Therefore, the thermal resistance of 1 cm thick still air is equivalent to the thermal resistance of a 30 cm-thick glass layer!!

❖Disregarding the thermal resistances of glass layers, the thermal resistance and U-factor of a double-pane window can be expressed as:

$$\frac{1}{U_{\text{double-pane (center region)}}} \cong \frac{1}{h_i} + \frac{1}{h_{\text{space}}} + \frac{1}{h_o}$$

$$h_{\text{space}} = h_{\text{rad, space}} + h_{\text{conv, space}}$$

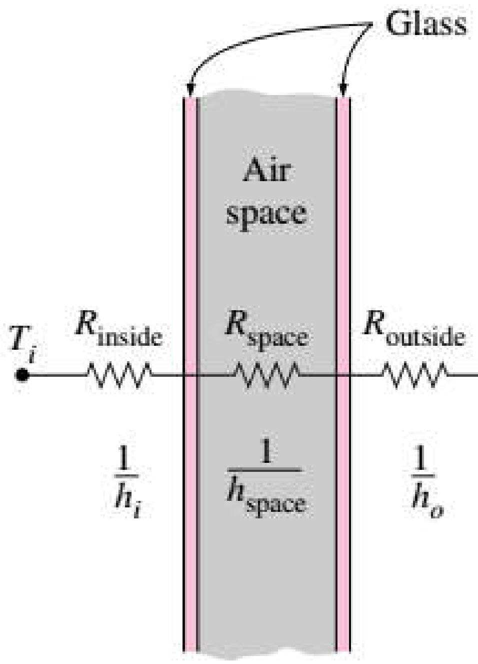


❖Roughly half of the heat transfer through the air space of a double-pane window is by radiation and the other half is by conduction (or convection, if there is any air motion).

❖ Therefore, there are two ways to minimize h_{space} and thus the rate of heat transfer through a double-pane window:

1) Minimize radiation heat transfer through the air space. This can be done by reducing the emissivity of glass surfaces by coating them with low-emissivity material. Recall that the effective emissivity of two parallel plates of emissivities ε_1 and ε_1 is given by:

$$\varepsilon_{\text{effective}} = \frac{1}{1/\varepsilon_1 + 1/\varepsilon_2 - 1}$$



❖The emissivity of an ordinary glass surface is 0.84. Therefore, the effective emissivity of two parallel glass surfaces facing each other is 0.72.

❖But when the glass surfaces are coated with a film that has an emissivity of 0.1, the effective emissivity reduces to 0.05, which is one-fourteenth of 0.72.

❖It can be shown that coating just one of the two parallel surfaces facing each other by a material of emissivity ε reduces the effective emissivity nearly to ε. Therefore, it is usually more economical to coat only one of the facing surfaces!

❖The corresponding values of heat transfer coefficient of the space is given in the following table:

(*a*) *Air space thickness = 13 mm*

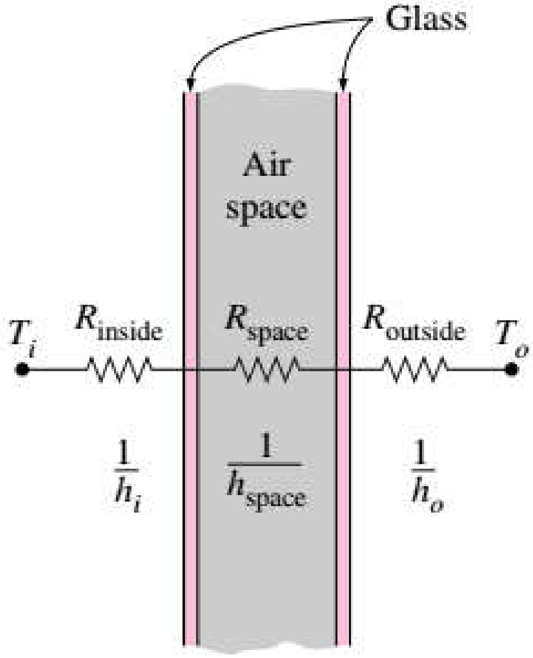
T_{avg}, °C	ΔT, °C	h_{space}, W/m$^2\cdot$°C* $\varepsilon_{effective}$ 0.72	0.4	0.2	0.1
0	5	5.3	3.8	2.9	2.4
0	15	5.3	3.8	2.9	2.4
0	30	5.5	4.0	3.1	2.6
10	5	5.7	4.1	3.0	2.5
10	15	5.7	4.1	3.1	2.5
10	30	6.0	4.3	3.3	2.7
30	5	5.7	4.6	3.4	2.7
30	15	5.7	4.7	3.4	2.8
30	30	6.0	4.9	3.6	3.0

(*b*) *Air space thickness = 6 mm*

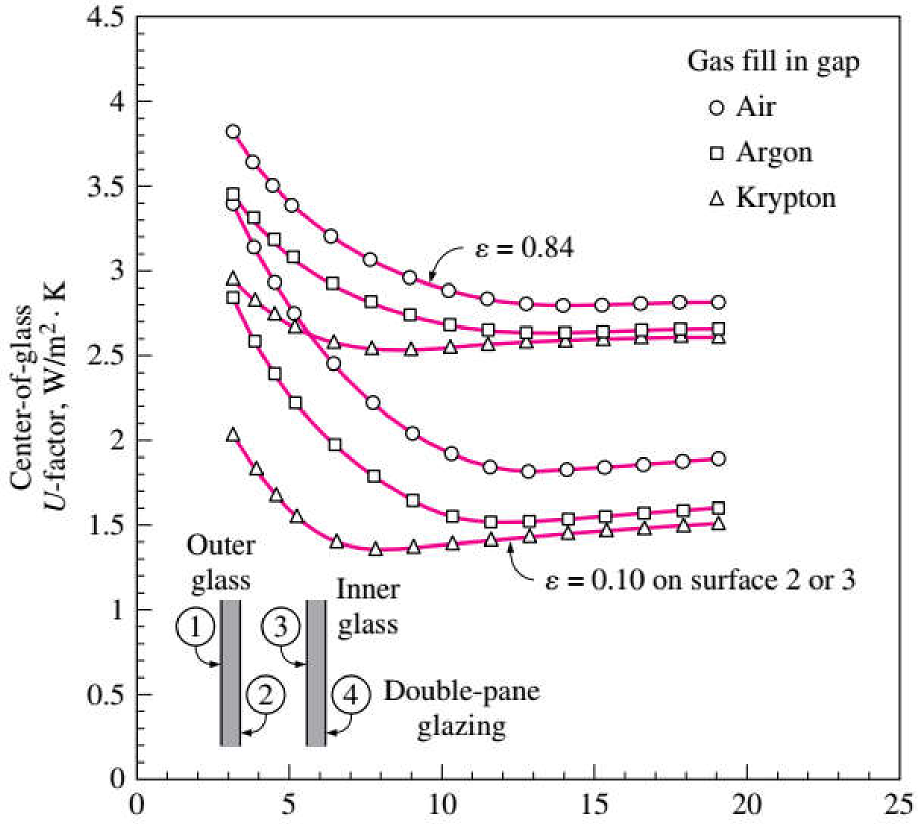
T_{avg}, °C	ΔT, °C	h_{space}, W/m$^2\cdot$°C* $\varepsilon_{effective}$ 0.72	0.4	0.2	0.1
0	5	7.2	5.7	4.8	4.3
0	50	7.2	5.7	4.8	4.3
10	5	7.7	6.0	5.0	4.5
10	50	7.7	6.1	5.0	4.5
30	5	8.8	6.8	5.5	4.9
30	50	8.8	6.8	5.5	4.9
50	5	10.0	7.5	6.0	5.2
50	50	10.0	7.5	6.0	5.2

1) *Minimize conduction heat transfer through air space*. This can be done by increasing the distance *d* between the two glasses.

- ✓ However, this cannot be done indefinitely since increasing the spacing beyond a critical value initiates convection currents in the enclosed air space, which increases the heat transfer coefficient and thus defeats the purpose.
- ✓ Besides, increasing the spacing also increases the thickness of the necessary framing and the cost of the window

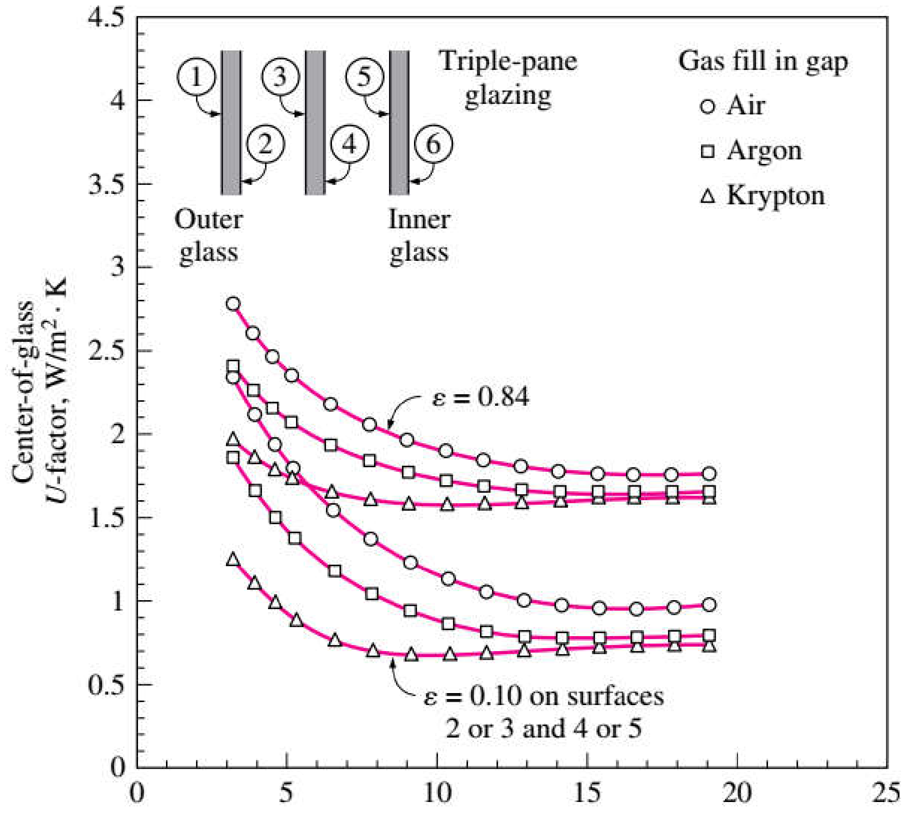


- Experimental studies have shown that when the spacing d is less than about 13 mm, there is no convection, and heat transfer through the air is by conduction. But as the spacing is increased further, convection currents appear in the air space, and the increase in heat transfer coefficient offsets any benefit obtained by the thicker air layer. As a result, the heat transfer coefficient remains nearly constant.
- Therefore, it makes no sense to use an air space thicker than 13 mm in a double-pane window!!
- Note from the figure that the coating one of the interior surfaces of a double-pane window with a material having an emissivity of 0.1 reduces the rate of heat transfer through the center section of the window by half!



Heat Transfer through windows

- ✓ The thermal resistance of the window can be increased further by using triple- or quadruple-pane windows whenever it is economical to do so.
- ✓ Note that using a triple-pane window instead of a double-pane reduces the rate of heat transfer through the center section of the window by about <u>one-third.</u>
- ✓ Another way of reducing conduction heat transfer through a double-pane window is to use a *less-conducting fluid* such as <u>argon or krypton</u> to fill the gap between the glasses instead of air. The gap in this case needs to be well sealed to prevent the gas from leaking outside.
- ✓ Of course, another alternative is to evacuate the gap between the glasses completely, but it is not practical to do so



Edge-of-Glass U-Factor of a Window

❖The glasses in double- and triple-pane windows are kept apart from each other at a uniform distance by **spacers** made of metals or insulators like aluminium, fiberglass, wood, and butyl. Continuous spacer strips are placed around the glass perimeter to provide edge seal as well as uniform spacing.

❖ However, the spacers also serve as undesirable "thermal bridges" between the glasses, which are at different temperatures, and this short-circuiting may increase heat transfer through the window considerably.

❖Heat transfer in the edge region of a window is two-dimensional, and lab measurements indicate that the edge effects are limited to <u>a 6.5-cm-wide</u> band around the perimeter of the glass.

Frame U-Factor

❖The framing of a window consists of the entire window except the glazing.

❖Heat transfer through the framing is difficult to determine because of the different window configurations, different sizes, different constructions, and different combination of materials used in the frame construction.

❖The type of glazing such as single pane, double pane, and triple pane affects the thickness of the framing and thus heat transfer through the frame.

❖ Most frames are made of wood, aluminium, vinyl, or fiberglass. However, using a combination of these materials (such as aluminium-clad wood and vinyl-clad aluminium) is also common to improve appearance and durability.

Frame U-Factor

❖Aluminium is a popular framing material because it is inexpensive, durable, and easy to manufacture, and does not rot or absorb water like wood. However, from a heat transfer point of view, it is the least desirable framing material because of its high thermal conductivity. It will come as no surprise that the *U*-factor of solid aluminium frames is the highest, and thus a window with aluminium framing will lose much more heat than a comparable window with wood or vinyl framing.

❖Heat transfer through the aluminium framing members can be reduced by using plastic inserts between components to serve as thermal barriers. The thickness of these inserts greatly affects heat transfer through the frame. For aluminium frames without the plastic strips, the primary resistance to heat transfer is due to the interior surface heat transfer coefficient.

❖The U-factors for various frames are listed in the Table as a unction of spacer materials and the glazing unit thicknesses.

✓Note that the U-factor of metal framing and thus the rate of heat transfer through a metal window frame is more than three times that of a wood or vinyl window frame.

Frame material	*U*-factor, W/m² · °C*
Aluminum:	
Single glazing (3 mm)	10.1
Double glazing (18 mm)	10.1
Triple glazing (33 mm)	10.1
Wood or vinyl:	
Single glazing (3 mm)	2.9
Double glazing (18 mm)	2.8
Triple glazing (33 mm)	2.7

Interior and Exterior Surface Heat Transfer Coefficients

❖Heat transfer through a window is also affected by the convection and radiation heat transfer coefficients between the glass surfaces and surroundings.

❖The effects of convection and radiation on the inner and outer surfaces of glazings are usually combined into the combined convection and radiation heat transfer coefficients h_i and h_o respectively. Under still air conditions, the combined heat transfer coefficient at the inner surface of a vertical window can be determined from:

$$h_i = h_{\text{conv}} + h_{\text{rad}} = 1.77(T_g - T_i)^{0.25} + \frac{\varepsilon_g \sigma (T_g^4 - T_i^4)}{T_g - T_i} \qquad (\text{W/m}^2 \cdot {}^\circ\text{C})$$

❖Where T_g: the glass temperature in K, T_i: indoor air temperature in K, ε_g: emissivity of the inner surface of the glass exposed to the room (taken to be 0.84 for uncoated glass),

❖ Here the temperature of the interior surfaces facing the window is assumed to be equal to the indoor air temperature. This assumption is reasonable when the window faces mostly interior walls, but it becomes questionable when the window is exposed to heated or cooled surfaces or to other windows.

Interior and Exterior Surface Heat Transfer Coefficients

❖The commonly used value of h_i for peak load calculation is: $h_i = 8.29\ W/m^2$

- which corresponds to the winter design conditions of T_i=22°C and T_g=7°C for uncoated glass with ε_g=0.84.
- But the same value of h_i can also be used for summer design conditions as it corresponds to summer conditions of T_i= 24°C and T_g= 32°C. The values of h_i for various temperatures and glass emissivities are given in the following table.

T_i, °C	T_o, °C	Glass emissivity, ε_g 0.05	0.20	0.84
20	17	2.6	3.5	7.1
20	15	2.9	3.8	7.3
20	10	3.4	4.2	7.7
20	5	3.7	4.5	7.9
20	0	4.0	4.8	8.1
20	−5	4.2	5.0	8.2
20	−10	4.4	5.1	8.3

❖ The commonly used values of ho for peak load calculations are the same as those used for outer wall surfaces (34.0 W/m²°C for winter and 22.7 W/m²°C for summer).

Overall U-Factor of Windows

❖The overall *U*-factors for various kinds of windows and skylights are evaluated using computer simulations and laboratory testing for winter design conditions; representative values are given in the table.

	Glass section (glazing) only			*Aluminum frame (without thermal break)*			*Wood or vinyl frame*					
Type	Center-of-glass	Edge-of-glass		Fixed	Double door	Sloped skylight	Fixed		Double door		Sloped skylight	
Frame width →	(Not applicable)			32 mm ($1\frac{1}{4}$ in)	53 mm (2 in)	19 mm ($\frac{3}{4}$ in)	41 mm ($1\frac{5}{8}$ in)		88 mm ($3\frac{7}{16}$in)		23 mm ($\frac{7}{8}$ in)	
Spacer type →	—	Metal	Insul.	All	All	All	Metal	Insul.	Metal	Insul.	Metal	Insul.
Glazing Type												
Single Glazing												
3 mm ($\frac{1}{8}$ in) glass	6.30	6.30	—	6.63	7.16	9.88	5.93	—	5.57	—	7.57	—
6.4 mm ($\frac{1}{4}$ in) acrylic	5.28	5.28	—	5.69	6.27	8.86	5.02	—	4.77	—	6.57	—
3 mm ($\frac{1}{8}$ in) acrylic	5.79	5.79	—	6.16	6.71	9.94	5.48	—	5.17	—	7.63	—
Double Glazing (no coating)												
6.4 mm air space	3.24	3.71	3.34	3.90	4.55	6.70	3.26	3.16	3.20	3.09	4.37	4.22
12.7 mm air space	2.78	3.40	2.91	3.51	4.18	6.65	2.88	2.76	2.86	2.74	4.32	4.17
6.4 mm argon space	2.95	3.52	3.07	3.66	4.32	6.47	3.03	2.91	2.98	2.87	4.14	3.97
12.7 mm argon space	2.61	3.28	2.76	3.36	4.04	6.47	2.74	2.61	2.73	2.60	4.14	3.97
Double Glazing [ε = 0.1, coating on one of the surfaces of air space (surface 2 or 3, counting from the outside toward inside)]												
6.4 mm air space	2.44	3.16	2.60	3.21	3.89	6.04	2.59	2.46	2.60	2.47	3.73	3.53
12.7 mm air space	1.82	2.71	2.06	2.67	3.37	6.04	2.06	1.92	2.13	1.99	3.73	3.53
6.4 mm argon space	1.99	2.83	2.21	2.82	3.52	5.62	2.21	2.07	2.26	2.12	3.32	3.09
12.7 mm argon space	1.53	2.49	1.83	2.42	3.14	5.71	1.82	1.67	1.91	1.78	3.41	3.19
Triple Glazing (no coating)												
6.4 mm air space	2.16	2.96	2.35	2.97	3.66	5.81	2.34	2.18	2.36	2.21	3.48	3.24
12.7 mm air space	1.76	2.67	2.02	2.62	3.33	5.67	2.01	1.84	2.07	1.91	3.34	3.09
6.4 mm argon space	1.93	2.79	2.16	2.77	3.47	5.57	2.15	1.99	2.19	2.04	3.25	3.00
12.7 mm argon space	1.65	2.58	1.92	2.52	3.23	5.53	1.91	1.74	1.98	1.82	3.20	2.95
Triple Glazing [ε = 0.1, coating on one of the surfaces of air spaces (surfaces 3 and 5, counting from the outside toward inside)]												
6.4 mm air space	1.53	2.49	1.83	2.42	3.14	5.24	1.81	1.64	1.89	1.73	2.92	2.66
12.7 mm air space	0.97	2.05	1.38	1.92	2.66	5.10	1.33	1.15	1.46	1.30	2.78	2.52
6.4 mm argon space	1.19	2.23	1.56	2.12	2.85	4.90	1.52	1.35	1.64	1.47	2.59	2.33
12.7 mm argon space	0.80	1.92	1.25	1.77	2.51	4.86	1.18	1.01	1.33	1.17	2.55	2.28

Overall U-Factor of Windows

❖Test data may provide more accurate information for specific products and should be preferred when available.

❖However, the values listed in the table can be used to obtain satisfactory results under various conditions in the absence of product-specific data. The U-factor of a fenestration product that differs considerably from the ones in the table can be determined by:

(1) determining the fractions of the area that are frame, center-of-glass, and edge-of glass (assuming a 65-mm-wide band around the perimeter of each glazing)

(2) determining the U-factors for each section

(3) multiplying the area fractions and the U-factors for each section and adding them up

$$\begin{aligned}\dot{Q}_{\text{window}} &= \dot{Q}_{\text{center}} + \dot{Q}_{\text{edge}} + \dot{Q}_{\text{frame}} \\ &= U_{\text{window}} A_{\text{window}} (T_{\text{indoors}} - T_{\text{outdoors}})\end{aligned}$$

$$U_{\text{window}} = (U_{\text{center}} A_{\text{center}} + U_{\text{edge}} A_{\text{edge}} + U_{\text{frame}} A_{\text{frame}})/A_{\text{window}}$$

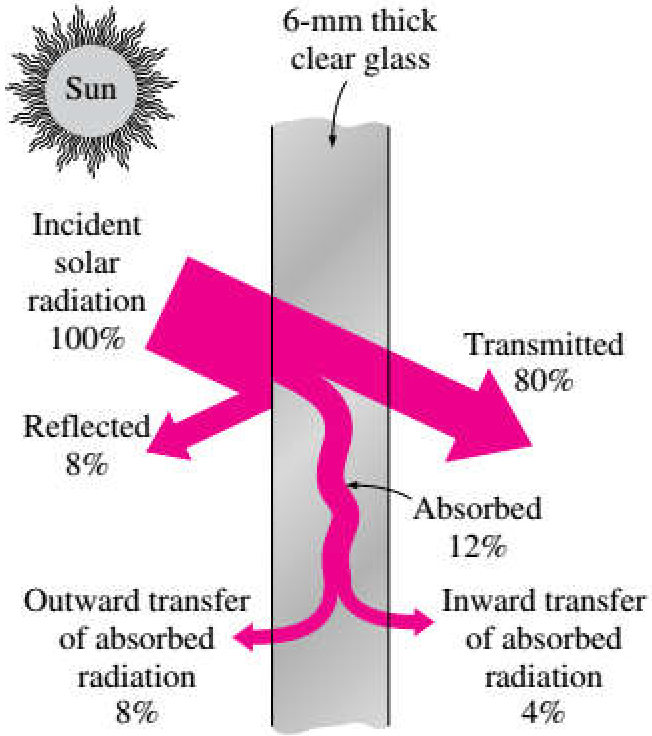
Overall U-Factor of Windows, Important conclusions

- The thicker the air space in multiple-glazed units, the lower the U-factor, for a thickness of up to 13 mm (in) of air space. For a specified number of glazings, the window with thicker air layers will have a lower U-factor. For a specified overall thickness of glazing, the higher the number of glazings, the lower the U-factor. Therefore, a triple-pane window with air spaces of 6.4 mm (two such air spaces) will have a lower U-value than a double-pane window with an air pace of 12.7 mm

- Wood or vinyl frame windows have a considerably lower U-value than comparable metal-frame windows. Therefore, wood or vinyl frame windows are called for in energy-efficient designs.

- When solar radiation strikes a glass surface, part of it (about 8 percent for uncoated clear glass) is reflected back to outdoors, part of it (5 to 50 percent, depending on composition and thickness) is absorbed within the glass, and the remainder is transmitted indoors
- The conservation of energy principle requires that the sum of the transmitted, reflected, and absorbed solar radiations be equal to the incident solar radiation. That is:

$$\tau_s + \rho_s + \alpha_s = 1$$

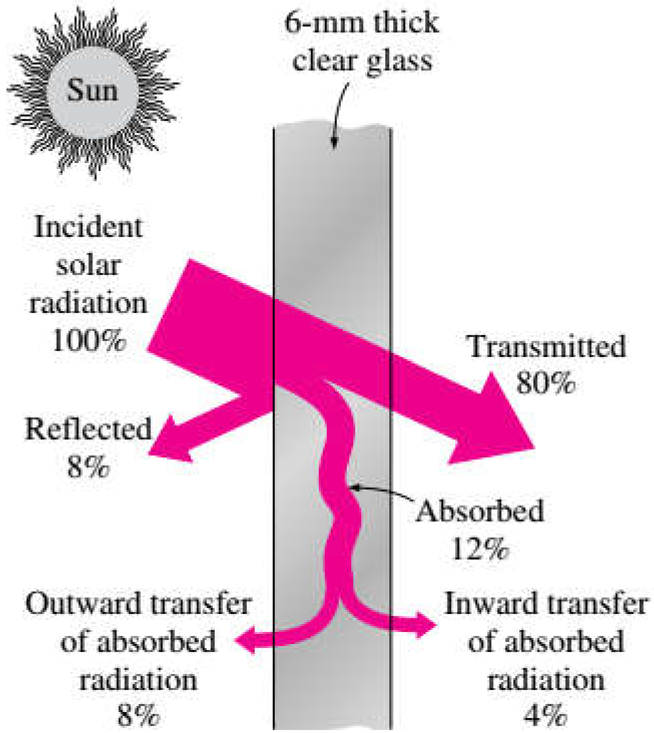


- The standard 3-mm thick single-pane double-strength clear window glass transmits 86 percent, reflects 8 percent, and absorbs 6 percent of the solar energy incident on it.
- The radiation properties of materials are usually given for normal incidence, but can also be used for radiation incident at other angles since the transmissivity, reflectivity, and absorptivity of the glazing materials remain essentially constant for incidence angles up to about 60º from the normal

- Solar radiation that is transmitted indoors is partially absorbed and partially reflected each time it strikes a surface, but all of it is eventually absorbed as sensible heat by the furniture, walls, people, and so forth. Therefore, the solar energy transmitted inside a building represents a heat gain for the building. Also, the solar radiation absorbed by the glass is subsequently transferred to the indoors and outdoors by convection and radiation. The sum of the *transmitted* solar radiation and the portion of the *absorbed* radiation that flows indoors constitutes the **solar heat gain** of the building.

- The fraction of incident solar radiation that enters through the glazing is called the solar heat gain coefficient SHGC and is expressed as:

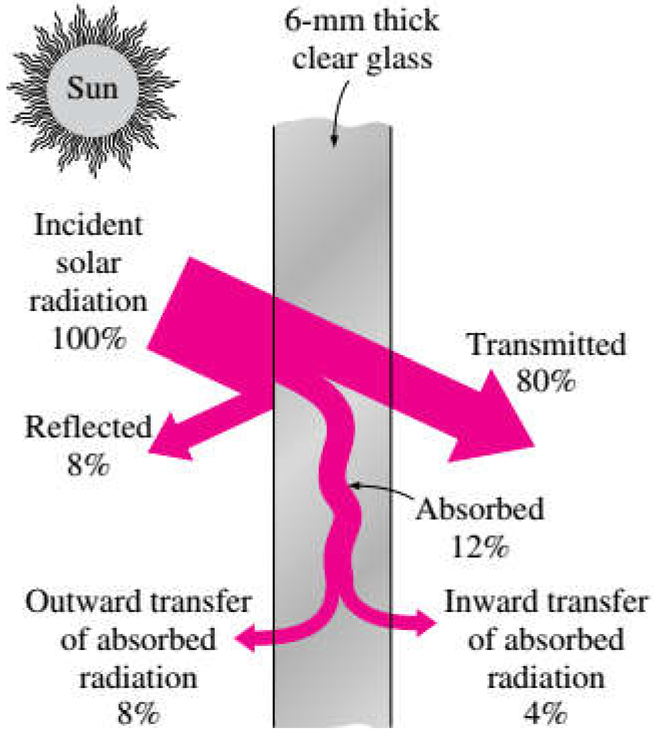
$$\text{SHGC} = \frac{\text{Solar heat gain through the window}}{\text{Solar radiation incident on the window}} = \frac{\dot{q}_{\text{solar, gain}}}{\dot{q}_{\text{solar, incident}}} = \tau + f_i \alpha_s$$



Solar Heat Gain Coefficient

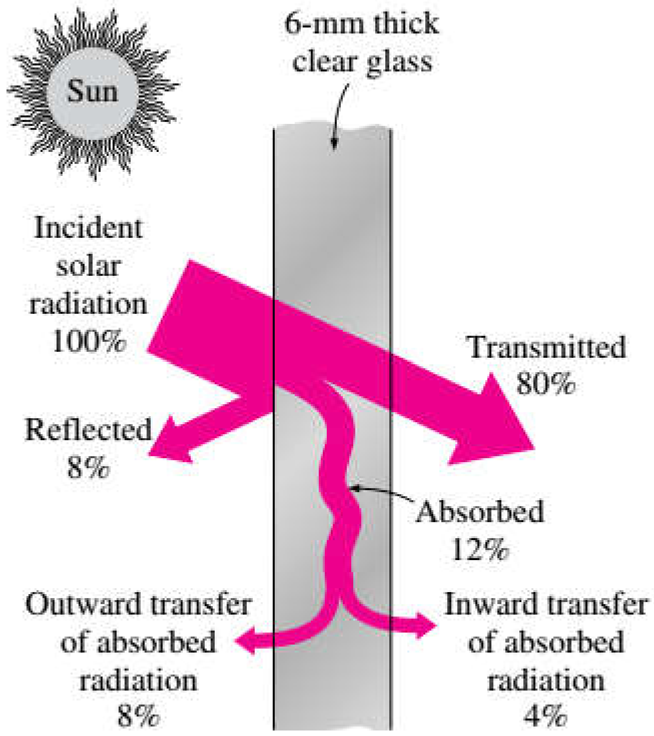
❖ The value of SHGC ranges from 0 to 1, with 1 corresponding to an opening in the wall (or the ceiling) with no glazing. When the SHGC of a window is known, the total solar heat gain through that window is determined from:

$$\dot{Q}_{\text{solar, gain}} = \text{SHGC} \times A_{\text{glazing}} \times \dot{q}_{\text{solar, incident}} \qquad \text{(W)}$$



- Another way of characterizing the solar transmission characteristics of different kinds of glazing and shading devices is to compare them to a well known glazing material that can serve as a base case. This is done by taking the standard 3-mm thick double-strength clear window glass sheet whose SHGC is 0.87 as the *reference glazing* and defining a **shading coefficient** SC as

$$SC = \frac{\text{Solar heat gain of product}}{\text{Solar heat gain of reference glazing}} = \frac{SHGC}{SHGC_{ref}} = \frac{SHGC}{0.87} = 1.15 \times SHGC$$



- Therefore, the shading coefficient of a single-pane clear glass window is SC= 1.0. The shading coefficients of other commonly used fenestration products are given in the following table for summer design conditions. The values for winter design conditions may be slightly lower because of the higher heat transfer coefficients on the outer surface due to high winds and thus higher rate of outward flow of solar heat absorbed by the glazing, but the difference is small.

- Note that the larger the shading coefficient, the smaller the shading effect, and thus the larger the amount of solar heat gain. A glazing material with a large shading coefficient allows a large fraction of solar radiation to come in.

Type of glazing	Nominal thickness mm	Nominal thickness in	τ_{solar}	SC*
(a) Single Glazing				
Clear	3	$\frac{1}{8}$	0.86	1.0
	6	$\frac{1}{4}$	0.78	0.95
	10	$\frac{3}{8}$	0.72	0.92
	13	$\frac{1}{2}$	0.67	0.88
Heat absorbing	3	$\frac{1}{8}$	0.64	0.85
	6	$\frac{1}{4}$	0.46	0.73
	10	$\frac{3}{8}$	0.33	0.64
	13	$\frac{1}{2}$	0.24	0.58
(b) Double Glazing				
Clear in, clear out	3[a]	$\frac{1}{8}$	0.71[b]	0.88
	6	$\frac{1}{4}$	0.61	0.82
Clear in, heat absorbing out[c]	6	$\frac{1}{4}$	0.36	0.58

*Multiply by 0.87 to obtain SHGC.

[a]The thickness of each pane of glass.

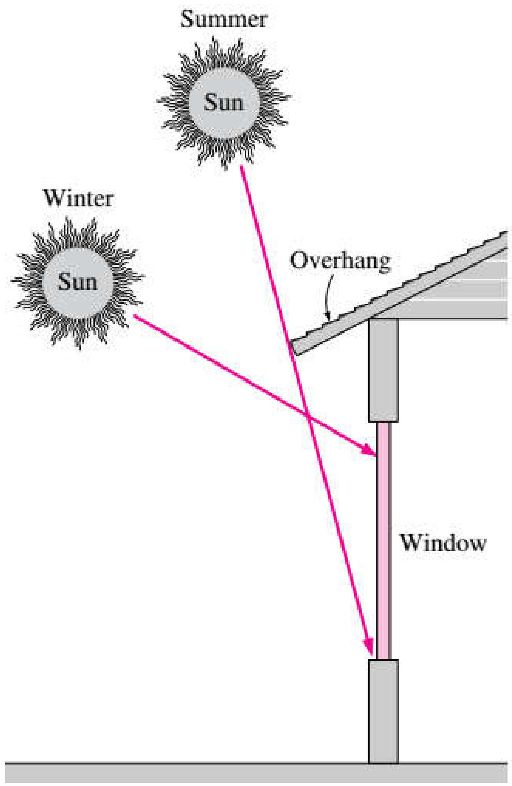
[b]Combined transmittance for assembled unit.

[c]Refers to gray-, bronze-, and green-tinted heat-absorbing float glass.

- Shading devices are classified as *internal shading* and *external shading,* depending on whether the shading device is placed *inside* or *outside*. External shading devices are more effective in reducing the solar heat gain since they intercept the sun's rays before they reach the glazing. The solar heat gain through a window can be reduced by as much as 80 percent by exterior shading.

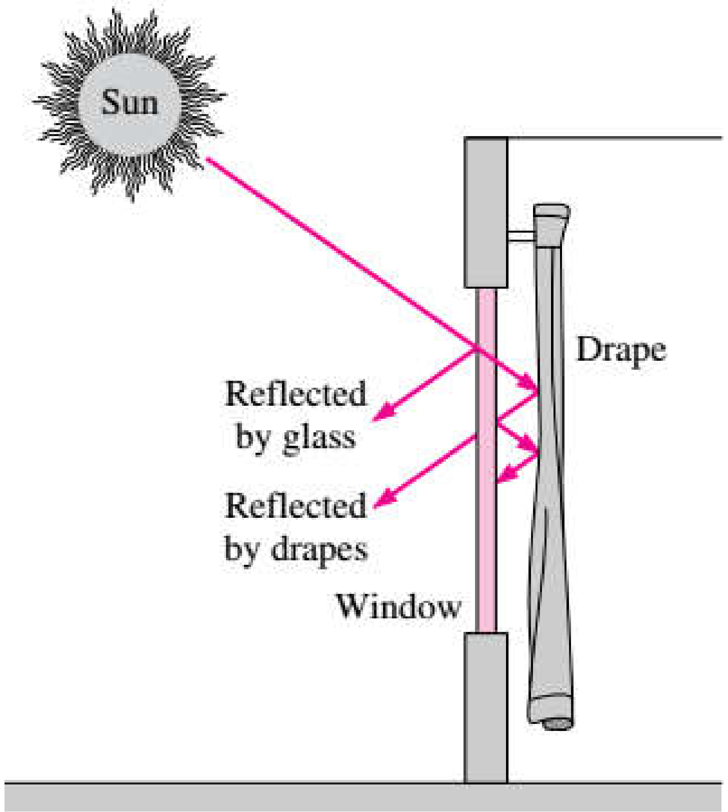
- Roof overhangs have long been used for exterior shading of windows. The sun is high in the horizon in summer and low in winter. A properly sized roof overhang or a horizontal projection blocks off the sun's rays completely in summer while letting in most of them in winter, as shown in the figure.

- Such shading structures can reduce the solar heat gain on the south, southeast, and southwest windows in the northern hemisphere considerably.



- Some type of internal shading is used in most windows to provide privacy and aesthetic effects as well as some control over solar heat gain. Internal shading devices reduce solar heat gain by reflecting transmitted solar radiation back through the glazing before it can be absorbed and converted into heat in the building.

- *Draperies* reduce the annual heating and cooling loads of a building by 5 to 20 percent, depending on the type and the user habits. In summer, they reduce heat gain primarily by reflecting back direct solar radiation.
- The semiclosed air space formed by the draperies serves as an additional barrier against heat transfer, resulting in a lower *U*-factor for the window and thus a lower rate of heat transfer in summer and winter. The solar optical properties of draperies can be measured accurately, or they can be obtained directly from the manufacturers.



- The shading coefficient of draperies depends on the openness factor, which is the ratio of the open area between the fibers that permits the sun's rays to pass freely, to the total area of the fabric. Tightly woven fabrics allow little direct radiation to pass through, and thus they have a small openness factor.

- The reflectance of the surface of the drapery facing the glazing has a major effect on the amount of solar heat gain. Light-colored draperies made of closed or tightly woven fabrics maximize the back reflection and thus minimize the solar gain. Dark-colored draperies made of open or semi-open woven fabrics, on the other hand, minimize the back reflection and thus maximize the solar gain.