Research Article

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Influence of insulated glass units thickness and weight reduction on their functional properties

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Abstract: Multi-glazed Insulated Glass Units (IGUs) are commonly used in the building industry. Larger number of gas-filled gaps is beneficial with regard to decrease of thermal losses in glazing, however the increased weight and thickness of a glazing unit cause additional difficulties during production, transport and installation of such elements. This disadvantage may be partially eliminated by using glass panes with thickness lower than 4 mm and by decreasing the thickness of gas-filled gaps between the individual glass panes. This article analyses the influence of reduction of weight and thickness of glass panes thickness and gas-filled gaps onto their functional properties. The analysis concerned two aspects: heat losses through glazing and static values occurring in IGUs loaded with changes in atmospheric pressure, temperature and wind pressure. Thermal transmittance and static values were defined for individual variations of structures' construction on basis of adopted calculation models. It was demonstrated that using glass panes of thickness 2 and 3 mm is justified in IGUs with respect to changes of atmospheric pressure and temperature. The IGU structures with glass panes of reduced thickness have shown larger deflections and stress when subject to wind load. The thickness reduction of gas-filled gaps is beneficial with respect to decrease of resultant load caused by climatic factors, however it causes an increase in heat loss.

Keywords: glass in building, transparent partitions, heat losses through glazing, loads on building structures

1 Introduction

Insulated glass units (IGUs) are a commonly used element of structures constituting transparent construction parti-

tions. Such a partition is composed of at least two panes joined with a spacer at the edges to obtain a tight joint [1]. The space between the panes is a tight gap filled with gas to allow for reduction of heat losses in buildings. For a number of years the residential building industry has been dominated by a standard set consisting of an insulated unit of two glass panes (one gap) with a declared value of thermal transmittance $U = 1.1 \text{ W/m}^2\text{K}$. Such a unit is composed of two 4 mm thick glass panes, separated by a gap (space) filled with argon of 16 mm standard thickness. At present, due to the increased interest in energy-saving and passive construction and the reinforcement of requirements concerning thermal protection of buildings [2, 3] there is a demand for improving thermal insulation of building partitions, including glazing. Therefore increased use of multi-glazed units seems a necessity - the advantage of such units is reduction of thermal transmittance and reduction of heat losses through glazing.

However, multi-glazed units have the basic disadvantage that is a significant increase of weight and thickness of such elements, which may cause difficulties during production, transport and installation of insulated glass units. Also, the structure of window frames must be adopted to withstand the increased weight of IGUs. This disadvantage may be partially eliminated by using glass panes of thickness lower than 4 mm and by reducing the thickness of gas-filled gaps between the component glass panes [4–6].

The objective of the analysis, carried out in the article below, was to determine the influence of reduction of glass panes thickness and gas-filled gaps thickness in insulated glass units on their functional properties.

The analysis focused on two aspects: heat losses through glazing (thermal transmittance) and the static values (resultant load, deflection, stress) occurring in IGUs subjected to climatic factors (changes of atmospheric pressure and temperature, wind load).

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2 Analysis of IGUs thermal transmittance

2.1 Calculation methodology

Thermal transmittance U [$\text{W}/\text{m}^2\text{K}$] for insulated glass units was determined using calculation method based on a standard [7]. The value U depends on:

- thermal surface coefficients on the internal and external side of a partition; values of those coefficients depend on ambient conditions, in the first place on air movement speed rate,
- thickness of component glass panes, due to good thermal conductivity of glass this influence is minor,
- thermal resistance of tight gas-filled gaps - this influence has been analysed in chapter 2.2,
- location of a glass pane; in this article the assumed location of the IGUs is vertical, in case of horizontal or inclined IGUs the U value is increased.

2.2 Thermal resistance of tight gas-filled gaps

The thermal resistance of a tight gap filled with gas R_s [$\text{m}^2\text{K}/\text{W}$] is calculated using the following formula

$$R_s = \frac{1}{h_r + h_g} \quad (1)$$

where:

h_r – thermal conductivity by radiation [$\text{W}/\text{m}^2\text{K}$],

h_g – gas thermal conductivity [$\text{W}/\text{m}^2\text{K}$].

In accordance with the calculation model, as described in [7] the h_r value depends on average gas temperature in a gas-filled gap T_m [K] and, firstly, on emissivity ϵ [-] of surfaces of the glass panes limiting the gap. It is assumed that $\epsilon = 0.837$ for glass panes without modifying coating. A low E coating reduces surface emissivity to $\epsilon = 0.1 \div 0.04$. Application of such coating limits the thermal conductivity by radiation, thus increasing the thermal resistance of a gas-filled gap by several times [8, 9].

The h_g parameter describes gas thermal conductivity by conduction, with regard to convection. The influence of convection is disregarded for thin gaps, which means that the h_g value is inversely proportional to gap thickness, and the thermal resistance R_s dependence on the gas-filled gap thickness is approximately linear. When a certain limit value has been exceeded, the influence of convection becomes visible - further increase of thickness of the gas layer is no longer beneficial. The limit value of thickness for

Figure 1: Dependence of thermal resistance of an argon filled gap on its thickness and on temperature difference ΔT of the limiting surfaces, description provided in the text.

a gap filled with gas depends above all on temperature differences ΔT [K] on the surfaces limiting this gap [10]. The described phenomenon is presented in Figure 1, where the dependence of gas-filled gap thermal resistance on its thickness was shown for a layer of argon. The following assumptions were made: $T_m = 283.15$ K (10°C), emissivity of limiting surfaces $\epsilon_{1s} = 0.837$ and $\epsilon_{2s} = 0.04$, wind speed rate 4 m/s. On the basis of graph in Figure 1 it was found that:

- adding gas-filled gaps to an insulated glass unit is beneficial because the ΔT values for individual gaps are usually lower than in a double-glazed unit,
- in case of large ΔT values, for example in winter time, reduction of gas-filled gap thickness may not result in decrease of its thermal resistance.

2.3 Influence of gas-filled gap thickness on the thermal transmittance of an IGU

The analysis of the gas-filled gap thickness influence on the U value was performed for two different variants of environmental conditions:

- external temperature $t_e = 0^\circ\text{C}$, internal temperature $t_i = 20^\circ\text{C}$, wind speed rate 4 m/s - those are approximate standard conditions defined in [7],
- winter conditions - drop in external temperature $t_e = -20^\circ\text{C}$.

Figure 2 presents the design of the IGUs under analysis. The thickness of the component glazing is marked as d , and the thickness of the gas-filled gap is marked as s . For the purpose of identifying the individual elements of the IGU, the following indices were applied: the chambers were labelled with subsequent numbers starting from the

Figure 2: Structure of IGU: double-glazed unit, b) triple-glazed unit, a) quadruple-glazed unit.

A - Component glass pane, B - Gas-filled gap, C - Low-E coating, D - Sealant, E - Edge spacer with moisture absorber.

Table 1: Variations' characteristics of heat transfer coefficient of IGUs.

Gas-filled gap thickness s [mm]	Thermal transmittance U [W/m ² K]					
	Standard conditions			Winter conditions		
	Double-glazed	Triple-glazed	Quadruple-glazed	Double-glazed	Triple-glazed	Quadruple-glazed
8	1.63 (46.4%)	0.95 (69.1%)	0.66 (73.0%)	1.58 (19.0%)	0.92 (43.3%)	0.65 (62.3%)
10	1.41 (26.5%)	0.80 (42.8%)	0.55 (44.8%)	1.36 (2.6%)	0.78 (20.8%)	0.54 (35.6%)
12	1.25 (11.9%)	0.70 (24.3%)	0.48 (25.3%)	1.30 (-2.5%)	0.67 (4.9%)	0.47 (17.1%)
14	1.12 (0.7%)	0.62 (10.6%)	0.42 (10.9%)	1.31 (-1.2%)	0.63 (-1.4%)	0.42 (4.0%)
16	1.11	0.56	0.38	1.33	0.64	0.40
18	1.13 (1.1%)	0.53 (-5.8%)	0.35 (-8.6%)	1.34 (1.0%)	0.65 (1.3%)	0.41 (1.3%)

Figure 3: Dependence of thermal transmittance on gas-filled gap thickness for conditions: $t_e = 0^\circ\text{C}$, $t_i = 20^\circ\text{C}$.

Figure 4: Dependence of thermal transmittance on chamber thickness for conditions: $t_e = -20^\circ\text{C}$, $t_i = 20^\circ\text{C}$.

outside air side, the exterior glass pane is marked as “ex”, the interior glass pane is marked as “in”, while the remaining glass panes are labelled with the index with the chambers encasing them numbered in order.

Calculations of the U -value assumed that one of the limiting surfaces of each chamber features the Low-E coating (intermittent line in Figure 2). This design is advantageous in terms of reducing heat loss. It was also assumed

that the thickness of all glass panes is 4 mm, gaps filled with argon.

The results of calculations are demonstrated in Figure 3 and 4 and in Table 1. In the diagrams, the intermittent line designates the critical chamber thickness, when the influence of convection becomes visible. In Table 1 the values in brackets designate change in U value with regard to a unit with 16 mm thick gaps filled with argon.

2.4 Results discussion

The U value is a measurement of heat losses occurring in insulated glass units in predetermined conditions of heat transfer. It is not reasonable to use gas-filled gaps thicker than limit thickness values, exceeding of which makes the influence of convection visible. The limit values increase in case of greater number of glass panes in the IGU and drop in external temperature.

In double-glazed and triple-glazed units, where the gas-filled gaps are 16–18 mm thick, the U value is significantly larger in winter conditions than in standard conditions. In case of thinner gaps or quadruple-glazed units the U values may be more beneficial in winter conditions. We are considering two co-existing factors here: greater temperature difference value ΔT intensifies convective and radiative heat transfer in gas-filled gaps, but lowering the average gas temperature T_m in the gaps limit this heat transfer.

On the basis of performed calculations, it may be stated that using gas-filled gaps that are too narrow contributes to an increase in the heat losses through glazing, which is visible especially in the case of triple-glazed and quadruple-glazed units. In such units using gaps smaller than 12 mm leads to significant deterioration of the thermal properties of the partition.

3 Analysis of static values of an insulated glass unit in operation conditions

3.1 Calculation methodology

Insulated glass units have particular properties when it comes to transfer of climatic load. Each modification of gas temperature in a gas-filled gap or external atmospheric pressure creates a load on component glass panes and causes their deflection (Figure 5a, 5b). As a result of glass panes deflection, the gas in a tight gap changes its volume and pressure, partially compensating for the changes of pressure and temperature, however that doesn't change the fact that all changes of weather conditions, pressure and temperature are unfavourable for those structures. For example, deflections of glass panes are visible as the image seen in the light reflected by the glazing is distorted. There are attempts undertaken to reduce the loads of climatic influence by using devices equalizing gas pressure in the gas-filled gaps with the atmospheric pressure [11,

12]. Those solutions are in the testing phase now and are not mass produced.

In the case of applied surface load, for example wind pressure (Figure 5c), the changes of gas parameters in the gaps have a beneficial influence on the load distribution, as it is distributed on all glass panes in the unit.

The distribution of static values - resultant load per area q [kN/m²], deflection w [mm] and stress σ [MPa] of component glass panes in a unit is therefore a result of momentary balance between external loads and parameters of gas in tight gaps: pressure, volume and temperature.

Figure 5: Typical deflections of insulated glass units: a) increase of external pressure or decrease of gas temperature in the gaps, b) decrease of external pressure or increase of gas temperature in the gaps, c) wind pressure.

To determine a resultant load applied to each of the component glass panes, it is necessary to calculate the gas operating pressure, at which the system is in equilibrium. For a double-glazed unit appropriate calculation models are specified, among others, in [13–15]. In the article [16] the author has presented his own model allowing for estimation of gas operating pressure for a unit with any number of gas-filled gaps. It was assumed in this model that gas in the gaps meets the general gas equation.

$$\frac{p_0 \cdot v_0}{T_0} = \frac{p_{se} \cdot v_{se}}{T_{se}} = \text{const} \quad (2)$$

where:

p_0 , T_0 , v_0 – initial gas parameters in the gap: pressure [kPa], temperature [K], volume of the gap [m³], obtained during the production process,

p_{se} , T_{se} , v_{se} – service parameters, respectively.

It was also assumed that each of the gas-filled gaps changes its volume due to deflection of the limiting glass panes.

$$\Delta v_j = \int_0^b \int_0^a w(x, y) dx dy = \alpha_j \cdot q_j \quad (3)$$

where:

Δv_j – change of gas-filled gap volume caused by deflection of one of the glass panes limiting this gap [m³],

Table 2: Static values in component glass panes - increase of atmospheric pressure by 3 kPa.

Structure of IGU [mm]	Resultant load per area q [kN/m ²]				Deflection w [mm]				Stress σ [MPa]			
	ex	1-2	2-3	in	ex	1-2	2-3	in	ex	1-2	2-3	in
$d_{ex} \cdot s_1 \cdot d_{1-2} \cdot s_2 \cdot d_{in}$	Triple-glazed units											
4-16-4-16-4	0.129	0.000	-	-0.129	1.05	0.00	-	-1.05	2.44	0.00	-	2.44
4-12-4-12-4	0.098	0.000	-	-0.098	0.80	0.00	-	-0.80	1.85	0.00	-	1.85
3-12-3-12-3	0.042	0.000	-	-0.042	0.82	0.00	-	-0.82	1.42	0.00	-	1.42
4-12-2-12-4	0.098	0.000	-	-0.098	0.80	0.00	-	-0.80	1.85	0.0	-	1.85
6-12-2-12-4	0.154	-0.006	-	-0.147	0.37	-0.41	-	-1.20	1.29	0.48	-	2.77
6-12-2-12-3	0.082	-0.009	-	-0.073	0.20	-0.60	-	-1.41	0.69	0.70	-	2.45
$d_{ex} \cdot s_1 \cdot d_{1-2} \cdot s_2 \cdot d_{2-3} \cdot s_3 \cdot d_{in}$	Quadruple-glazed units											
4-16-4-16-4-16-4	0.189	0.062	-0.062	-0.189	1.54	0.50	-0.50	-1.54	3.56	1.17	1.17	3.56
4-12-4-12-4-12-4	0.144	0.048	-0.048	-0.144	1.17	0.39	-0.39	-1.17	2.71	0.89	0.89	2.71
3-12-3-12-3-12-3	0.063	0.021	-0.021	-0.063	1.21	0.40	-0.40	-1.21	2.10	0.70	0.70	2.10
4-12-2-12-2-12-4	0.145	0.006	-0.006	-0.145	1.18	0.39	-0.39	-1.18	2.73	0.45	0.45	2.73
6-12-2-12-2-12-4	0.231	-0.003	-0.015	-0.213	0.56	-0.20	-0.97	-1.74	1.94	0.24	1.12	4.02
6-12-2-12-2-12-3	0.133	-0.007	-0.019	-0.107	0.32	-0.47	-1.26	-2.06	1.11	0.54	1.46	3.57

$w(x,y)$ – function of deflection, [m] dependence of the deflection value on the coordinates (x,y) of any point located on a glass pane with width a [m] and length b [m],
 α_j – proportionality factor [m⁵/kN]; it is a change in volume with unit resultant load per area of the glass pane,
 q_j – resultant load per area on a glass pane that limits a gap [kPa].

The assumption that the deflection dependence on the load is linear is a sufficient approximation in case if the deflection value does not exceed the thickness of a glass pane [17].

On the basis of formulas (1) and (2) it is possible to create an equation for each gas-filled gap that describes its operational volume in equilibrium condition, with a determined load. The solution of this equation (for double-glazed units) or simultaneous equations (for multi-glazed units) allows for determining operational pressure in the gas-filled gaps, as described in detail in [16]. The resultant load for each of the component glass panes is defined separately on basis of pressure difference between the gaps or between the gap and its environment, with regard to external surface loads, e.g. wind pressure. The knowledge of resultant load allows for calculating maximal deflection and stress for each glass pane by means of dependencies known in Kirchhoff-Love theory of plates, for example in accordance with [18].

3.2 Influence of gas-filled gaps thickness and glass panes thickness on static values of IGUs

The analysis of influence of the thickness of gas-filled gaps and glass panes thickness on static values of insulated glass units has been carried out in accordance with the method presented in [16], on basis of a unit with following dimensions: 0,8×1,2 m. It was assumed: Young's modulus for glass 70 GPa and Poisson's ratio 0.2. Assumed initial conditions were: $p_0 = 100$ kPa, $T_0 = 293.15$ K (20°C). Two types of load were analysed:

- increase of atmospheric pressure by 3 kPa, as an example of load applied symmetrically (drop in gas temperature in the gas-filled gaps by 8.8 K brings the same results),
- wind load pressure of 0.3 kN/m², as in Figure 5c, as an example of non-symmetrical load.

Following sign convention was assumed: the resultant load per area and deflection are considered positive, if their direction is from exterior to interior (from left to right in Figure 2).

Tables 2 and 3 present the calculation results for static values of each of the component glass panes (index designations as in Figure 2 were used). Triple-glazed and quadruple-glazed units of various structures were subjected to analysis.

Figure 6 presents charts demonstrating the influence of component glass panes thickness on maximal deflection w and stress σ in an IGU, with change in atmospheric pressure load by 3 kPa and with constant thickness of the gas-filled gap $s = 12$ mm.

Table 3: Static values in component glass panes - load “wind from the left” 0.3 kN/m^2 .

Structure of IGU [mm]	Resultant load per area $q \text{ [kN/m}^2\text{]}$				Deflection $w \text{ [mm]}$				Stress $\sigma \text{ [MPa]}$			
	ex	1-2	2-3	in	ex	1-2	2-3	in	ex	1-2	2-3	in
Triple-glazed units												
$d_{ex} \cdot s_1 \cdot d_{1-2} \cdot s_2 \cdot d_{2-3} \cdot d_{in}$												
4-16-4-16-4	0.107	0.098	-	0.094	0.87	0.80	-	0.77	2.02	1.85	-	1.77
4-12-4-12-4	0.106	0.099	-	0.096	0.86	0.8	-	0.78	1.99	1.86	-	1.80
3-12-3-12-3	0.102	0.100	-	0.098	1.97	1.92	-	1.89	3.43	3.33	-	3.28
4-12-2-12-4	0.146	0.018	-	0.136	1.19	1.15	-	1.11	2.75	1.33	-	2.56
6-12-2-12-4	0.229	0.008	-	0.063	0.55	0.53	-	0.51	1.91	0.61	-	1.19
6-12-2-12-3	0.259	0.009	-	0.031	0.62	0.61	-	0.60	2.17	0.71	-	1.05
Quadruple-glazed units												
$d_{ex} \cdot s_1 \cdot d_{1-2} \cdot s_2 \cdot d_{2-3} \cdot s_3 \cdot d_{in}$												
4-16-4-16-4-16-4	0.086	0.076	0.070	0.067	0.70	0.62	0.57	0.55	1.63	1.44	1.32	1.26
4-12-4-12-4-12-4	0.084	0.076	0.071	0.069	0.68	0.62	0.58	0.56	1.57	1.43	1.34	1.30
3-12-3-12-3-12-3	0.079	0.076	0.073	0.072	1.52	1.46	1.42	1.39	2.64	2.53	2.46	2.42
4-12-2-12-2-12-4	0.144	0.017	0.016	0.123	1.17	1.11	1.05	1.00	2.71	1.28	1.22	2.31
6-12-2-12-2-12-4	0.225	0.008	0.008	0.060	0.54	0.52	0.50	0.48	1.88	0.60	0.58	1.12
6-12-2-12-2-12-3	0.252	0.009	0.009	0.030	0.61	0.59	0.58	0.57	2.11	0.69	0.67	1.00

Figure 6: Influence of component glass panes thickness on: a) deflection, b) stress, in an exemplary unit loaded with increase of atmospheric pressure by 3 kPa. **Figure 7:** Influence of gas-filled gaps thickness on: a) deflection, b) stress, in an exemplary unit loaded with increase of atmospheric pressure by 3 kPa.

Figure 7 presents parallel method of analysis of the influence of gas-filled gap thickness with the assumed component glass panes thickness d equal to 4 mm.

3.3 Results discussion

The presented calculation has demonstrated that the component glass panes in units transfer loads in a specific manner, respectively to the way the load is applied.

In case of climatic load acting symmetrically (change of atmospheric pressure, homogeneous change of gas temperature in the gas-filled gaps) the static values increase

approximately proportionally to the increase in summary thickness of the gas-filled gaps. The deflection and stress are thus almost three times larger in a quadruple-glazed unit than in a double-glazed unit (Figure 7). Considering the above, it is beneficial to decrease the thickness of gas-filled gaps, as it results in decrease of deflection and stress.

When it comes to the influence of component glass panes thickness on the static values, the calculations have demonstrated that for each unit there is a critical thickness, with highest values of stress in component glass panes (intermittent line in Figure 6b). It results from the fact that thick glass panes are very rigid, therefore the stress value is low even in case of large loads, however very thin glass panes are more susceptible to deflection - in this case the change of pressure in the gaps resulting from change of their volume equalizes to a greater extent the change in atmospheric pressure and the resultant load decreases. For example, with modification of a glass pane thickness d from 4 mm to 2 mm in a quadruple-glazed unit the increase of deflection w is very slight (from 1.17 to 1.23 mm), yet the decrease of stress σ is significant (from 2.72 to 1.42 kPa).

Decrease in thickness of internal component glass panes (with indices 1-2, 2-3) has no negative results, as those glass panes are not significantly affected by the loads.

Still, differentiating the thickness of external glass panes may bring certain negative results (with indices “ex” and “in”) in case when one of them is thicker. In such case the atmospheric load is equalized by gas pressure in the gas-filled gaps to a lesser extent. It is visible that the total of absolute values of the component glass panes increases (even though the algebraic sum always equals 0), which is not beneficial. For example, thickening the glass pane with index “ex” from 4 mm to 6 mm resulted in increase of deflection and stress in all remaining glass panes of the units (Table 2).

An IGU affected by wind load behaves quite differently. The external load is distributed onto all glass panes in the unit (the total of resultant loads on glass panes equals the external load). The value of load affecting a particular glass pane depends on its location within the IGU, but firstly on its rigidity. The decrease of component glass panes thickness leads to the increase of deflection and stress in the unit. For example, in the units composed of 2 mm glass panes only even a small wind load results in large deflections, which in consequence limits the possibility of using such units.

Another example of decrease of internal component glass panes (with indices 1-2, 2-3) from 4 to 2 mm (Table 3). In this case glass panes with indices “ex” and “in”, as more

rigid ones, take over major part of the external load, thus their deflection and stress increases. However it is beneficial to thicken the “ex” glass pane directly affected by load, e.g. to 6 mm, as demonstrated in the calculations.

The distribution of loads in a glass pane affected by wind load is almost independent from the thickness of gas-filled gaps.

4 Conclusions

Shaping of glass insulated units, that is selection of thickness of component elements is a complex problem, especially in the case of multi-glazed units, where multiple variants are possible for an individual structure. This problem should be considered with respect to heat losses through glazing as well as with respect to the results of environmental loads affecting the glass panes. It is stated that some of the actions beneficial due to thermal properties of the glazing cause increased deflection and stress in the IGUs. Thus it is necessary to search for a kind of compromise between the two above mentioned aspects.

It was demonstrated in the article that reduction of thickness of some of the component glass panes in a unit in order to decrease the unit's weight doesn't lead to a significant increase of the deflection and stress of the unit, and in certain conditions those values are reduced. Above all, it is possible to reduce internal component glass panes even to 2 mm, while the external glass panes to 3 mm.

IGUs with glass panes of reduced thickness must be however used with care in locations exposed to large wind load. In such cases it is beneficial to increase thickness of the external glass pane, directly exposed to the wind load “ex”.

Reduction of thickness of the gas-filled gaps leads in most cases to worsening of the thermal properties of a partition, but also to decreased deflection and stress in the IGUs exposed to a climatic load. It is especially important in triple-glazed and quadruple-glazed units. Such units are exposed to much larger resultant loads than double-glazed units. The analysis described in this article has shown that reduction of gas-filled gaps in multi-glazed units below 12 mm is not justified due to significant increase of the heat transfer coefficient.

With the 12 mm thickness the heat losses in standard conditions increase by approximately 25%, but the summary value of gas layers and related deflections and stresses decrease by 25% (for quadruple-glazed units) which may be an acceptable compromise between the pros and cons of this solution.

Nomenclature

a width (of glass pane), [m]
b length (of glass pane), [m]
d thickness (of glass pane), [mm]
h thermal conductivity, [$\text{m}^2\text{K/W}$]
p pressure, [kPa]
q resultant load per area, [kN/m^2]
R thermal resistance, [$\text{W/m}^2\text{K}$]
s thickness (of gas-filled gap), [mm]
T temperature (of gas in the gap), [K]
t temperature (of air), [K] or [$^{\circ}\text{C}$]
U thermal transmittance, [$\text{W/m}^2\text{K}$]
v volume (of the gap), [m^3]
w deflection, [mm]
w(x,y) function of deflection, [m]

Greek letters

α proportionality factor, [m^5/kN]
 ΔT temperature difference, [K]
 Δv volume change, [m^3]
 ϵ surface emissivity, [-]
 σ stress, [MPa]

Subscripts and markings

0 initial gas parameters
1, 2, 3 specific gas-filled gap
1-2, 2-3 glass panes (between gaps)
1s, 2s surfaces (limiting the gap)
e external
ex exterior glass pane
g gas
i internal
in interior glass pane
j glass pane (limiting the gap)
m mean
r radiation
s gas gap
se service gas parameters

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