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To cite this article: V A Maiorov 2020 IOP Conf. Ser.: Mater. Sci. Eng. 939 012049

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Heat transfer through a double-glazed window by convection

V A Maiorov¹

¹Yaroslav-the-Wise Novgorod State University 41, B. St. Peterburgskaya str., 173003 Veliky Novgorod, Russia

E-mail: Vitaly.Mayorov@novsu.ru

Abstract. The formulation and method of solving the problem of convective heat transfer through a double-glazed window are presented. A description is given of the influence of the main parameters of the glass on the mechanism and quantitative characteristics of the process. The presence of the optimal thickness of the gas-filled chamber, at which its thermal resistance has a maximum value, is revealed. The possibilities of reducing convective heat losses through double-glazed windows by increasing the number of glasses and the use of low-heat-conducting gas filler are analyzed in detail. The main characteristics of the process of convective heat transfer for single and double chamber double-glazed windows with various gas fillers are given.

1. Formulation of the problem

The physical model of the process of convective heat transfer through a vertical single-chamber glass unit is shown in figure 1. Chamber width δ . The indoor air temperature is constant $t_i = 20^{\circ}$ C, the outdoor temperature is t_0 . The temperature of the inner surfaces of the glasses t_2 and t_3 . Due to the presence of a temperature difference between the glasses in a gas-filled chamber, free-convection circulation occurs - the gas rises up near the warm glass and drops down near the cold glass. Coefficient $\alpha_{c,23}$ characterizes the intensity of convective heat transfer between glasses. External $\alpha_{c,o1}$ and internal $\alpha_{c,d1}$ heat transfer coefficients take into account only the convective component of heat transfer. Here, the normative values [1] of the last two coefficients are accepted: $\alpha_{c.01} = 20 \text{ W}/(\text{m}^2 \cdot \text{K})$, $\alpha_{c.4i} = 3.6 \text{ W}/(\text{m}^2 \cdot \text{K})$. Glasses have the same thickness $\delta_g = 4$ mm and the thermal conductivity coefficient $\lambda_g = 1$ W/(m·K). For calculation of convective heat transfer transmitted through a single-chamber double-glazed window of heat flow

$$q_{\rm c} = \frac{t_{\rm i} - t_{\rm o}}{R_c} \tag{1}$$

it is necessary to determine the components of the total thermal resistance of convective heat transfer:

$$R_{\rm c} = \frac{1}{\alpha_{\rm c.01}} + \left(\frac{\delta}{\lambda}\right)_{\rm g} + \frac{1}{\alpha_{\rm c.23}} + \left(\frac{\delta}{\lambda}\right)_{\rm g} + \frac{1}{\alpha_{\rm c.4i}} = R_{\rm c.01} + R_{\rm c.23} + R_{\rm c.4i} + 2\left(\frac{\delta}{\lambda}\right)_{\rm g}.$$
 (2)

Under the accepted conditions, all components, except $R_{c.23}$, in this expression are constant values: $R_{\rm c.o1} = 0.05 \text{ m}^2 \cdot \text{K/W}; R_{\rm c.4i} = 0.278 \text{ m}^2 \cdot \text{K/W}, (\delta/\lambda)_{\rm g} = 0.004 \text{ m}^2 \cdot \text{K/W}.$

The remaining term of the thermal resistance of convective heat transfer through a gas-filled chamber

$$R_{c.23} = 1/\alpha_{c.23}$$
 (3)

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contains an unknown value of the coefficient $\alpha_{c,23}$ of free convective heat transfer through the gas layer.

The intensity of the convective heat transfer through the glass packet under the accepted conditions is influenced by the thickness of the gas layer δ , the outside temperature to and the type of gas filler. It is required to find out the influence of the indicated parameters, to determine the thermal resistance of convective heat transfer through the glass packet and to choose the optimal combination of parameters to reduce the intensity of this process.





Figure 1. Physical model of the process of heat transfer by convection through a single-chamber double-glazed window.

Figure 2. Dependences of Nu on Ra for free convective heat transfer in a vertical cavity: 1 – set of equations (4); 2 – equation (7).

2. Features of free convective heat transfer through a gas-filled chamber

The intensity of the free convective heat transfer in the vertical gas layer $\alpha_{c.23}$ is recommended to be described by a set of criteria equations [1]:

$$Nu = 1 + 1.7596678 \cdot 10^{-10} Ra^{2.2984755}, Ra \le 10^4;$$
(4a)

$$Nu = 0.028154Ra^{0.4134}, 10^4 \le Ra \le 5 \cdot 10^4;$$
(4b)

$$Nu = 0.0673838Ra^{1/3}, 5 \cdot 10^4 \le Ra.$$
(4c)

Here the Nusselt criterion is

$$Nu = \frac{\alpha_{c.23}\delta}{\lambda},\tag{5}$$

The Rayleigh criterion

$$Ra = Gr Pr = \frac{g\beta\rho^2 \delta^3 c(t_3 - t_2)}{\mu\lambda} = \frac{g\beta\delta^3 (t_3 - t_2)}{\nu^2} Pr.$$
 (6)

These criteria include: $g = 9.81 \text{ m/s}^2$ – acceleration of gravity; β is the temperature coefficient of volume expansion (for gases $\beta = 1/T = 1/[273.15 + (t_2 + t_3)/2]$); ρ is the gas density; *c* is the heat capacity of the gas; λ is the thermal conductivity of the gas; μ , *v* are the dynamic and kinematic viscosity coefficients of the gas. The Rayleigh criterion is sometimes written in the form of a product of the Grashof criteria *Gr* and Prandtl $Pr = \mu c/\lambda$. The physical properties of the gas are calculated at the average gas temperature in the cavity.

The set of equations (4) was obtained in [2] as a result of generalization and analysis of all available relevant experimental data for vertical gas interlayers, the ratio of whose height to thickness δ is greater than 40. Solid line 1 in figure 2 correlates this data. Equations (4a)–(4c) are the equations of the individual parts of curve 1 in the corresponding sections. The boundaries of these areas are marked. A large number of significant digits in equations (4a)–(4c) are used to precisely match the individual parts of curve 1 at the boundaries of the sections.

For comparison, figure 2 shows a straight line 2, which corresponds to the approximate criteria equation:

$$Nu = 0.035(Gr \cdot Pr()^{0.38}) \tag{7}$$

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It follows from expression (5) that the Nusselt criterion has the physical meaning of the ratio of the magnitude of the heat flux transferred by convection to the magnitude of the heat flux transmitted by the thermal conductivity through the stationary gas filling the interlayer. From the data in figure 2, it follows that Nu = 1 for values of Ra <1000. In this range of Ra numbers in the cavity, there is a slow circulating laminar gas flow in the form of a single cell. Such circulation occurs at any non-zero temperature difference $(t_3 - t_2)$ of the glasses. The temperature distribution in the gas gap is linear, and the heat flux through the gap is equal to that which is transmitted by the thermal conductivity through the stationary gas filling the gap. This mode is called conductive. As the Ra number increases, the intensity of gas circulation increases and convective heat transfer begins to appear. The temperature distribution in the gap gradually deviates from linear. The number Nu deviates from unity and slowly increases. In this case, a stable laminar single-cell flow regime is maintained until, at approximately Ra = 6000, a secondary cell begins to form in the flow. With a further increase in the Ra number, the flow structure gradually becomes more complicated and the intensity of convective heat transfer increases. A detailed description of the change in the flow structure in the vertical gap is given in [3]. It should be noted that for double-glazed windows with a maximum temperature difference between indoor and outdoor air, the upper limit of the numbers Ra is in the range of 6000–10000.

The value of $R_{c,23}$ of thermal resistance is the main characteristic of convective heat transfer through the gas layer. In view of (3) and (5), we can write:

$$R_{c.23} = (1/Nu) \cdot (\delta/\lambda). \tag{8}$$

It follows that the reference for comparison is the thermal conductivity resistance δ/λ of the gas layer. With an increase in the Nusselt number, the value of $R_{\kappa,23}$ decreases in comparison with this standard.

It follows from expressions (4)–(6) that the value of the Nusselt criterion is influenced by the thickness of the gas layer δ , the temperature difference between the glass surfaces ($t_3 - t_2$), and the physical properties (type) of the gas filler. Let us find out the influence of each of them.

2.1. The effect of the thickness of the gas layer on its thermal resistance

In figure 3, curve *I* shows the dependence of the thermal resistance of free convective heat transfer through a vertical air gap on its thickness. Constant parameters are selected in accordance with the recommendations [1]: the physical properties of air are determined at an average temperature of 10°C; the temperature difference of the inner surfaces of the glasses $(t_3 - t_2) = 15^{\circ}$ C. With increasing δ , the number *Ra* increases in proportion to δ^3 . For small values of δ , the number *Nu* = 1 and, therefore, the value $R_{c.23} = \delta/\lambda$ increases linearly with increasing δ in the conductive heat transfer mode. Then, as the Nusselt number increases caused by the growth of δ , a smooth deviation from the straight line occurs

with a transition through a pronounced maximum and subsequent decrease and reaching a constant value in the horizontal section. For values of $\delta > 30$ mm, the value of $R_{c.23}$ remains constant and does not depend on the thickness of the gas layer. This horizontal section corresponds to the criterion equation (4c), according to which the number Nu increases in proportion to δ .

On curve 1, two points are of particular interest. The first point a is the maximum value of the thermal resistance $R_{c.23.onr}$ at the optimum thickness $\delta_{opt} = 16.48$ mm of the gas layer. The slope of the curve at the maximum point is zero and it is equal to the slope of the curve in the horizontal section at $\delta > 30$ mm. Therefore, the value of δ_{opt} corresponds to a value of the number Ra_{opt} at which the slope of curve *1* in figure 2 is 1/3, which is equal to the slope of its straight section at $Ra > 5 \cdot 10^4$. For the data in figure 2 we get a fixed value $Ra_{opt} = 8104$. $Nu_{opt} = 1.17$ corresponds to it – point *a* in figure 2.

The second point *b* corresponds to the minimum value $\delta_{\min} = 12.17$ mm of the thickness of the gas layer. For $\delta > \delta_{\min}$, a change in the thickness of the gas layer does not cause a significant change in $R_{c.23}$. A decrease in the thickness of the interlayer less than δ_{\min} leads to a rapid linear decrease in its thermal resistance. Therefore, for the accepted conditions, a double-glazed unit with a gas interlayer with a thickness of at least δ_{\min} should be used. Point *b* is located near curve *1* at the intersection of its linear ascending section with a dashed horizontal line. The corresponding δ_{\min} value of $Ra_{\min} = 3267$ is obtained from the condition $Nu_{\min} = 0.0674Ra_{\min}^{1/3} = 1$. This is the Ra_{\min} value in figure 2 is depicted by point b on the abscissa. The ratio $\delta_{opt}/\delta_{\min} = (Ra_{opt}/Ra_{\min})^{1/3} = 1.354$ remains constant.



Figure 3. The dependence of the thermal resistance of free convective heat transfer through a vertical air gap on its thickness: 1 – when using equations (4) in the calculations; 2 – when using equation (7).



Figure 4. The effect of the physical properties of gas on the dependence of the thermal resistance of free-convective heat transfer between glasses on the distance between them: 1 - air: 2 - argon; 3 - krypton.

An increase in the thickness of the gas-filled chamber above the optimal value δ_{opt} leads to a decrease in the resistance of convective heat transfer and is therefore undesirable. Judging by curve *I* in figure 3, it is difficult to determine the exact boundary of the maximum allowable thickness. For example, if we take the value $\delta_{max} = 18$ mm (point *c*), then we get $Ra_{max} = 10554$, $Nu_{max} = 1.297$.

Using the data in figure 3, the following can be used to determine the range of variation of the permissible parameters of the double-glazed unit:

$$3267 < Ra < 10554.$$
 (9)

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For comparison, curve 2 in figure 3 shows the dependence obtained using the approximate criteria equation (7). It consists of two sections: the initial increasing linear section at point *d* is abruptly replaced by a falling section. The value of the number $Ra_d = 6782$ corresponding to the abscissa $\delta_d = 15.53$ mm of the break point *d* is obtained from the condition $Nu_d = 0.035(Ra_d)^{0.38} = 1.0$ – point *d* on the abscissa axis in figure 2. Approximate curve 2 basically reproduces the form of the exact dependence 1. In the range of $\delta > 15$ mm, approximate curve 2 gives overestimated $R_{c,23}$ values with an error of about 10%.

2.2. The effect of the physical properties of gas

To increase the thermal resistance of the gas layer, gases with low thermal conductivity should be used. Table 1 shows the physical properties of such gases at a temperature of 10°C. Figure 4 reflects the influence of the physical properties of gases on the value of thermal resistance of freely convective heat transfer through a vertical gas layer. The temperature difference of the glass surfaces in all cases is assumed to be constant $(t_3 - t_2) = 15^{\circ}$ C. With a decrease in the thermal conductivity of gases, the slope of the initial linear portion of the curves increases, the maximum acquires a more pronounced character, but the value corresponding to the maximum of the optimum thickness δ_{opt} of the gas layer decreases. Ultimately, with a decrease in the thermal conductivity of gases, higher values of thermal resistance are achieved for any thickness of the gas interlayers. The values of the characteristic quantities δ_{opt} and $R_{c.23.opt}$ for these conditions are indicated in table 1. It should be noted once again that with a decrease in the thermal conductivity of gases, the value δ_{opt} of the gas layer also decreases. Reducing the optimal thickness of the gas layer allows you to both reduce the amount of expensive inert gas (krypton), and create multi-chamber double-glazed windows of acceptable thickness.

Table 1. The physical properties of gases [1].

Gas	t	$v \cdot 10^5$	Pr	λ	ρ	$\mu \cdot 10^5$	С	$\delta_{ m opt}$	R _{c.23.opt}
	[°C]	[m ² /s]		[W/m·K]	[kg/m ³]	$[N \cdot s/m^2]$	[J/kg·K]	[mm]	[m ² ·K/W]
Air	10	1.429	0.711	0.02496	1.232	1.761	1008	16.48	0.565
Argon	10	1.274	0.667	0.01684	1.699	2.164	519	15.6	0.792
Krypton	10	0.674	0.653	0.00900	3.560	2.400	245	10.3	0.976

2.3. The effect of the temperature difference of the glass surfaces $(t_3 - t_2)$

The data in figure 4 were obtained at a constant temperature difference between the glass surfaces $(t_3 - t_2) = 15^{\circ}$ C. An increase in the temperature difference of the glass surfaces causes a linear increase in the number *Ra* and a corresponding increase in the intensity of free convective heat transfer. The shape of the curves in figure 4 and the characteristic values of these curves δ_{opt} and $R_{c.23.\text{opt}}$.

Figure 5 shows the dependence of the optimal thickness of the gas interlayers on the temperature difference on them. For each curve, the relation is true

$$(\delta_{\text{opt}})^3 \cdot (t_3 - t_2) = Ra_{\text{opt}} \cdot (v^2/g\beta Pr) = C, \tag{10}$$

in which the constant *C* depends on the type of gas. The dashed line marks the values of δ_{opt} at a normalized value $(t_3 - t_2) = 15^{\circ}$ C, for which the results are shown in the previous figure 4. An increase in the temperature difference between the glasses leads to a decrease in the optimal distance between them. In this case, the corresponding value of $R_{c.23.opt}$ also decreases.

More clearly the effect of the temperature difference between the glasses on the thermal resistance of convective heat transfer between them is shown in figure 6. Here, in the form of curves 1-4, using four air-filled double-glazed units with a distance between the glasses of 10, 15, 20, and 30 mm as an example, it is shown how an increase in the temperature difference causes a decrease in $R_{c.23}$. Moreover,

the greater the distance between the glasses, the earlier it occurs and the more sharply this decrease is caused by an increase in the intensity of gas circulation between the glasses. As a result, $at(t_3 - t_2) > 25^{\circ}C$, the distance between the glasses practically ceases to affect the value of thermal resistance.



Figure 5. The dependence of the optimal distance between glasses on the temperature difference between them: 1 - air; 2 - argon; 3 - krypton; 4 - xenon.



Figure 6. The dependence of the thermal resistance of the air chamber on the temperature difference on it: $1 - \delta = 10$ mm; $2 - \delta = 15$; $3 - \delta = 20$; $4 - \delta = 30$; $5 - 2\delta = 20$; $6 - 2\delta = 30$ mm.

Such an undesirable effect of the temperature difference on the value of thermal resistance can be reduced if the gas layer with glass is divided into two parts of equal thickness. Then, on each of the halves, half of the total temperature difference is realized. This is the second way to increase the thermal resistance of convective heat transfer through the glass. In figure 6 curves 5 and 6 depict the total thermal resistance of two air chambers divided in half with a total thickness of 20 and 30 mm, respectively, depending on the value of the total temperature difference on them. These curves should be compared with curves 3 and 4 for undivided air chambers with a thickness of 20 and 30 mm, respectively. The difference between the pairs of these curves is very significant. The thermal resistance of a bisected chamber with a total thickness of 20 mm remains constant (curve 5), when, as a similar value of an undivided air chamber of the same thickness (curve 3), it halves with an increase in the temperature difference from zero to 40° C. An even more significant difference with increasing temperature difference is observed between curves 6 and 4.

3. Results and discussion

To solve the formulated problem (1) - (6) by determining the characteristics of convective heat transfer transmitted through a single-chamber glass packet of heat flow, it is necessary to calculate the thermal resistance of convective heat transfer through the gas interlayer $R_{c.23}$. To do this, under the conditions adopted in the statement of the problem for calculating $R_{c.23}$, you must first determine the temperatures of the inner surfaces of the glasses t_2 and t_3 .

Here, to solve, we use the method of successive approximations. Calculations are performed using spreadsheets.

We enter in the table the values of all constant parameters: δ , t_i , t_o , $\alpha_{c.01}$, $\alpha_{c.4i}$, δ_g , λ_g , type of gas filler. In a first approximation, we choose arbitrary values of the temperature of the inner surfaces of the glasses

 t_2 and t_3 from the interval between t_0 and t_i . For this, for example, you can use the condition for the equality of temperature drops in all sections: $t_3 - t_2 = t_2 - t_0 = t_i - t_3$. We calculate the average temperature of the gas layer $(t_2 + t_3)/2$. For this temperature, we select from the tables or calculate the physical properties of the gas filler λ , ν , *Pr*. Then we calculate the numbers *Ra* (6), *Nu* (4) and the value $R_{c,23}$ (8). Next, we calculate the individual components and the total value R_c (2) of the total thermal resistance of convective heat transfer. By the formula (1) we find the value of the convective heat flux q_c . After that, we determine the temperature of all glass surfaces:

$$t_1 = t_0 + q_c \cdot R_{c.01}; \ t_2 = t_1 + q_c \cdot (\delta/\lambda)_g; \ t_3 = t_2 + q_c \cdot R_{c.23}; \ t_4 = t_1 - q_c \cdot R_{c.4i} .$$
(11)

The calculation of the first approximation is completed. The values of the temperature of the inner surfaces of the glasses t_2 and t_3 obtained in the first approximation are used for repeated calculations in the second approximation. The calculations are repeated until in two successive approximations the values of the total thermal resistance of convective heat transfer R_c do not coincide with an accuracy of the third significant digit. The solution quickly converges. Usually no more than three to four approximations are required.

Similarly, calculations are performed for a two-chamber double-glazed window. In this case, in the case of an equal distance between the glasses and the same type of gas filler, the temperature differences on both gas layers are assumed to be the same. The physical properties of the gas are calculated at an average temperature of two gas interlayers.

Tables 2, 3 shows examples of calculating by method of successive approximations the main characteristics of convective heat transfer through single- and two-chamber double-glazed windows, respectively, at constant $t_1 = 20^{\circ}$ C, $t_0 = 0^{\circ}$ C for two types of gas filling: air, argon. The final results are shown on the last line of each option. In a first approximation, the temperature selection of the inner surfaces of the glasses was carried out from the condition of equality of the temperature difference in all areas: $t_3 - t_2 = t_2 - t_0 = t_1 - t_3$.



Figure 7. Changes in the temperatures t_2 and t_3 of the inner surfaces of the glasses and the density of the convective heat flux q_c in a single-chamber airfilled double-glazed window with decreasing temperature t_0 of the outside air.

Figure 7 shows how the temperature of the inner surfaces of the glasses and the density of the convective heat flux in a single-chamber double-glazed window filled with air change with a decrease in the temperature of the outside air. The distance between the glasses is $\delta = 15$ mm. The remaining parameters are indicated in the statement of the problem.

A	to	t_1	t_2	t_3	t_4	ti	Ra	Nu	$R_{\rm c}$	$q_{ m c}$
mation	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]			[m ² ·K/W]	[W/m ²]
					Air					
1st	0.00	6.67	6.67	13.33	13.33	20.00	2712	1.014	0.929	21.54
2nd	0.00	1.08	1.16	13.93	14.02	20.00	5244	1.062	0.901	22.19
3rd	0.00	1.11	1.20	13.75	13.84	20.00	5156	1.060	0.903	22.16
4th	0.00	1.11	1.20	13.76	13.85	20.00	5161	1.060	0.903	22.16
					Argon					
1st	0.00	6.67	6.67	13.33	13.33	20.00	3200	1.020	1.209	16.54
2nd	0.00	0.83	0.89	15.34	15.40	20.00	6987	1.121	1.131	17.69
3rd	0.00	0.88	0.96	15.02	15.09	20.00	6804	1.113	1.136	17.61
4th	0.00	0.88	0.95	15.04	15.11	20.00	6816	1.114	1.135	17.62

Table 2. The main characteristics of convective heat transfer through a single-chamber double-glazed window with a distance between glasses of $\delta = 15$ mm at constant $t_i = 20^{\circ}$ C, $t_o = 0^{\circ}$ C.

Table 3. The main characteristics of convective heat transfer through a two-chamber double-glazed window with the same distance between the glasses $\delta = 15$ mm at constant $t_i = 20^{\circ}$ C, $t_0 = 0^{\circ}$ C.

Appro	to	t_1	t_2	t_3	t_4	t_5	t_6	ti	Ra	Nu	$R_{ m c}$	$q_{ m c}$
ximation	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]			[m ² ·K/W]	[W/m ²]
						Air						
1st	0.00	5.00	5.00	10.00	10.00	15.00	15.00	20.00	2036	1.007	1.533	13.04
2nd	0.00	0.65	0.70	8.49	8.54	16.32	16.38	20.00	3186	1.020	1.518	13.17
3rd	0.00	0.66	0.71	8.47	8.53	16.29	16.34	20.00	3178	1.020	1.518	13.17
						Argon						
1st	0.00	5.00	5.00	10.00	10.00	15.00	15.00	20.00	2402	1.010	2.103	9.51
2nd	0.00	0.48	0.51	8.90	8.94	17.32	17.36	20.00	4044	1.034	2.062	9.70
3rd	0.00	0.48	0.52	8.88	8.91	17.27	17.31	20.00	4029	1.034	2.063	9.70

For both types of double-glazed windows filled with krypton, very large values of the Nusselt number lead to a significant decrease in resistance to convective heat transfer. This is due to the fact that the *Ra* numbers in these cases significantly exceed the permissible values determined by condition (9) due to the fact that the accepted value of the thickness of gas-filled chambers $\delta = 15$ mm is one and a half times higher than the optimal value $\delta_{opt} = 10.3$ mm for a single-chamber double-glazed window. For double-glazed windows filled with air and argon, the thickness of gas-filled chambers $\delta = 15$ mm used in the calculations is quite close to the optimal values.

4. Conclusion

A method for solving the problem of convective heat transfer through a double-glazed window by the method of successive approximations is developed. The solution is applicable for double-glazed windows with any number of glasses. The presented solution method allows you to perform a detailed analysis of the influence of the thickness of the gas layer, the physical properties of the gas filler and the temperature difference between the glasses on the thermal resistance of convective heat transfer through the glass packet. The main characteristics of the process for single and double chamber double-glazed windows with various gas fillers are given.

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