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Selection of a method for calculating heat gain from solar radiation to determine the load on the climate system of the cabin of a mobile car

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Introduction. The article analyzes and selects the most rational methods for calculating the heat gain from solar radiation. The correct calculation of this component of the heat balance allows you to correctly determine the power of the projected cabin climate system, which will ensure optimal working conditions at the workplace of mobile car operators.
Problem Statement. The objective of this study is to analyze and select a rational method for calculating heat gain from solar radiation for the correct determination of the thermal load on the climate system of the cabin of a mobile car.
Theoretical Part. To implement the task, the most common methods for calculating solar radiation were described and analyzed in detail and the most accurate ones were recommended.
Conclusions. The more labor-intensive method of V.N. Bogoslovskiy (taking into account the time of day) can be recommended for automated calculations in Excel, and the method of P.Y. Gamburg (taking into account the sides of the horizon) — for comparative estimated engineering calculations. When conducting "in-depth" model calculations and accounting for solar radiation, the ASHRAE method is explicitly suitable, which has two important advantages: it takes into account the solar factor in relation to a specific type of glazing and is adapted for automated calculations in ANSYS FLUENT.

Keywords: solar radiation, cabin, glazing, mobile car, climate control system.

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Introduction. Solar radiation accounts for a significant part of the heat inflow into the cabin of a mobile car (70-80 %) [1, 2]. This proves that the accuracy of determining the thermal load on the cabin climate system depends on the component of the Q_5 balance — solar radiation. Therefore, it is necessary to elaborate on its definition by analyzing various calculation methods and techniques. Moreover, the results of the calculations have very significant discrepancies among themselves. The amount of solar radiation obtained by the method [3, 4] is 30 % higher than that obtained by more modern methods, for example, by the ASHRAE method.

The light- and heat-transparent walls of the cabin are the most common ways of penetration of solar radiation, part of which (short-wave radiation) enters the cabin without obstacles, and the other part (convective heat) is absorbed by the glasses and enters due to the temperature difference. Figure 1 shows a diagram of the heat and humidity balance of the cab of a mobile car.

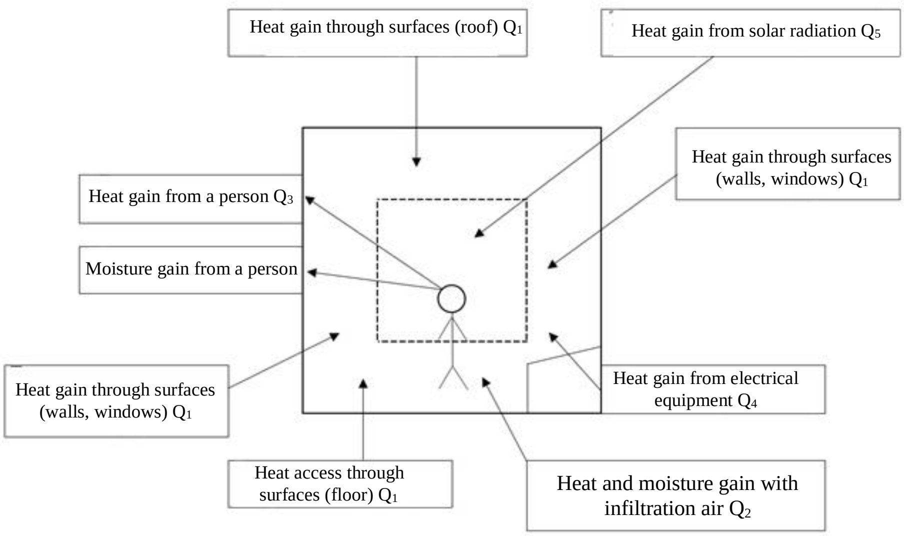

Fig. 1. Calculation model of heat and moisture transfer to the cabin of a mobile car in summer

In addition to the heat gain from solar radiation Q_5, the most significant in the heat balance are heat flows through the surfaces Q_1; from the infiltrated air Q_2; from the operator Q_3; from lighting and electrical appliances Q_4 [5–8].

Problem Statement. The objective of this study is to analyze and select a rational method for calculating heat gain from solar radiation for the correct determination of the thermal load on the climate system of the cabin of a mobile car.

Theoretical Part. The main methods for calculating heat gain from solar radiation are the following.

Method 1

Only those surfaces that face the sun are taken into account. Heat inflows from solar radiation, taking into account the degree of transmission of sunlight:

$$Q_5 = (A_к \cdot I \cdot K_k \cdot F_k)/\alpha_н + I \cdot K_б \cdot F_б + I \cdot K_ф \cdot F_ф, \quad (1)$$

where $A_к$ — the proportion of absorption of sunlight by the cabin roof; I — the intensity of radiation; $K_к$ — roof heat transfer coefficient, W/(m^2·K); $K_б$ and $K_ф$ — the coefficients of transmission of sunlight by glasses equal to $K_ф = 0.46$; $K_б = 0.8$; $F_к$, $F_б$ and $F_ф$ — the area of the roof and windows on the side and front wall, m^2.

This method gives an error in calculations due to the fact that the surfaces not facing the sun (side, back and floor) are under the influence of only scattered solar radiation, the magnitude of which is insignificant [2, 9, 10].

In the calculations, the outdoor air velocity was set to 0 m/s, and the indoor air was assumed to be 1.5 m/s. In this case, the total heat inflow from solar radiation was Q_5 = 2,603 W.

The total heat inflow through the cabin light openings was: $Q_{rad}^{glass} = 1155 + 1040 = 2195$ W.

Method 2

It is based on the calculation of the heat inflow from solar radiation through the cabin windows according to the method developed by P. Y. Hamburg (using shading coefficients) [6].

The total heat inflow into the cabin Q_{1c} (in watts) includes heat inflow through opaque walls and heat inflow through light openings, i.e.

$$Q_{1c} = Q_{1c}^{mass} + Q_{1c}^{light}. \quad (2)$$

Q_{1c}^{light} (W) is calculated for each side of the world:

$$Q_{1c}^{light} = Q_{ок} \cdot F \cdot \tau, \quad (3)$$

where $Q_{ок}$ — the specific heat inflow through a single glass, W/m^2; F — the window area, m^2; τ — the window shading coefficient by the shading device.

In our case, we select the coefficients τ from Table 1 according to the supplier's data from the technical characteristics of the glasses for the cabin of the mobile car.

Table 1

Technical characteristics of glasses

Glass	Thickness, mm	Light transmission, LT, %	Solar energy transmission, ET, %	Solar energy absorption, EA, %	Light reflection, LR, %	Reflection of IR radiation of the sun, % (estimated)
Colorless	4	90	83	9	8	7
	6	89	80	12	8	6
Planibel AGC green	4	80	56	38	7	6
	6	74	46	48	7	6
Planibel AGC blue	6	73	45	45	7	6
Planibel Torn	6	78	64	20	13	8
Pilkington, K-glass	4	82	61	9	11	19
	6	81	58	12	11	19
Pilkington, I-glass	4	86	61	5	9	26

The values of $Q_{ок}$ are given in the reference tables in [6]. At the same time, the greatest heat inflow is taken into account. Table 2 provides the results of the calculations of heat inflows from solar radiation through the cabin windows using the method of P. Y. Hamburg at 45° latitude of the cabin location at its different orientations on the sides of the horizon.

Table 2

Calculation of heat inflows from solar radiation through light openings, Krasnodar (45° latitude)

Cabins	Cardinal directions	Type of glazing	Area of the light opening, m^2	Heat gain according to the table	Shading coefficient, τ	$Q_{1c}^{свет}$, W
Orientation to the South						
1st cabin variant	South	Planibel AGC green	2.41	300	0.74	528.4
	North	Planibel AGC green	1.41	58	0.74	60.5
	East	Colorless	1.52	315	0.89	426.1
	West	Colorless	1.52	315	0.89	426.1
					Total	1 442
Orientation to the South-East						
1st cabin variant	South-West	Colorless	1.52	270	0.89	365.3
	North-East	Colorless	1.52	165	0.89	223.2
	South-East	Planibel AGC green	2.41	270	0.74	475.5
	North-West	Planibel AGC зеленое	1.41	165	0.74	172.2
					Total	1 236
South- East						
2nd cabin variant	South	Planibel AGC green	2.41	300	0.74	528.4
	North	Planibel AGC green	0.41	58	0.74	17.6
	East	Colorless	1.52	315	0.89	426.1
	West	Colorless	1.52	315	0.89	426.1
					Total	1 399

Method 3 (by shading)

Calculation of heat flows from solar radiation according to GOST 14 269-03 and CS 11765852-02-2016 [3]. Heat gain from solar radiation Q_{1c} consists of heat access through massive cabin surfaces and heat gain through light openings (formula (2)). Determination of heat gain from radiation light through the openings of the workplace according to the formula:

$$Q_{1c}^{свет} = I \cdot \sum_{i} (1 - K_i) \cdot F_i, \qquad (4)$$

where I — the intensity of solar radiation; K_i — the shading coefficient of the i-th surface; F_i — the area of the i-th light opening, m^2.

Taking into account the shading of the windows of the mobile car cabin, we will determine the heat flows from solar radiation through the light openings:

$$Q_{1c}^{light} = 950 \cdot (1 - 0{,}74) \cdot (2{,}41 + 3{,}8 + 1{,}4) = 2169 \text{ W}.$$

Then the heat gain from heat transfer through massive surfaces is equal to:

$$Q_{1c}^{ceiling} = K \cdot F \cdot \Delta t; \qquad (5)$$

$$Q_{1c}^{ceiling} = 1{,}87 \cdot 2{,}3 \cdot 21 = 91 \text{ Вт}.$$

The total heat flows through the glass amounted to 2,260 watts.

Method 4

Calculation according to the method of V. N. Bogoslovskiy [1, 10].

The total heat gain penetrating into the cabin through the light openings, W/m²:

$$q_{\Sigma} = q_{с.и.} + q_{т.п.}. \tag{6}$$

The heat gain from solar radiation in case of a vertical cabin window is equal to, W/m²:

$$q_{с.и.} = \left(q_{пр} \cdot К_{инс} + q_{рас} \cdot К_{обл}\right) К_{отн} \cdot \tau_2, \tag{7}$$

where $q_{пр}$, $q_{рас}$ — the heat gain taking into account direct and scattered solar radiation, W/m²; $К_{обл}$, $К_{отн}$ — the coefficients of irradiation and relative penetration of solar radiation, respectively; τ_2 — the coefficient of shading of the light opening with bindings; $К_{инс}$ — the coefficient of insolation, determined according to the formula

$$К_{инс} = \left(1 - \frac{L_г \operatorname{ctg} \beta - a}{H}\right)\left(1 - \frac{L_в \operatorname{tg} A_{с.о.} - c}{B}\right), \tag{8}$$

where $L_г$, $L_в$ — the width of horizontal and vertical shading devices, m; β — the angle between the window surface and the perpendicular projection of the solar beam, in degrees; $A_{с.о.}$ — solar azimuth of the glazing; a, c — the distance between shading devices and the window, m; H, B — window height and width, respectively.

Figure 2 shows the results of the calculation of the total heat gain into the cabin through the light openings, and a graph of the heat gain from solar radiation by the hours of the day in the hottest summer month according to this method.

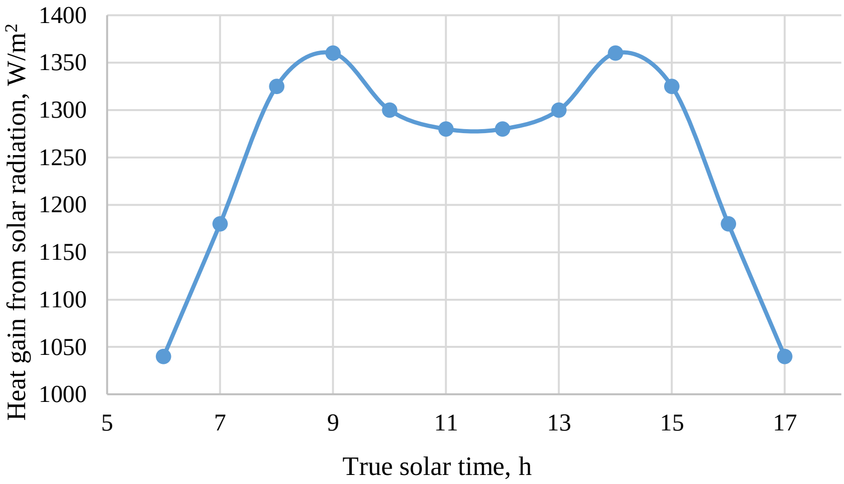

Fig. 2. Heat gain into the cabin from solar radiation by the hour of the day in July

Method 5

Calculation according to the methodology proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, ASHRAE [7].

The heat inflow from direct solar radiation $Q_п$ is equal to:

$$Q_п = S \cdot SHGC(\theta) \cdot IAC(\theta, \Omega) \cdot F_п, \tag{9}$$

where S — heat flow from direct solar radiation, W/m², falling on the wall, assumed to be equal depending on the geographical location, time of day and orientation of the cabin; SHGC(θ) — solar heat gain coefficient from direct solar radiation, depending on the technical characteristics of the double-glazed window and the angle of incidence θ; IAC(θ, Ω) —indoor solar attenuation coefficient from direct solar radiation, depending on θ, the presence of internal sun protection devices and the shadow angle Ω — the angle between the horizontal plane of the glazing and the projection of the sunbeam on the vertical plane perpendicular to the considered glazing plane; $F_П$ — glazing area, m².

The advantage of the described technique is that the heat inflow is determined relative to the flow on the wall, and the amount of radiant energy penetrating into the cabin is calculated due to the heat gain coefficient SHGC and the attenuation coefficient of the heat gain coefficient IAC. In this regard, it is necessary to define the term "solar factor". It means (g) the ratio of the total heat flow penetrating into the cabin to the flow of incident solar radiation (Fig. 3) [7].

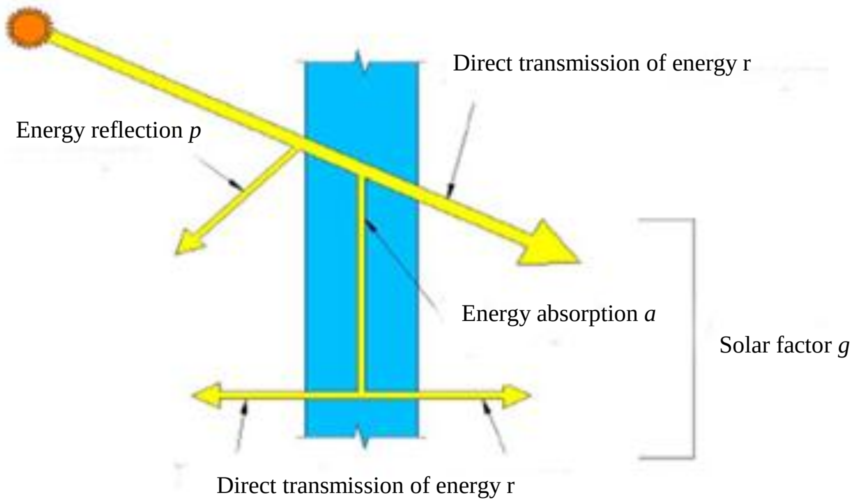

Fig. 3. Physical meaning of the solar factor [7]

The solar factor is one of the main parameters given in the technical specifications for a double-glazed window [7]. In this case, the solar factor gives a real reference to a certain type of glass, taking into account direct and scattered solar radiation penetrating into the cabin, which eliminates the need to take into account additional values of $q_п$ and $q_р$. In this case, the formula for heat gain from scattered solar radiation is transformed:

$$Q_р = (S \cdot K_{инс} + 0{,}75D \cdot K_{обл}) \cdot g \cdot k_{СЗУ} \cdot \tau_2 \cdot F_п, \tag{10}$$

where g — solar factor of the glass; $k_{СЗУ}$ — the heat transmission coefficient of sun protection devices.

It should also be noted that the basic principles of the ASHRAE methodology have been introduced into the ANSYS software package, which makes it attractive for practical model calculations. In the solar load model, it is possible to obtain data on the amount of solar radiation in a specific period of time using the solar calculator program.

Let us summarize in Table 3 the total values of heat gain from solar radiation to the workplace of the mobile car operator, calculated by various methods.

Table 3

Total values of heat gain from solar radiation

Calculation method	Without taking into account the sides of the horizon	GOST 14269-03, not taking into account the sides of the horizon	Method of P. Y. Hamburg, taking into account the sides of the horizon	Nethod of V. N. Bogoslovskiy, taking into account the sides of the horizon and the time location
Heat gain from the sun, W	2 195	2 260	1 394	1 346

Conclusions. When determining the heat gain from solar radiation by methods that do not take into account the sides of the horizon and the time of day, the amount of heat gain is significantly greater than with their consideration (Table 3). Methods that are not based on taking into account the sides of the horizon are impractical to use in engineering calculations due to the primitive approach and, as a result, the "roughness" of determining the calculated values. They, as a rule, give inflated values by almost 2 times. On the contrary, the methods of V. N. Bogoslovskiy (accounting for the time of day) and P. Y. Hamburg, taking into account the sides of the horizon, give almost identical results (a difference of 48 watts), which proves the correctness of determining the calculated values. The ASHRAE technique has two advantages — it not only takes into account the solar factor of a particular glazing, but is also adapted to automated calculations in ANSYS FLUENT.

To calculate the total heat gain from solar radiation, we can recommend the method of P. Y. Hamburg [6], which is applicable for comparative evaluation engineering calculations due to its simplicity, in comparison with the method of V. N. Bogoslovskiy. V. N. Bogoslovskiy's more labor-intensive method (taking into account the time of day) can be recommended for automated calculations in Excel.

The analysis of the calculation results presented in Table 3 shows that the greatest value of heat gain for summer is from solar radiation and is 1,393.2 W. At an outdoor air velocity of 2.7 m/s, the transmission heat gain is the main one, equal to 914.1 W, operational heat gain is less important. The data obtained are necessary to determine the air flow and load on the selected heat exchange equipment. For the calculation, we select the highest value at an outdoor air velocity of 2.7 m/s.

When conducting model computer calculations and accounting for solar radiation, the ASHRAE technique is the most suitable one. It has two important advantages — it takes into account the solar factor in relation to a specific type of glazing and is adapted to automated calculations in ANSYS FLUENT.

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