The choice of the method for calculating heat supply from solar radiation to determine the load on the climate system of the cabin of a mobile machine

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Abstract. The aim of the study is to analyze and select a rational method for calculating heat supply from solar radiation for the correct determination of the thermal load on the climate system of the cabin of a mobile machine. The correct calculation of this component of the heat balance allows to correctly determine the power of the climate system of the cabin, which ensures optimal working conditions at the workplace of operators of mobile machines. To achieve the goal, the most common methods for calculating solar radiation were described and analyzed in detail, and the most accurate ones were recommended. The more laborious Bogoslovsky method (taking into account the time of the day) can be recommended for automated calculations in Excel, and the Hamburg method (taking into account the horizon sides) – for comparative evaluative engineering calculations. When carrying out “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.

1. Introduction
Solar radiation makes up a significant part of the heat inflow into the cabin of mobile cars (70-80 %) [1, 2]. This proves that the accuracy of determining the thermal load on the climate system of the cabin decisively depends on the balance component Q₅ – solar radiation. Therefore, it is necessary to dwell in more detail on its definition, having analyzed various calculation methods and techniques. Moreover, the calculation results have very significant discrepancies between themselves, for example, the value 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. Light and heat-transparent walls of the cabin are the most common ways of penetrating of solar radiation, part of which (short-wave radiation) enters the cabin without obstacles, and the other part (convective heat) is absorbed by the glass and enters inside due to the temperature difference. Figure 1 shows a diagram of the thermal – humidity balance of the cabin.

In addition to the heat supply from solar radiation Q₅, the most significant in the heat balance are heat flows through the enclosing surfaces Q₁, from the infiltrated air Q₂, from the operator Q₃; from lighting and electrical appliances Q₄ [5, 6].
2. Basic methods for calculating heat supply from solar radiation

Method 1. Only those barriers that are facing the sun are taken into account. Heat inflows from solar radiation, taking into account the degree of transmission of sunlight:

\[ Q_5 = (A_r \cdot I \cdot K_r) / \alpha_{in} + I \cdot K_s + I \cdot K_f \cdot F_r, \]  

where \( A_r \) — share of absorption of sunlight by the roof of the cab; \( I \) — radiation intensity; \( K_r \) — roof heat transfer coefficient, \( W/(m^2\cdot\text{K}) \); \( K_s, K_f \) — the glass transmittance of sunlight equal to \( K_f = 0.46; K_s = 0.8; F_r, F_s, F_f \) — area of roof and windows on the side and front wall, \( m^2 \).

Method 1 gives an error associated with the fact that the walls not facing the sun (side, back and the floor) are exposed only to scattered solar radiation, the value of which is insignificant [2].

In the calculations, the speed of the outdoor air is set to 0 m/s, and the indoor air is taken to be 1.5 m/s. In this case, the total inflow of heat from solar radiation will be \( Q_5 = 2603 \) W.

The total heat flow through the light openings of the cab will be:

\[ Q_{rad}^{glass} = 1155 + 1040 = 2195 \text{ W}. \]

Method 2. Based on the calculation of the heat inflow from solar radiation through the glass of the cabin according to the method developed by P. Yu. Hamburg (using shading coefficients).

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

\[ Q_{1c} = Q_{1c}^{mass} + Q_{1c}^{light}. \]  

\( Q_{1c}^{light} \) (W) is calculated for each cardinal point:

\[ Q_{1c}^{light} = Q_{win} \cdot F \cdot \tau \]  

where \( Q_{win} \) — specific heat gain through single glass, W/m2; \( F \) — window area, m2; \( \tau \) — shading coefficient of the window by the shading device.

In our case coefficient \( \tau \) is chosen from Table 1 according to the supplier of the cabin glass specifications.

The values of \( Q_{win} \) are given in the reference tables. In this case, the largest heat inflow is taken into account. Results of calculations of heat inflows from solar radiation through the cabin windows by P. Yu. Hamburg are presented in Table 2 at the latitude 45\(^\circ\) of the location of the cabin with different orientations along the sides of the horizon.
### Table 1. Technical characteristics of glasses.

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

### Table 2. Calculation of heat inflows from solar radiation through skylights of Krasnodar latitude 45°.

| Cabins        | Sides of the horizon | Glazing type          | Skylight area, m² | Heat gain according to the table | Shading coefficient, τ | Q₁c light, W |
|---------------|----------------------|-----------------------|-------------------|----------------------------------|------------------------|--------------|
| South orientation |                      |                       |                   |                                  |                        |              |
| 1st version of the cabin | 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        |
| Sum              |                      |                       |                   |                                  |                        | 1442         |
| Southeast orientation |                  |                       |                   |                                  |                        |              |
| 1st version of the cabin | S-West             | colorless            | 1.52              | 270                              | 0.89                   | 365.3        |
|                   | N-East              | colorless            | 1.52              | 165                              | 0.89                   | 223.2        |
|                   | S-East              | Planibel AGC green   | 2.41              | 270                              | 0.74                   | 475.5        |
|                   | N-West              | Planibel AGC green   | 1.41              | 165                              | 0.74                   | 172.2        |
| Sum              |                      |                       |                   |                                  |                        | 1236         |
| South orientation |                      |                       |                   |                                  |                        |              |
| 2nd version of the cabin | 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        |
| Sum              |                      |                       |                   |                                  |                        | 1399         |

Method 3 (via shading). Calculation of heat gains from solar radiation in accordance with GOST 14269-03 and STO 11765852-02-2016. Heat gains from solar radiation $Q_{1c}$ consist of heat gains through massive cabin berriers and heat gains through skylights (formula (2)). Determination of the heat gain from radiation through the light openings of the workplace according to the formula:

$$Q_{1c}^{\text{light}} = 1 \cdot \sum_{i} (1 - K_i) \cdot F_i,$$

where $I$ – solar radiation intensity; $K_i$ – shading coefficient of the $i$-th berrier; $F_i$ – area of the $i$-th light opening, m²
Taking into account the shading of the cabin glass, let us determine the heat gain from solar radiation through the light openings:

\[ Q_{1c}^{\text{light}} = 950 \cdot (1 - 0.74) \cdot (2.41 + 3.8 + 1.4) = 2169 \text{ W}. \]

Then the heat gain from heat transfer through massive barriers is:

\[ Q_{1c}^{\text{ceiling}} = K \cdot F \cdot \Delta t \]  
\[ Q_{1c}^{\text{ceiling}} = 1.87 \cdot 2.3 \cdot 21 = 91 \text{ W}. \]

The total heat gain through the glass was 2260 W.

Method 4. Calculation by the method of Bogoslovsky.

Total heat gain entering the cabin through skylights, W/m² [1]:

\[ q_\Sigma = q_{\text{s.r.}} + q_{\text{h.t.}}. \]

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

\[ q_{\text{s.r.}} = (q_{\text{dir}} \cdot K_{\text{ins}} + q_{\text{scat}} \cdot K_{\text{irrad}}) K_{\text{rel}} \cdot \tau_2 \]

where \( q_{\text{dir}}, q_{\text{scat}} \) – heat gain that takes into account direct and scattered solar radiation, W/m²; \( K_{\text{irrad}}, K_{\text{rel}} \) – the coefficients of irradiation and relative penetration of solar radiation, respectively; \( \tau_2 \) – shading coefficient of the skylight by bindings; \( K_{\text{ins}} \) – insolation coefficient determined in accordance with the formula:

\[ K_{\text{ins}} = \left( 1 - \frac{L_h \cdot \text{ctg} \beta \cdot a}{H} \right) \left( 1 - \frac{L_v \cdot \text{tg} a_{s.g} - c}{B} \right), \]

where \( L_h, L_v \) – width of horizontal and vertical shading devices, m; \( \beta \) – the angle between the window surface and the perpendicular projection of the sunbeam, °; \( a_{s.g} \) – solar azimuth of glazing; \( a, c \) – distance between shading devices and window, m; \( H, B \) – window height and width, m.

The results of the calculation according to the Bogoslovsky method of the total heat flow penetrating into the cabin through the light openings, and the graph of changes in heat input from solar radiation by the hours of the day in the hottest summer month into the cabin are shown in Figure 2.

**Figure 2.** Heat input to the cabin from solar radiation according to different hours of the day in July.

Method 5. Calculation according to the method proposed by the American society of heating, refrigerating and air-condition engineers, ASHRAE [7-9].

Heat inflow from direct solar radiation \( Q_d \) is equal to:

\[ Q_d = S \cdot \text{SHGC}(\theta) \cdot \text{IAC}(\theta, \Omega) \cdot F_g \]

where \( S \) – heat flow from direct sunlight, W/m², falling on the wall, taken equal depending on the geographic location, time of the day and orientation of the cabin; \( \text{SHGC}(\theta) \) – solar heat gain coefficient.
from direct solar radiation, depending on the technical characteristics of the glass unit, the angle of incidence \( \theta \); IAC(\( \theta, \Omega \)) – indoor solar attenuation coefficient from direct solar radiation, depending on \( \theta \), the presence of internal sun protection devices and a shadow angle \( \Omega \) – the angle between the horizontal plane of the glazing and the projection of the sunbeam onto the vertical plane, perpendicular to the plane of glazing in question; \( F_g \) – glazing area, m².

The advantage of the described technique is that the determination of the heat inflow is made relative to the flow incident on the wall, and the amount of radiant energy penetrating into the cabin is calculated using the SHGC heat gain coefficient and the IAC heat gain attenuation coefficient. In this regard, it is necessary to define the term "solar factor". It is the ratio of the total heat flow entering the cabin to the flux of incident solar radiation (Figure 3).

\[ Q_s = (S \cdot K_{ins} + 0.75D \cdot K_{trad}) \cdot g \cdot k_{SPD} \cdot \tau_2 \cdot F_g \]  

(10)

where \( g \) – solar factor of the glass; \( k_{SPD} \) – coefficient of the heat transmission of the sun protection devices.

We also note that the basic principles of the ASHRAE method 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 [13-15].

Let’s summarize the total values of the heat gain from solar radiation to the operator’s workplace, calculated according to various methods in Table 3.

| Calculation method | Without considering the sides of the horizon | GOST 14269-03, Without considering the sides of the horizon | Hamburg, taking into account the sides of the horizon | Bogoslovsky, taking into account the sides of the horizon and the hour zone |
|--------------------|---------------------------------------------|-------------------------------------------------|-------------------------------|------------------------------------------------|
| Heat gain from the sun, W | 2195 | 2260 | 1394 | 1346 |

**Figure 3.** The physical meaning of the solar factor.

The solar factor is one of the main parameters given in the technical specifications for a glass unit [10-12]. 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 \( q_d \) and \( q_s \) values. In this case, the formula for the heat gain from scattered solar radiation is transformed:
3. Discussion
When determining heat gains 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 turns out to be much higher than with taking them into account (Table 3). Methods without taking into account the sides of the horizon are inappropriate to use in engineering calculations because of the primitive approach and, as a consequence of the roughness of determining the calculated values, they usually give overestimated values (by almost 2 times). On the contrary, the methods of Bogoslovsky (taking into account the time of the day) and Hamburg, taking into account the sides of the horizon, give practically the same results (discrepancy of 48 W), which proves the correctness of determining the calculated values. The ASHRAE method has two advantages: it not only takes into account the solar factor of a particular glazing, but is also adapted for automated calculations in ANSYS FLUENT.

4. Conclusions
1. To calculate the total heat gain from solar radiation, the Hamburg method can be recommended, which is applicable for comparative engineering calculations, due to its simplicity in comparison with the Bogoslovsky method.
2. The more laborious Bogoslovsky method (taking into account the time of the day) can be recommended for automated calculations in Excel.
3. Analysis of the calculation results presented in Table 3, shows that the greatest value of heat inflows for the summer mode occurs from solar radiation and is 1393.2 W at an outside air speed of 2.7 m/s, the transmission heat gain is also the main one, equal to 914.1 W, and the operating heat gains take a lower value. The obtained data are necessary to determine the air flow rate and the load on the selected heat exchange equipment; for the calculation, we select the highest value at an outside air speed of 2.7 m/s.
4. When carrying out model computer calculations and accounting for solar radiation in an explicit form, the ASHRAE method is well suited, 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.

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