Elements of microclimate normalization system in the cabin of TORUM grain mandy combine

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Abstract. The article conducted a study of the working conditions of the combine operator, as a result of which it was revealed that the occupational hazards of an employee are unfavorable microclimate parameters. Based on the analysis of the thermal state of the combine cab during the summer and winter operation, a microclimate normalization system has been proposed, for which the main functional characteristics (cooling and heating capacity) have been determined. According to the results of the calculation, the relationship between these characteristics and the working speed of the combine is established. So, with the increase in the speed of the combine up to 20 km/h, the cooling capacity of the climate system increases by 36%, and the heat output – by 22%. The surface areas of the main elements of the microclimate normalization system (condenser and evaporator), providing the necessary performance, are also determined.

1. Introduction
Agriculture is one of the most promising and rapidly progressing types of economic activity in Russia. Being in second place in the world in the export of wheat and being a record holder in harvesting these grains, agriculture provides employment to only 9% of Russians. In this regard, this sector of the economy is characterized by a relatively low percentage of people working under the influence of hazardous and harmful factors (29.6%) [1], which should not seem to be a significant problem from the point of view of labor protection. However, some types of agricultural work, such as combine harvesting of grain crops, are characterized by an increased level of technospheric hazards. Consider them in more detail.

The process of harvesting crops using combines includes the following operations: cutting the plant, it’s threshing, separating the grain from the pile and other impurities [2]. When performing these works, the combine operator is exposed to a complex of harmful factors, such as:
- acoustic and vibration factors;
- factors of the labor process (severity, tension);
- light environment;
- microclimate;
- chemical factor and dust.

The above-mentioned occupational hazards with prolonged contact contribute to the occurrence of pathologies of the respiratory system, vision, hearing, cardiovascular system and musculoskeletal system, which can later lead to disability or, in the absence of timely diagnosis and treatment, to death [3]. The harmful effects of the above factors are aggravated by the fact that the combine operator is
located in a closed limited cabin volume (2-4 m³ in total). That is why it is important to prevent or minimize their harmful effects on humans through the development of engineering protection systems.

For the prevention of occupational diseases, the combine operator needs a system of technical means that reduce the harmful effects and, consequently, the risk of damage to health. Modern combines have the most of these devices. For example, noise reduction in the cab of the combine is often achieved by using an acoustic screen placed between the cab and the engine. The screen is made of steel sheet with a thickness of 1 mm and is covered at the edges on the engine side with a sound-absorbing layer with a thickness of 10-15 mm. The acoustic efficiency of such a screen does not exceed 7 dB. In order to reduce more intense noise, silencers are used [4]. Heat influx into the cabin of the combine from the engine and transmission is reduced by performing it in the form of a solid capsule with separation from the engine compartment and transmission. Such a constructive technique in conjunction with the cabin vibration isolation provides not only thermal protection for the operator, but also a reduction in noise and vibration levels.

Achieving a comfortable for the combine operator level of natural light in the cabin is not a big deal and is done by tinting the glass, as a result of which they acquire the ability to reflect the sun's rays.

Window tinting of the combine cabin is also a passive means of thermal protection, used along with wall insulation. However, these protections are often insufficient with the temperature difference created inside and outside the cab at 20-25 °C. Therefore, the air in the cabin is further cooled to the optimum temperature, for example, with a ventilation or air conditioning system. At the same time, the overpressure created by a fan or air conditioner ensures that dusty and polluted air does not enter the cabin [5].

2. Analysis of achievements and publications
The correct choice of the climate system is based primarily on the calculation of the heat exchange of the operator’s cabin, including the use of various methods. After analyzing the work on this issue, the authors identified the following methods and techniques:
1. Experimental method with measurements of parameters. For example, in work [6], to obtain the total heat input to the cabin, it is necessary to measure the temperature difference outside and inside the cabin, first with the heater off of known power, then with.
2. Engineering calculation. A fairly approximate method of determining the total heat gain, characterized by the heat transfer coefficient of various surfaces in the process of convective and radiative heat transfer [7]. This method is presented in more detail in this article.
3. Mathematical modeling of heat exchange and transfer. Complicated method using a mathematical approach and system analysis of the thermal regime of the cabin. The microclimate parameters in the cabin are described by a system of differential equations [8].
4. Computer simulation. The most common approach in modern scientific research, which allows three-dimensional modeling of non-stationary processes of heat and mass transfer and subsequent analysis of physical phenomena through the use of modern software (ANSYS, NX CAE, etc.) [9].

3. Formulation of goals, objectives
The purpose of the study is to calculate the main elements of the climate system for the cab of the combine harvester TORUM.
Tasks:
1) Determine the heat gains and heat losses, as well as the parameters and the amount of air supplied to the cabin, taking into account the range of operating speeds of the combine. It should be borne in mind that the climate system under operating conditions (summer mode – +45 °C, winter mode – –20 °C) should ensure a decrease / increase in air temperature in the cabin to comfortable in the workplace +24 °C.
2) Calculate the main elements of the climate system in the combine cab – the condenser of the cooling system and the evaporator of the air heating system.
4. Main part

1) The calculation of heat leakage and heat loss was started by determining the value of the heat transfer coefficient \( K \) (W/(m\(^2\)K)), dependent on thermal conductivity of the wall \( \lambda \) (W/(m.K)), its thickness \( \delta \) (m) and heat transfer coefficient \( \alpha \) (W/(m\(^2\)K)) for outer and inner wall surface [7]:

\[
K = \frac{1}{\sum \frac{\delta}{\lambda} + \frac{1}{\alpha_{\text{out}}} + \frac{1}{\alpha_{\text{in}}}} \tag{1}
\]

Coefficient \( K \) was determined for four types of walls of the combine harvester: end walls, side walls, floor and roof. In this case, the fact that almost all walls (except for the front and side walls) have a multi-layer heterogeneous structure due to insulating and facing materials was taken into account.

Coefficient \( \alpha \) for the outer surface of the wall was calculated based on the range of operating speeds of the combine \( U \) (m/s) and its cabin length \( l \) (m):

\[
\alpha_{\text{out}} = 15 + \frac{3U}{l^{0.2}} \tag{2}
\]

For the inner wall surface coefficient \( \alpha \) was adopted on the recommendations of Russian Standard equal 10 W/(m\(^2\)K). Baseline data for the calculation and the results of the calculation are presented in Table 1.

| №  | Wall type      | Layer material     | \( \lambda \), W/(m.K) | \( \delta \), m | K coefficient, W/(m\(^2\)K), at the speed of the combine \( U \), km/h |
|----|----------------|--------------------|------------------------|-----------------|---------------------------------------------------------------------------------|
| 1  | Floor          | steel              | 47                     | 0.002           | 1.76 1.83 1.87                                                                 |
|    |                | felt               | 0.04                   | 0.015           |                                                                                  |
|    |                | rubber mat         | 0.16                   | 0.004           |                                                                                  |
|    |                | steel              | 47                     | 0.002           |                                                                                  |
| 2  | Roof           | felt               | 0.04                   | 0.015           | 1.82 1.89 1.92                                                                 |
|    |                | leather upholstery| 0.15                   | 0.002           |                                                                                  |
|    |                | steel              | 47                     | 0.002           |                                                                                  |
| 3  | Rear-end wall  | felt               | 0.04                   | 0.015           | 1.82 1.89 1.92                                                                 |
|    |                | leather upholstery| 0.15                   | 0.002           |                                                                                  |
| 4  | Front-end wall | glass              | 0.85                   | 0.005           | 5.56 6.67 7.14                                                                 |
| 5  | Sidewalls      | glass              | 0.85                   | 0.005           | 5.56 6.67 7.14                                                                 |

In order to identify the ways of entry into the cabin of heat leakages and their further calculation, the thermodynamic system shown in Figure 1 was considered.
The purpose of the main elements of the refrigeration unit is as follows. Compressor 4 increases the pressure of the refrigerant vapor – freon R134a. In the condenser 2, freon, cooled by the fan 1, goes into the liquid phase at a constant temperature. Thermostatic valve 3 serves to reduce the pressure of the liquid refrigerant by throttling to a pressure at which freon boils in the evaporator 5. In the evaporator, freon goes into a vapor state, taking away from the environment (the air of the combine cab) the latent heat of vaporization. Freon vapors enter the compressor, after which the cycle repeats.

Heat influx into the cabin of the combine is carried out from internal sources $Q_{in}$ (from the operator and his assistant; from lighting and electrical equipment) and from sources located outside the cabin $Q_{out}$. (from outside air through fences and from infiltration; from solar radiation). The calculation of heat leakage was made in accordance with the formulas:

- through fencing $Q_1$, W:

$$ Q_1 = \sum K_i \cdot F_i (t_{out} - t_{in}), $$

(3)

where $F_i$ – cabin wall area, m$^2$, was determined by Figure 2; $t_{out}$ – outside cab temperature, °C; $t_{in}$ – cabin temperature, °C.
- from infiltration \( Q_2 \), W:
\[
Q_2 = k \cdot Q_1,
\]
where \( k \) – dimensionless coefficient, equal 0.3.
- from the combine operator and his assistant \( Q_3 \), W:
\[
Q_3 = q_1 \cdot n,
\]
where \( q_1 \) – heat emission of one person, equal to 117 W; \( n \) – number of people in the cabin.
- from lighting and electrical equipment \( Q_4 \), was taken equal 47 W [7].
- from solar radiation \( Q_5 \), W:
\[
Q_5 = \frac{A_r \cdot I \cdot F_r + K_w \cdot F_w}{\alpha_{out}},
\]
where \( A_r \) – heat absorption coefficient of the sun by a cabin roof equal to 0.5; \( I \) – solar radiation intensity, equal to 950 W/m\(^2\); \( K_r \) – roof heat transfer coefficient, W/(m\(^2\)∙K); \( K_w \) – solar transmittance glasses, equal to 0.1; \( F_r \) and \( F_w \) – roof area and windows on the side wall, m\(^2\); \( \alpha_{out} \) – the heat transfer coefficient from air to the outer surface of the wall was determined by the formula:
\[
\alpha_{out} = 8 + 0.7 \cdot \frac{(U + 15)}{10.2}.
\]

The calculation results are displayed in the Table 2.

Table 2. The results of the calculation of the total heat gain \( Q_\Sigma \).

| № | Type of heat gain                      | Value \( Q_\Sigma \), W, at the speed of the combine \( U \), km/h |
|---|--------------------------------------|---------------------------------------------------------------|
| 1 | Through fencing \( Q_1 \)            | 852.02, 989.68, 1048.29                                       |
| 2 | From infiltration \( Q_2 \)          | 255.61, 296.90, 314.49                                        |
| 3 | From the combine operator and his assistant \( Q_3 \) | 234, 314.49, 47                                               |
| 4 | From lighting and electrical equipment \( Q_4 \) | 47                                                             |
| 5 | From solar radiation \( Q_5 \)        | 408.39, 403.38, 397.61                                         |
| 6 | Total heat gain \( Q_\Sigma \)        | 1797.02, 1970.96, 2041.39                                      |

The amount of outside air that must be supplied to the combine cabin to assimilate excess heat and reduce the temperature to the optimum +24 °C:
\[
G = \frac{Q_\Sigma}{c_p \cdot (t_{\text{cab.}} - t_{\text{cool.}})}
\]
where \( c_p \) – specific heat of air, equal to 1.01 kJ/(kg∙°C); \( t_{\text{cab.}} \) – optimum cabin air temperature, °C; \( t_{\text{cool.}} \) – chilled air temperature, °C, served directly to the person, was taken equal to 3-5 °C below \( t_{\text{cab.}} \) for the prevention of colds.

In order to select air conditioning equipment in the combine cab, the following main functional characteristics have been identified. [10]:
- cooling capacity \( Q_0 \), kW:
\[
Q_0 = \rho_{\text{cool.}} \cdot G(I_{\text{out}} - I_{\text{cool}}),
\]
where \( \rho_{\text{cool.}} \) – cooled air density, kg/m\(^3\); \( I_{\text{out}} \) and \( I_{\text{cool.}} \) – enthalpy of outdoor and cooled air, respectively, kJ/kg.
- mechanical power consumption \( N_0 \), kW, was taken equal 2.
- coefficient of performance \( \eta_0 \):
\[
\eta_0 = \frac{Q_0}{N_0}
\]
The results of the calculation are presented in Table 3.

**Table 3.** The results of the calculation of the main parameters of the air conditioning system.

| №  | Parameter                              | Parameter value when the speed of the combine U, km/h | 0   | 10  | 20  |
|----|----------------------------------------|------------------------------------------------------|-----|-----|-----|
| 1  | Air flow for cooling G_{cool}, m³/h     |                                                      | 593.08 | 650.48 | 673.73 |
| 2  | Cooling capacity Q_c, kW               |                                                      | 4.96 | 5.44 | 6.77 |
| 3  | Mechanical power consumption N_o, kW   |                                                      | 1.8 | 2 | 2.1 |
| 4  | Refrigeration coefficient η_o          |                                                      | 2.76 | 2.72 | 3.22 |

Heat loss in the cabin of the combine is carried out:
- through fencing Q₁, W, similar to the formula (3);
- from infiltration Q₂, W, similar to the formula (4);
- from accidental losses Q₃, W, was assumed to be equal to default 0.
- from evaporation of snow or ice on the cabin surface Q₄, W:

\[ Q_4 = \frac{n \cdot r_{\text{steam}} \cdot m_{\text{steam}}}{3600}, \]  \hspace{1cm} (11)

where \( n \) – number of passengers; \( r_{\text{steam}} \) – steam release rate per person; \( m_{\text{steam}} \) – amount of steam exhaled by man.

The calculation results are displayed in Table 4.

**Table 4.** The results of the calculation of the total heat loss \( Q_\Sigma \).

| №  | Type of heat loss | Value Q, W, at the speed of the combine U, km/h | 0   | 10  | 20  |
|----|-------------------|------------------------------------------------|-----|-----|-----|
| 1  | Through fencing Q₁ |                                                  | 1785.18 | 2073.61 | 2196.40 |
| 2  | From infiltration Q₂ |                                               | 535.55 | 622.08 | 658.92 |
| 3  | From accidental loss Q₃ |                                           | 0 | | |
| 4  | From evaporation of snow or ice on the surface of the cabin Q₄ | | 97.22 | | |
| 5  | Total heat loss Q₇ |                                                  | 2417.95 | 2792.91 | 2952.54 |

The amount of outside air that must be supplied to the combine cabin to raise the temperature to the optimum +24 °C:

\[ G = \frac{Q_\Sigma}{c_p \cdot \rho_{\text{out}} \cdot (t_{\text{out}} - t_{\text{cab}})}, \]  \hspace{1cm} (12)

Where \( \rho_{\text{out}} \) – heated air density, kg/m³; \( t_{\text{cab}} \) – optimum cabin air temperature, °C; \( t_{\text{out}} \) – heated air temperature, °C, was taken equal 40-45 °C based on hygienic standards.

In order to select equipment for heating the cab of the combine, the main functional characteristic was defined - heat output \( Q_{\text{heat}}, \) kW, full recycling mode [10]:

\[ Q_{\text{heat}} = c_p \cdot \rho_{\text{out}} \cdot G(t_{\text{out}} - t_{\text{cab}}), \]  \hspace{1cm} (13)

The results of the calculation are presented in Table 5.

**Table 5.** The results of the calculation of the main parameters of the heating system.

| №  | Parameter                     | Parameter value when the speed of the combine U, km/h | 0   | 10  | 20  |
|----|--------------------------------|------------------------------------------------------|-----|-----|-----|
| 1  | Air consumption for heating G_{heat}, m³/h |                                                      | 124.69 | 144.02 | 152.26 |
| 2  | Heat output Q_{heat}, kW |                                                      | 2.42 | 2.79 | 2.95 |

Thus, the above calculation showed that such a parameter as the speed of movement of the combine is one of the most significant in calculating the cooling and heating performance of the microclimate.
normalization systems in the cabins of self-propelled machines. Thus, the results of the calculations shown in Figure 3 allow us to conclude that an increase in the speed of the combine from 0 to 10 km/h led to an increase in the cooling capacity by 10%, and the heating capacity by 15%. With a further increase in speed from 10 to 20 km/h, the cooling capacity increased by 26%, the heating capacity – by 7%.

![Figure 3. Graphic dependence of cooling and heating capacity Q of the climate system of a combine on its speed of movement U.](image)

2) The calculation of the capacitor is reduced to the determination of its surface area F, m²:

\[ F = \frac{Q}{K \cdot \theta_{\text{mean}}} \],  \hspace{1cm} (14)

where \( Q \) – thermal load on the capacitor, W; \( K \) – condenser wall heat transfer coefficient, W/(m²·K); \( \theta_{\text{mean}} \) – mean log temperature difference, K.

Thermal load on the air cooler \( Q \), W, equal to the total cooling capacity \( Q_0 \), W, and compressor power \( N_c \), W, necessary to eliminate excess heat:

\[ Q = Q_0 + N_c \].  \hspace{1cm} (15)

Value \( Q \) at the maximum speed of the combine was 8.87 kW.

The heat transfer coefficient of the condenser wall \( K \) was calculated by the formula (16) and was 166.67 W/(m²·K).

\[ K = \frac{1}{\frac{1}{\alpha_{\text{in}}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_{\text{out}}K_{\text{rib}}}} \].  \hspace{1cm} (16)

Where \( \delta \) – condenser wall thickness, m; \( \lambda \) – wall thermal conductivity, W/(m·K); \( \alpha_{\text{in}} \) and \( \alpha_{\text{out}} \) – heat transfer coefficient of the refrigerant inside the condenser and outside air, W/(m²·K); \( K_{\text{rib}} \) – condenser ribbing degree.
Mean logarithmic temperature difference $\theta_{\text{mean}}$, K, was determined based on outdoor and cooled air temperatures $t_{\text{out}}$ and $t_{\text{cool}}$, °C, and refrigerant condensation temperatures $t_{\text{cond}}$, °C, adopted equal to 8°C above $t_{\text{out}}$ [10]:

$$\theta_{\text{mean}} = \frac{t_{\text{out}} - t_{\text{cool}}}{\ln \frac{t_{\text{cond}} - t_{\text{cool}}}{t_{\text{cond}} - t_{\text{out}}}}$$

(17)

Value $\theta_{\text{mean}}$ made up 37.5°C.

The surface area of the capacitor in accordance with formula (14) is equal to 1.42 m².

The calculation of the evaporator is also reduced to determining its surface area, $F$, m²:

$$F = \frac{Q}{K \cdot [T_{\text{cond}} - (T_{\text{out}} - T_{\text{heat}})/2]}$$

(18)

where $Q$ – evaporator heat load, W; $K$ – evaporator wall heat transfer coefficient, W/(m²·K); $T_{\text{heat}}$ – heated air temperature, K.

The thermal load on the evaporator $Q$ is equal to the heating capacity of the heating system and amounted to 2950 W.

The heat transfer coefficient of the evaporator wall $K$ was chosen to be 40.71 W/(m²·K) [10], considering the recommended speed of the refrigerant vapor movement through the evaporator tube, equal to 5.9 m/s.

The surface area of the evaporator in accordance with formula (18) is 1.39 m².

5. Conclusion

1. Improving the working conditions of combiners is impossible without developing integrated systems for normalizing the microclimate and reducing noise in the cabins of self-propelled combine harvesters to standard values and maximum permissible levels.

2. There was approximated an engineering calculation of heat leakage and heat loss by the known method [7], parameters and amount of air supplied to the cabin were identified, values of the surface areas of the main elements of the microclimate normalization system were obtained taking into account the requirements of the technical specification for the calculation of the climate system to ensure a comfortable microclimate in the cab of the combine harvester.

3. Further calculations are planned to be carried out using the mathematical and computer models of heat and mass transfer developed by the authors under conditions of active ventilation of the cabin, which will provide a more detailed and reliable picture of the formation of air flow and dangerous and harmful factors in the production environment and propose effective thermal protection measures.

4. For a reasonable and final selection of the main equipment of the air conditioning system for the cabin of the TORUM combine, it is planned:

   - to compose the air treatment scheme;
   - to determine the heat load on the main equipment of air conditioners with regard to air recirculation;
   - to calculate and select the main equipment of the air conditioning system for the cab of the combine, taking into account the length of the refrigerant pipes;
   - to perform the calculation and selection of the main equipment of the conditioning system of the cabins of the combine, when using a variable capacity compressor in the system Denso 7SBU16C.

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