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DEVELOPMENT OF MICROCLIMATE NORMALIZATION SYSTEM ELEMENTS IN THE CABIN OF TORUM GRAIN HARVESTER

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The working conditions of the combine operator are investigated. It is revealed that the leading occupational hazards of the worker are microclimate adverse parameters. Based on the analysis of the harvester cabin thermal state during summer and winter operation, a system of microclimate normalization is proposed, for which the main functional characteristics — cold and heat capacity — are determined. According to the calculation results, the relationship between these characteristics and the operating speed of the combine is established. Computer modelling of heat and mass transfer in the conditions of active ventilation of the cabin allows us to get a more detailed picture of the formation of streams of air movement and temperature in the working area of the operator and to recommend measures of thermal protection.

Keywords: agriculture, harvester, labor protection, microclimate, harmful factors, climate system.

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РАЗРАБОТКА ЭЛЕМЕНТОВ СИСТЕМЫ НОРМАЛИЗАЦИИ МИКРОКЛИМАТА В КАБИНЕ ЗЕРНОУБОРОЧНОГО КОМБАЙНА TORUM

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Исследованы условия труда оператора комбайна. Выявлено, что ведущими профессиональными вредностями работника являются неблагоприятные параметры микроклимата. На основании анализа теплового состояния кабины комбайна при летнем и зимнем режиме работы предложена система нормализации микроклимата, для которой определены основные функциональные характеристики — холодо- и теплопроизводительность. По результатам расчета установлена взаимосвязь между указанными характеристиками и рабочей скоростью движения комбайна. Компьютерное моделирование тепломассопереноса в условиях активной вентиляции кабины позволяет получить более детальную картину формирования потоков движения воздуха и температуры в рабочей зоне оператора и рекомендовать меры теплозащиты.

Ключевые слова: сельское хозяйство, комбайн, охрана труда, микроклимат, вредные факторы, климатическая система.

Introduction. Agriculture is one of the most promising and rapidly developing economic activities in Russia. Being on the second place in the world in wheat export and being the champion in grain harvest, agriculture provides employment for 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 dangerous and harmful factors (29.6 %) [1], which should not be a significant problem in terms of labor protection. However, some types of agricultural activities, such as combine harvesting of grain crops, are characterized by an increased level of technosphere hazards. Let us consider them in more detail.

The process of harvesting grain crops by combines includes the following operations: cutting the plant, its threshing, separating grain from thrashed heap and other impurities [2]. When performing these works, the operator of the combine is influenced by a complex of harmful factors, such as:

acoustic and vibration factors;

labor process factors (severity, intensity);

light environment;

microclimate;

chemical factor and dust.

The above-mentioned occupational hazards during prolonged contact contribute to the occurrence of pathologies of the respiratory system, vision, hearing, cardiovascular system and musculoskeletal system, which can further lead to disability or, without timely diagnosis and treatment, to death [3]. The impact of harmful factors is aggravated by the fact that the operator of the combine is in a confined space of the cabin (only 2-4 m^3). That is why it is important to prevent or minimize their harmful effects on the employee by developing engineering protection systems.

For occupational diseases prevention, the operator of the combine needs a system of technical means that reduce the harmful effects and, as a result, the risk of damage to health. Modern harvesters are equipped with most of such tools. For example, noise reduction in the cab is often achieved by using an acoustic screen placed between the cab and the engine. The screen is made of a steel sheet with a thickness of 1 mm and is situated at the edges of the engine with a sound-absorbing layer with a thickness of 10-15 mm. Acoustic efficiency of such a screen does not exceed 7 dB. Silencers are used to reduce more intense noise [4]. Heat flows into the cabin of the combine from the engine and transmission are reduced by its form - a single capsule with separation from the engine compartment and transmission. Such design together with the vibration of the cab not only provides thermal protection to the operator, but the reduction in noise levels and vibration.

Achieving a comfortable level of natural light in the cabin for the operator of the combine is not difficult and is carried out by windows tinting. As a result, they acquire the ability to reflect sun rays.

Tinted glass of the harvester cabin is also a passive means of thermal protection, used along with the insulation of the walls. However, these means of protection are often insufficient when the temperature difference in and out of the cabin is 20-25°C. Therefore, the air in the cabin is further cooled to the optimum temperature by ventilation or air conditioning system. At the same time, the excess pressure created by the fan or by the air conditioner ensures that dusty and contaminated air does not get into the cabin [5].

Setting goals and objectives. The purpose of the study is to calculate the basic elements of the climate system for the cabin of TORUM combine harvester.

Objectives:

To determine heat gain and heat loss, 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 noted that the climate system in operation (summer mode — +45°C, winter mode — -20°C) should provide a decrease/increase in the temperature in the cabin to the comfortable temperature of +24°C in the workplace.

To calculate the climate system main elements in the cabin — condenser cooling system and the evaporator of the air heating system.

To evaluate the efficiency of the climate system as a whole.

Main part. 1) The calculation of heat gain and heat loss started by determining the value of the heat transfer coefficient K (W/(m^2·K)), depending on the thermal conductivity coefficient of the wall λ (W/(m·K)), its thickness δ (m) and the heat transfer coefficient α (W/(m^2·K)) for the outer and inner surface of the wall [6]:

$$K = \frac{1}{\sum\frac{\delta}{\lambda} + \frac{1}{\alpha_{н}} + \frac{1}{\alpha_{в}}} \qquad 1)$$

K coefficient was determined for four types of walls of the harvester cabin: end and side walls, floor and roof. In this case, it was taken into account the fact that almost all walls, except the front end and side, have a multilayer heterogeneous structure due to insulating and cladding materials.

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

$$\alpha_{н} = 15 + \frac{3U}{l^{0,2}}. \qquad 2)$$

For the inner wall surface the coefficient α was taken according to the recommendations [7] equal to 10 W/(m^2·K). The initial data for the calculation and the calculation results are presented in table 1.

Table 1

Initial data for calculation and calculation results of the coefficient K

No.	Wall type	Layer material	λ, W/(m·K)	δ, m	K coefficient, W/(m^2·K), at combine speed U, km/h		
					0	10	20
1	Floor	steel	47	0.002	1.76	1.83	1.87
		felt	0.04	0.015			
		rubbermat	0.16	0.004			
2	Ceiling	steel	47	0.002	1.82	1.89	1.92
		felt	0.04	0.015			
		upholstery leather	0.15	0.002			
3	Rear end wall	steel	47	0.002	1.82	1.89	1.92
		felt	0.04	0.015			
		upholstery leather	0.15	0.002			
4	Front end wall	glass	0.85	0.005	5.56	6.67	7.14
5	Side walls	glass	0.85	0.005	5.56	6.67	7.14

To find heat gain ways in the cabin and their further calculations we have considered thermodynamic system pictured in Fig. 1.

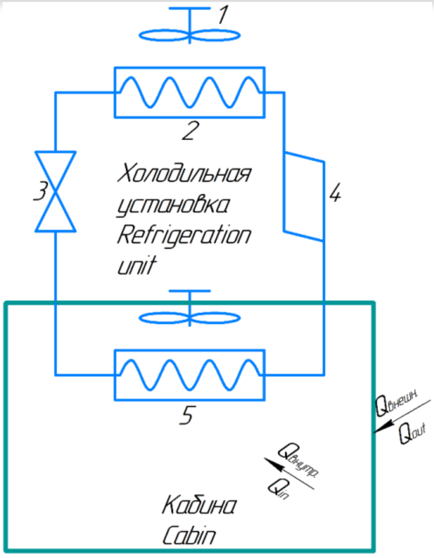


Fig. 1. Thermodynamic system "cabin-refrigeration unit"

The purpose of the main elements of the refrigeration unit is as follows. The compressor 4 increases the pressure of the vaporous refrigerant — freon R134a. In the condenser 2, freon, cooled by the fan 1, passes into the liquid phase at a constant temperature. Temperature control valve 3 is used 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 passes into a vaporous state, taking away from the environment (the air of the combine cabin) the latent heat of vaporization. Refrigerant vapor goes to the compressor. After this, the cycle repeats itself.

Heat gain into the cab of the harvester according to fig. 1 is from inner sources $Q_{внутр}$. (from the operator and his assistant; from lighting and electrical equipment) and from sources located outside the cabin $Q_{внешн}$. (from outside air through fences and from infiltration; from solar radiation).

The calculation of heat gain was made in accordance with the formulas:

through the fence Q_1, W:

$$Q_1 = \Sigma K_i \cdot F_i (t_н - t_в),$$

3)

where F_i — the area of the cabin wall, m^2, was determined by Fig. 2; $t_н$ — the temperature outside the cabin, °C; $t_в$ — the temperature inside the cabin, °C.

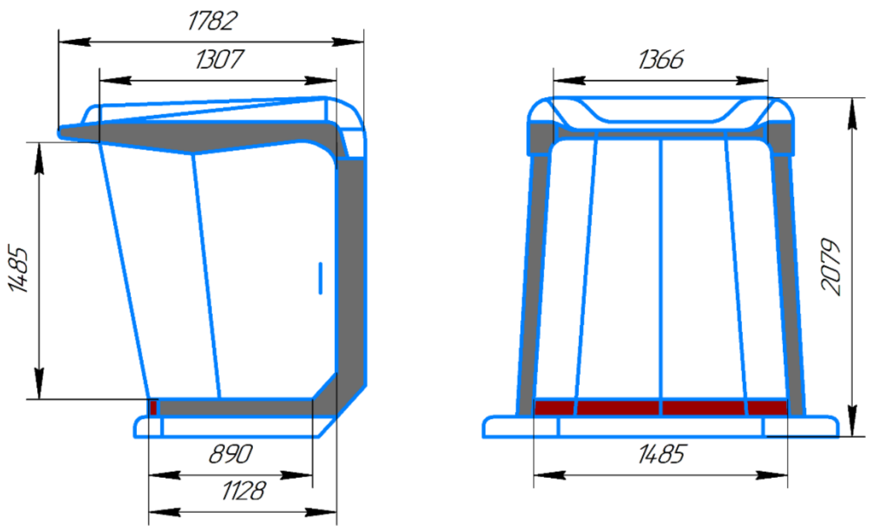


Fig. 2. Geometric dimensions of the cab of TORUM combine harvester from the infiltration of Q_2, W:

$$Q_2 = k \cdot Q_1,$$ 4)

where k is a dimensionless coefficient equal to 0.3.

from the combine operator and his assistant Q_3, W:

$$Q_3 = q_1 \cdot n, \quad (5)$$

where q_1 is the heat transfer of one person equal to 117 W; n is the number of people in the cabin.

from lighting and electrical equipment, the heat input Q_4 was taken to be 47 W [6].

from solar radiation Q_5, W:

$$Q_5 = \frac{A_к \cdot I \cdot K_к \cdot F_к}{\alpha_н} + I \cdot K_{ок} \cdot F_{ок}, \quad (6)$$

where $A_к$ — the coefficient of sunlight heat absorption by the cabin roof, equal to 0.5; I — the intensity of solar radiation, equal to 950 W/m^2; $K_к$ — the coefficient of heat transfer of the roof, W/(m^2·K); $K_{ок}$ — the coefficient of sunlight transmission by glass, equal to 0.1; $F_к$ and $F_{ок}$ — the area of the roof and windows on the side wall, m^2; $\alpha_н$ — the coefficient of heat transfer from the air to the outer surface of the wall, which was determined by the formula:

$$\alpha_н = 8 + \frac{0{,}7 \cdot (U + 15)}{l^{0{,}2}}. \quad (7)$$

The calculation results are shown in table 2.

Table 2

Calculation results of the total heat gain Q_Σ

No.	Heat gain type	Value Q, Вт, at the speed of the combine U, km/h		
		0	10	20
1	Through the fence Q_1	852.02	989.68	1048.29
2	From the infiltration Q_2	255.61	296.90	314.49
3	From the combine operator and his assistant Q_3	234		
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_Σ	1797.02	1970.96	2041.39

The amount of outside air that must be supplied to the harvester cabin to assimilate the excess heat and reduce the temperature to the optimum +24 °C:

$$G = \frac{Q_\Sigma}{c_p \cdot (t_к - t_{ох})}, \quad (8)$$

where c_p — specific heat of air, equal to 1.01 kJ/(kg·°C); $t_к$ — the optimum temperature in the cabin, °C; $t_{ох}$ — the temperature of the cooled air, °C, supplied directly to a person was estimated to be equal to 3-5 °C below $t_к$ to prevent cold-related diseases.

To assess the operation of the air conditioning system in the cabin of the combine, its main functional characteristics were determined [8]:

cooling capacity $Q_о$, kW:

$$Q_0 = \rho_{ох} G (I_н - I_{ох}), \quad (9)$$

where $\rho_{ох}$ is the density of the cooled air, kg/m^3; $I_н$ and $I_{ох}$ — the enthalpy of the outside and cooled air, respectively, kJ/kg.

the mechanical power consumption $N_о$, kW, was assumed to be 2.

cooling coefficient $\eta_о$:

$$\eta_0 = \frac{Q_0}{N_о}. \quad (10)$$

The calculation results are presented in table 3.

Table 3

Calculation results of the main parameters of the air conditioning system

No.	Parameter	Value of the parameter at the speed of the combine U, km/h		
		0	10	20
1	Air flow for cooling G_{ox}, m^3/h	593.08	650.48	673.73
2	Cooling capacity Q_o, kW	4.96	5.44	6.77
3	Mechanical power consumption N_o, kW	1.8	2	2.1
4	Cooling coefficient η_o	2.76	2.72	3.22

Heat loss in the cabin of the combine is:
through the fence Q_1, W, similar to the formula (3);
from infiltration Q_2, W, similar to the formula (4);
from random losses Q_3, W, was taken by default equal to 0;
from evaporation of snow or ice on the surface of the cabin Q_4, W:

$$Q_4 = \frac{n \cdot r_п \cdot m_п}{3600}, \qquad 11)$$

where n is the number of passengers; $r_п$ is the rate of vapor release per person; $m_п$ is the amount of vapor exhaled by a person.

The calculation results are shown in table 4.

Table 4

Calculation results of the total heat loss Q_Σ

No.	Type of heat loss	Value Q, W, at the speed of the combine U, km/h		
		0	10	20
1	Through the fence Q_1	1785.18	2073.61	2196.40
2	From infiltration Q_2	535.55	622.08	658.92
3	From infiltration Q_3	0		
4	From evaporation of snow or ice on the cab surface Q_4	97.22		
5	Total heat loss Q	2417.95	2792.91	2952.54

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

$$G = \frac{Q_\Sigma}{c_p \cdot \rho_н (t_н - t_к)}, \qquad 12)$$

where $\rho_н$ is the density of the heated air, kg/m^3; $t_к$ is the optimal temperature of the air in the cabin, °C; $t_н$ is the temperature of the heated air, °C, which is taken to be 40-45 °C according to the hygienic standards.

To assess the operation of the harvester cabin heating system, its main functional characteristic was determined – the heat capacity $Q_{от}$, kW, in full recirculation mode [8]:

$$Q_{от} = c_p \cdot \rho_н \cdot G(t_н - t_к), \qquad 13)$$

The calculation results are presented in table 5.

Table 5

Calculation results of the main parameters of the heating system

No.	Parameter	Value of the parameter at the speed of the combine U, km/h		
		0	10	20
1	Air flow for heating $G_{от}$, m^3/h	124.69	144.02	152.26
2	Heat capacity $Q_{от}$, kW	2.42	2.79	2.95

Thus, the above calculation showed that such a parameter as the speed of the combine is one of the most affecting the value of the cooling and heat capacity of the microclimate normalization system in the cabins of self-propelled machines. The calculations showed (Fig. 3) that the increase in the speed of the combine from 0 to 10 km/h led to an increase in cooling capacity by 10 %, and heat capacity — by 15 %. With a further increase in the speed from 10 to 20 km/h, the cooling capacity increases by 26 %, the heat capacity by 7 %. At the same time, the standard air conditioning system of the combine is designed for a cooling capacity of not more than 5.6 kW, which is not enough to ensure an acceptable microclimate in the combine workplace (Fig. 3).

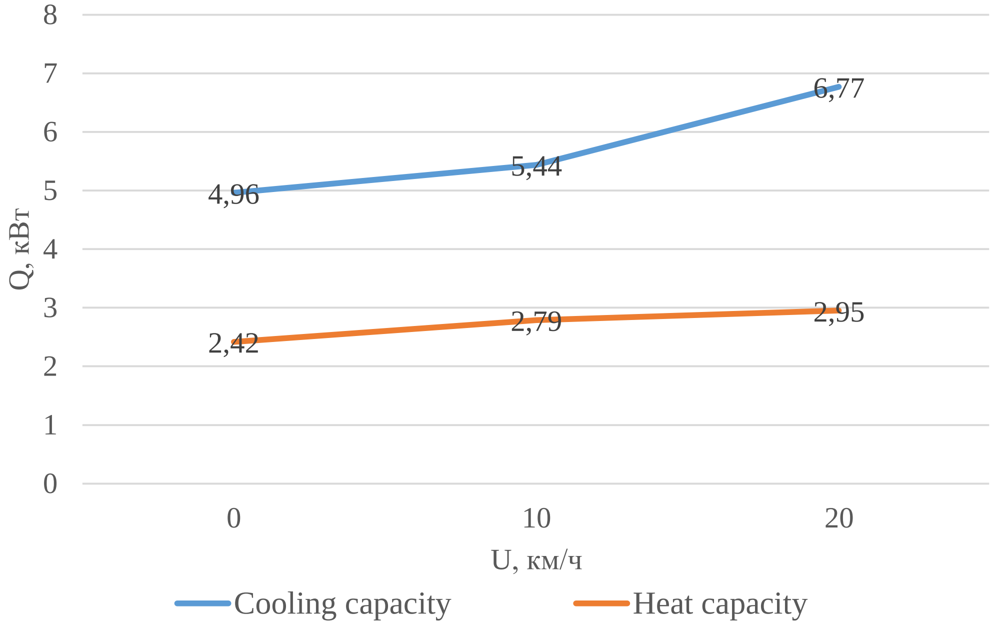


Fig. 3. Curve of the cooling and heat capacity Q of the climate system on the speed U of the harvester

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

$$F = \frac{Q}{K \cdot \theta_{cp}}, \quad 14)$$

where Q is the thermal load on the capacitor, W; K is the heat transfer coefficient of the capacitor wall, $W/(m^2 \cdot K)$; θ_{cp} is the average logarithmic temperature difference, K.

The thermal load on the air cooler Q, W, is equal to the sum of the cooling capacity Q_o, W, and the power of the compressor $N_к$, W, required to eliminate excess heat:

$$Q = Q_o + N_к. \quad 15)$$

The 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 amounted to 166.67 $W/(m^2 \cdot K)$.

$$K = \frac{1}{\frac{1}{\alpha_{вн}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_{нар} \cdot K_{реб}}}, \qquad 16)$$

where δ — the thickness of the condenser wall, m; λ — the coefficient of thermal conductivity of the wall, W/(m·K); $\alpha_{вн}$ and $\alpha_{нар}$ — the coefficient of heat transfer of the refrigerant inside the condenser and the air outside, W/(m^2·K); $K_{реб}$ — the degree of ribbing of the condenser.

The average logarithmic temperature difference $\theta_{ср}$, was determined according to the outdoor temperatures and cooled air $t_{нар}$ и $t_{ох}$, °C, and the condensation temperature of the refrigerant $t_к$, °C which was taken 8°C above $t_{нар}$ [9]:

$$\theta_{ср} = \frac{t_{нар} - t_{ох}}{\ln \frac{t_к - t_{ох}}{t_к - t_{нар}}}; \qquad 17)$$

The $\theta_{ср}$ value was 37.5 °C.

The surface area of the capacitor according to the formula (14) is 1.42 m^2.

The calculation of the evaporator is also reduced to the determination of its surface area F, m^2:

$$F = \frac{Q}{K \cdot [T_к - (T_{нар} - T_{наг})/2)]}, \qquad 18)$$

where Q is the thermal load on the evaporator, W; K is the heat transfer coefficient of the evaporator wall, W/(m^2·K); $T_{наг}$ is the temperature of the heated air, K.

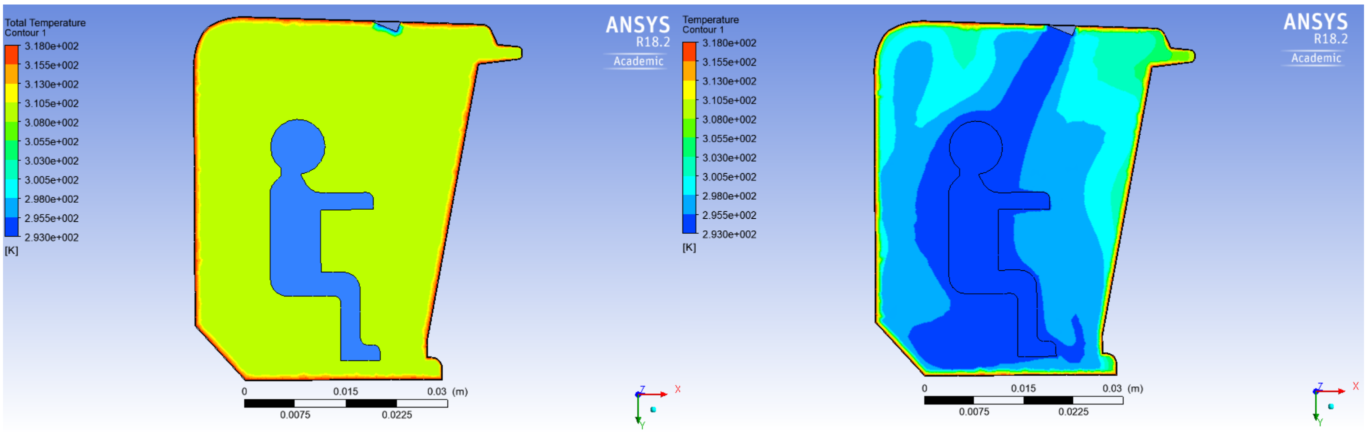
The thermal load on the evaporator Q is equal to the heat capacity of the heating system and amounted to 2950 watts.

The heat transfer coefficient of the evaporator wall K was chosen to be 40.71 W/(m^2·K) [10], taking into account the recommended velocity of the refrigerant vapor through the evaporator tube equal to 5.9 m/s.

The surface area of the evaporator according to the formula (18) is 1.39 m^2.

3) To obtain a more detailed picture of the impact of adverse microclimate on the operator, a simulation of the thermal state of the harvester cabin was carried out using the optimization system of engineering calculations — ANSYS, namely the Fluid Flow plug-in (CFX), which allows you to obtain high-quality models of hydrogasdynamic systems.

The initial data for the simulation were the results of calculations of the heat balance of the harvester cabin. The simulation results are shown in Fig. 4-7.



a) b)

Fig. 4. Temperature profile of the air in the cabine in the summer without the climate system (a); with the climate system (b)

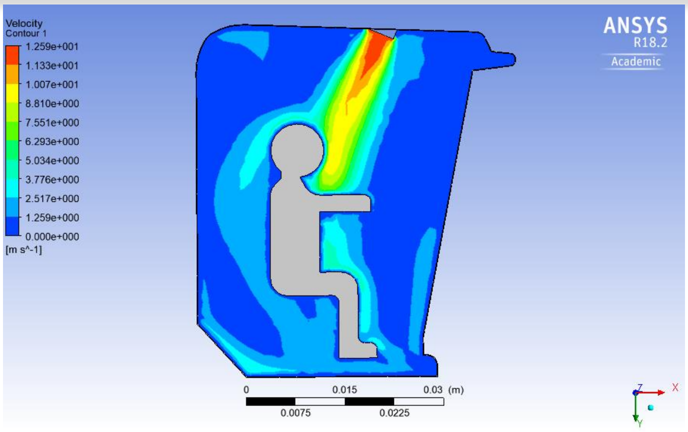
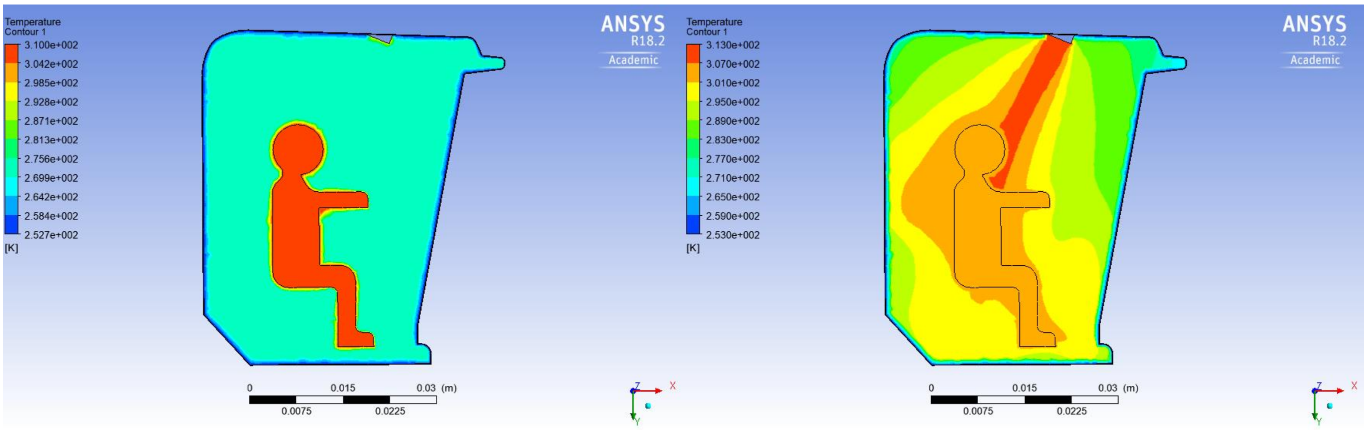


Fig. 5. Profile of air speed in the combine cabin in the summer mode of operation with a working climate system



a) b)

Fig. 6. Profile of the air temperature in the combine cabin in
the winter mode without the climate system (a); with the operating climate system (b)

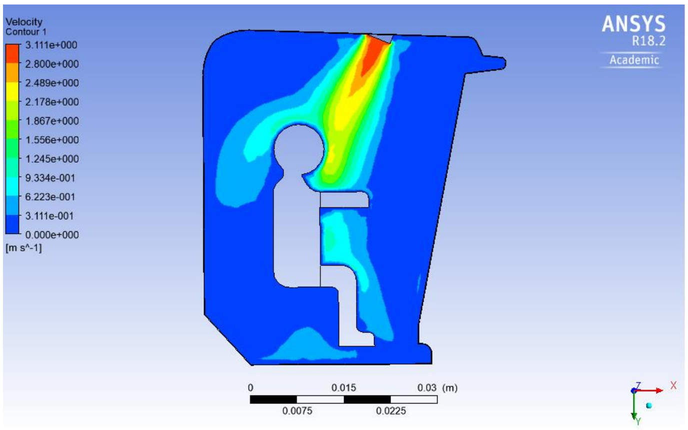


Fig. 7. Profile of air speed in the combine cabin in the winter mode of operation with the operating climate system

As it can be seen from the calculation results (Fig. 4-7), the operation of the selected climate system is effective, since it provides comfortable air temperatures in the cabin of the combine at different modes (in different periods of the year) not exceeding +24 °C.

Conclusion.

The approximate engineering calculation of heat gain and heat loss according to the known method [6] is made, the parameters and the amount of air supplied to the cabin are determined, the values of the surface areas of the main elements of the microclimate normalization system are obtained.

Computer modelling of heat and mass transfer in the conditions of active ventilation of the cabin allows you to get a more detailed picture of the formation of streams of air movement and temperature in the working area of the operator and to recommend thermal protection measures.

In the future for a reasonable and final selection of the main equipment of the air conditioning system for the cab of the Torum combine is planned:

to make a scheme of air treatment;

to determine the thermal load on the main equipment of air conditioners, taking into account air recirculation;

to make calculation and selection of the main equipment of air conditioning system for combine cabins taking into account the length of refrigerant hoses;

to perform calculation and selection of the main equipment of the air conditioning system of the harvester cabins, when variable capacity Denso 7SBU16C is used in the compressor system.

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