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RESEARCH ARTICLE

Development Of an Automatic Device for Heating the Vehicle Cabin Floor

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ABSTRACT

This paper is dedicated to solving the problem of ensuring normal working conditions in the vehicle cabins during the cold season. In the cold season, various covers, heated by the vehicle's electrical system, are used on the operator's seat, as well as thermal radiators with fans that blow on the side windows and, thus, increase the air temperature in the whole cabin. However, in winter, after a long period of parking of the vehicle in the cold or while it is moving, the air cools the cabin floor quite strongly, and the soles of the driver's feet freeze. If the driver needs to leave the vehicle frequently in winter, the snow left on the shoes melts and the water accumulates on the mat and then freezes. The soles of the feet are in very unfavorable conditions. In addition, the metal cabin floor, being in constant contact with water and snow, gradually rusts and becomes unusable. On the production vehicles, devices for heating the cabin floor are not installed. Drivers usually use electric heating mats. Existing devices have a number of significant drawbacks that limit their use in automobile transport. As a solution to this problem, the authors proposed the automatic device for heating the vehicle cabin floor. Its operation is based on the use of air heated in the engine compartment.

INTRODUCTION

It is known that the working conditions of mobile machine's operators are largely determined by the microclimate in the cabin, which is characterized by such key indicators as relative air humidity, air velocity, and its temperature (Gorshkov et al., 2006; Russi et al., 2022; Dmitriyev et al., 2017; (Dmitriyev et al., 2021)

In the warm season, air conditioners, fans, ventipanes, windows, etc. are used to reduce the temperature (Chen et al., 2022). In the cold season, various covers, heated by the vehicle's electrical system, are used on the operator's seat, as well as thermal radiators with fans that blow on the side windows and, thus, increase the air temperature in the whole cabin (Gürbüz et al., 2022a).

However, in winter, after a long period of parking of the vehicle in the cold or while it is moving, the air cools the cabin floor quite strongly, and the soles of the driver's feet freeze (Gürbüz et al., 2022b). At the same time, according to sanitary standards, the optimal temperature of the cabin floor surface (the operator's workplace) should be 18...22 °C, and the permissible temperature is 16...24 °C (Dmitriyev et al., 2023; He et al., 2023a; Kovalev et al., 2020).

If the driver needs to leave the vehicle frequently in winter, the snow left on the shoes melts and the water accumulates on the mat and then freezes. The soles of the feet are in very unfavorable conditions. In addition, the metal cabin floor, being in constant contact with water and snow, gradually rusts and becomes unusable.

LITERATURE REVIEW

On the production vehicles, devices for heating the cabin floor are not installed (Yang et al., 2022). Drivers usually use electric heating mats. For this purpose, a heating infrared film (for example, «Power Film - DC 12W») can also be used. It is a flexible and thin material, which is quite durable. The film can easily be put on various surfaces. This device is easy to install or dismantle (in the summer). The film is only 30 cm wide, and it can be cut every 50 cm. However, the device heats the floor for quite a long time (Lee & Hwang, 2022).

A common disadvantage of the electric cabin floor heating is that it's quite expensive to cover rather large areas of the floor (especially in trucks) with such heating mats, and they also consume a significant amount of electricity during operation (Srivastava et al., 2022; Grigorieva & Nikulshin, 2022).

Currently there is an aircraft floor heating device (Ajkhkhol'ts et al., 2008). It includes the floor made of heated panels. Panels are provided with the first cavities passing through them and which pass throughout the floor length in longitudinal direction of the aircraft, and there also provided is supply line passing from location place of aircraft electronic equipment to the first cavities. Supply line is intended to supply warm waste air formed during cooling of electronic equipment to the first cavities. Aircraft floor heating method consists in the fact that warm waste air formed during cooling of aircraft electronic equipment is passed through the cavities made in the panels forming the floor. Cavities pass throughout the floor length in longitudinal direction of the aircraft (Ilyushin & Martirosyan, 2024). Warm waste air is supplied to cavities via supply line passing from the location place of aircraft electronic equipment to the above cavities.

This system cannot be used in automobiles, but the idea of using warm waste air to heat the cabin floor (Li et al., 2022; Liu et al., 2024; He et al., 2023b; Talom & Beyene, 2009; Rudnev et al., 2019; Khasanova et al., 2020) was taken as a basis for the development of the device proposed in this paper.

MATERIALS AND METHODS

General description

In order to ensure normal working conditions in the vehicles' cabins during the cold season, the authors of this paper carried out theoretical studies, developed a device for heating the vehicle cabin floor, conducted a series of experiments and processed experimental data (table 1).

Algorithm

After theoretical research, the automatic device for heating the vehicle cabin floor, using the air heated in the engine compartment, was developed.

The first stage of experimental research was to determine the temperatures of the floor surface and of the air in the cabin of a vehicle in series production condition.

At the second stage, the temperatures of the floor surface and of the air in the cabin of a vehicle equipped with the developed device were measured.

Operational tests were carried out in winter on a ZIL-433360 truck.

During the third stage, the experimental data were processed.

Flow Chart

Table 1: Research algorithm.

No.	Name of the research phase
1	Theoretical research
2	Development of an automatic device for heating the vehicle cabin floor
3	Experimental studies
3.1	Determination of the temperatures of the floor surface and of the air in the cabin of a vehicle in series production condition
3.2	Determination of the temperatures of the floor surface and of the air in the cabin of a vehicle equipped with the developed device
3.3	Experimental data processing

RESULTS

Theoretical research

The authors have developed an automatic device that provides heating of the cabin floor under the feet of both the driver and the passenger. Its operation is based on the use of air heated in the engine compartment.

Theoretically, the operation process of the proposed device can be described using the principles of thermodynamics (Zhou et al., 2022; Ilyushin & Afanaseva, 2020).

Suppose that in a device there is an inhomogeneous physical field (distribution of transfer potential) φ (r, τ), where (r) is the radius of the vector, (τ) is time. Non-uniformity of the transfer potential distribution leads to a loss of thermodynamic equilibrium and is the cause of transfer flows. In the general case, in any area under consideration, macroscopic substance motion may occur, which is characterized by a velocity field V (r, τ). Sources or sinks of potential existing in the area under consideration are characterized by a volume density γ (r, τ).

Let us consider some finite volume (V), bounded by a surface (S). It is convenient to represent the element of this surface (dσ) by the value $df = n \cdot d\sigma$, where (n) is the normal unit vector.

The transfer of potential φ through the surface of the volume under consideration consists of the macroscopic substance movement and the transfer flow associated with the tendency to return to the thermodynamic equilibrium. Thus, the formula for the total transfer flow has the following form:

$$Q = \varphi V + q, \tag{1}$$

where q – value of the transfer flow.

The integral form of the condition for the volume under consideration (Zhou et al., 2022):

$$\int_{(V)} \frac{\partial \varphi}{\partial \tau} dV = -\oint_{(S)} Q df + \int_{(V)} \gamma dV. \tag{2}$$

The minus sign in front of the first term on the right side of relation (2) is associated with the opposite orientation of the vectors (df) and (Q).

The surface integral ($\oint_{(S)} Q df$) can be transformed into a volume integral using the Ostrogradsky-Gauss theorem:

$$\oint_{(S)} \mathrm{Qdf} = \int_{(V)} \mathrm{divQdV}. \tag{3}$$

The equation (2), taking into account the relation (3), can be written in an equivalent form:

$$\int_{(V)} \left[\frac{\partial \varphi}{\partial \tau} + \mathrm{divQ} - \gamma \right] \mathrm{dV} = 0. \tag{4}$$

In order for equality (4) to be satisfied for an arbitrary volume (V), it is necessary that the integrand be identically zero:

$$\frac{\partial \varphi}{\partial \tau} = -\mathrm{divQ} + \gamma \tag{5}$$

or taking into the account expression (1):

$$\frac{\partial \varphi}{\partial \tau} + \mathrm{div}(\varphi \mathrm{V}) = -\mathrm{divQ} + \gamma. \tag{6}$$

In order to obtain an equation from relation (6) that determines a particular transfer process, it is necessary to specify the transfer potential (φ) and use a particular law that connects the value of the transfer flow (q) with the distribution of the transfer potential.

To obtain the heat transfer equation, it is necessary to use the transfer potential in the form $\varphi = \rho C_p T$, where (ρ) is the density of the gas-air mixture; (C_p) is the specific isobaric heat capacity; (T) is the temperature of the mixture. The Fourier gradient law is used as the relationship that determines the irreversible transfer flow:

$$q = -\lambda \nabla T, \tag{7}$$

where λ – heat transfer coefficient; ∇ – gradient or divergence operator.

Under these assumptions, the heat transfer equation will have the following form:

$$\frac{\partial}{\partial \tau}\left(\rho C_p T\right) + \mathrm{div}\left(\rho C_p T\right) = \mathrm{div}(\lambda \nabla T) + \gamma_t, \tag{8}$$

where γ_t – distribution density of thermal energy sources (sinks).

Equation (8) is quite complex to analyze due to its nonlinearity, therefore, to solve the problem, we introduce the assumption of the density and heat capacity constancy. Due to this, the equation will take the following form:

$$\frac{\partial T}{\partial \tau} + \mathrm{div}(TV) = \mathrm{div}(a \nabla T) + \frac{\gamma_t}{\rho C_p}, \tag{9}$$

where a – thermal diffusivity coefficient ($a = \frac{\lambda}{C_p \cdot \rho}$).

The efficiency of the proposed device will depend on the amount of heat generated by the heated surfaces of the engine.

The total heat generation by the engine is (Pawar et al., 2023):

$$Q = Q_c + Q_r, \tag{10}$$

where Q_c – heat generation by convection; Q_r – heat generation by radiation.

The amount of heat generated by convection is determined by the following relation:

$$Q_c = \alpha_c \cdot (\tau_0 - \tau_a) \cdot F, \tag{11}$$

where α_c – coefficient of heat transfer by convection; τ_0 – temperature of the heated surface; τ_a – ambient air temperature; F – area of the surface giving off heat.

In case of natural convection it can be assumed that:

$$\alpha_c = a \cdot \sqrt[4]{\Delta t}, \tag{12}$$

where Δt – difference between the surface temperature and the temperature of the ambient air; a – experimental coefficient (for a horizontal surface facing upward, a = 2.8).

Heat generation by radiation is found from the equation:

$$Q_r = \alpha_r \cdot (\tau_0 - \tau_a) \cdot F, \tag{13}$$

where α_r – coefficient of heat transfer by radiation.

The coefficient of heat transfer by radiation is determined from the formula:

$$\alpha_r = C' \frac{\left[\frac{(273+\tau_0)^4}{100} + \frac{(273+\tau_a)^4}{10}\right]}{\tau_0 - \tau_a}, \tag{14}$$

where C' – emissivity.

The emissivity can be expressed by the following relation:

$$C' = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}}, \tag{15}$$

where C_1 and C_2 – emissivities of mutually irradiating surfaces; C_3 – emissivity of an absolutely black body (C_3 = 4.96).

The heat released by the engine can be transferred to heat the vehicle's cabin floor. For this purpose, the proposed device is used, which is a mixing heat exchanger, in which the heat transfer process occurs by direct contact and mixing of hot and cold heat carriers.

When substantiating the parameters of the device for heating the cabin floor, it is necessary to solve the following problems:

- determine the heating surface (S), ensuring the transfer of a required amount of heat from the hot heat carrier to the cold one;
- determine the amount of heat (Q) that can be transferred with a known surface (S);
- determine the final temperatures of the heat carriers with known values of (S) and (Q).

The main equations for solving the problems are following.

Heat transfer equation:

$$Q = k \cdot S \cdot \Delta t, \tag{16}$$

where k – heat transfer coefficient, which determines the amount of heat transferred per unit of time through a unit of surface.

Heat balance equation:

$$Q=M_1c_1\left(t_1^{'}-t_1^{''}\right)=M_2c_2\left(t_2^{'}-t_2^{''}\right), \quad (17)$$

where M_1 and M_2 – flow rates of hot (air heated in the engine compartment) and cold (air surrounding the cabin floor) heat carriers; c_1 and c_2 – corresponding heat carriers' heat capacities; $t_1^{'}$ and $t_1^{''}$, as well as $t_2^{'}$ and $t_2^{''}$ – initial and final temperatures of the hot and cold heat carriers.

Since in general the temperature of hot air and cold one in heat exchangers does not remain constant, equation (16) can be applied only in differential form for the surface element (dS), specifically $dQ = k\Delta t dS$. Then the total amount of heat transferred from hot air to cold one through the entire surface (S) is determined by the expression:

$$Q = \int_0^S k\Delta t dS = kS\Delta t_a. \quad (18)$$

In this equation, (Δt_a) represents the average temperature difference dependant on the nature of the change in air temperature along the heating surface. The latter in turn depends on the air flow movement pattern in the heat exchangers.

In equation (17), the value (M) can be replaced by the product $v \cdot S_{ad} \cdot \rho$, where (v) is the heat carrier's velocity; (S_{ad}) is the cross-sectional area of the air duct; (ρ), is the density of the heat carrier. Then, the heat balance equation will take the following form:

$$v_1 \cdot S_{ad1} \cdot \rho_1 \cdot c_1(t_1' - t_1'') = v_2 \cdot S_{ad2} \cdot \rho_2 \cdot c_2(t_2' - t_2''). \quad (19)$$

If we take the heat capacity of water as 1 kcal/(kg·K), then the expression $v \cdot S_{ad} \cdot \rho \cdot c = M \cdot c = z$ can be called the water equivalent of the heat carrier. The meaning of this concept is that its numerical value determines, as it were, the amount of water equivalent in heat capacity to the flow rate of the heat carrier per unit of time. In this case, equation (19) can be written as:

$$z_1\left(t_1^{'}-t_1^{''}\right)=z_2\left(t_2^{'}-t_2^{''}\right) \text{ or } \frac{z_1}{z_2}=\frac{\Delta t_2}{\Delta t_1}. \quad (20)$$

Thus, the ratio of the heat carriers' water equivalents will be inversely proportional to the temperature differences of these heat carriers.

This means that by setting the temperature change, it is possible to obtain the required flow rate of heated air (M_1). Then the required air duct diameter is found from the equation:

$$d_{ad} = \sqrt{\frac{4M_1}{\pi v}}. \quad (21)$$

One of the main factors influencing the efficiency of the device is the head loss coefficient due to the narrowing of the confuser. This coefficient is determined by the following relationship:

$$\xi_{nar} = \frac{1-\frac{1}{n}}{2}, \quad (22)$$

where n – degree of narrowing of the confuser.

The degree of narrowing of the confuser can be found using the formula:

$$n = \frac{S_o}{S_i}, \quad (23)$$

where S_o – cross-sectional area of the confuser's outlet opening, equal to the cross-sectional area of the air duct, $S_o = \frac{q}{v}$; S_i – cross-sectional area of the confuser's inlet opening.

Thus, taking into account expressions (21), (22) and (23), we obtain the dependence for determining the initial diameter of the confuser:

$$d_c = \sqrt{\frac{4M_1(1-\xi_{nar})}{\pi v}}. \tag{24}$$

The obtained dependencies allow us to determine the parameters of the developed device depending on the design features of a specific vehicle.

Structure and operation of the device

The schematic diagram of the device is shown in Figures 1 and 2.

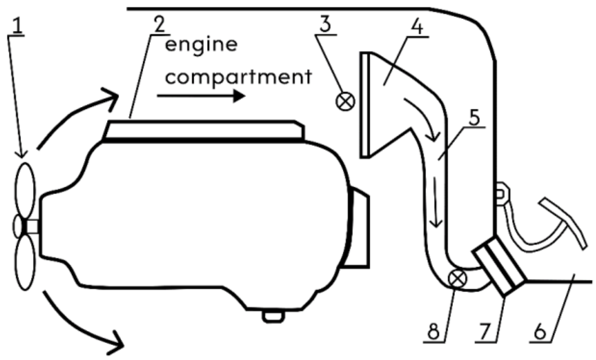

Figure 1: Schematic diagram of the automatic device for heating the cabin floor: 1 – fan impeller; 2 – cylinder head; 3 – thermostat; 4 –confuser; 5 – air ducts; 6 – cabin floor; 7- nozzle; 8-throttle

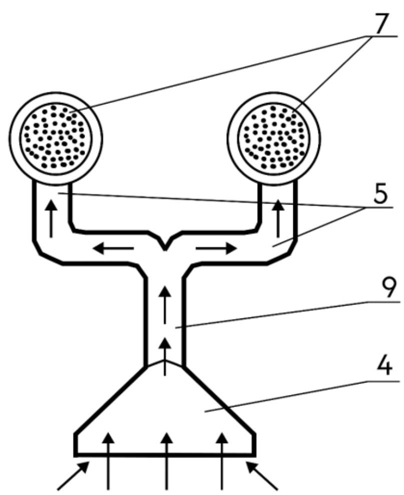

Figure 2: Schematic diagram of the automatic device for heating the cabin floor (top view): 4 – confuser; 5 – air ducts; 7 – nozzle; 9 – main air duct

The normal temperature regime of the vehicle engine operation is ensured by the tension of the fan belt, the design of the impeller 1, the opening or closing of the blinds, and the cooling liquid.

The highest temperature is created along the perimeter of the engine compartment in the upper part of the cylinder head 2 and the tube that removes hot gases. Therefore, the confuser 4 should be located mainly at the top of the engine compartment. The thermostat 3 can be located at the entrance or inside the confuser. The confuser can have a different shape depending on the engine compartment configuration. The thermostat is connected to the vehicle's electrical system and is a sensor for solenoids that open or close air ducts 5, going to the floor of the cabin 6 by the throttle 8. It allows maintaining the cabin floor temperature within the range from 16 to 24 °C.

The nozzle is a closed round space with holes in the upper part (fig. 3). Air comes out through these holes and heats the cabin floor under the driver's and passenger's feet. The nozzles are screwed to the floor with bolts or installed in specially made grooves.

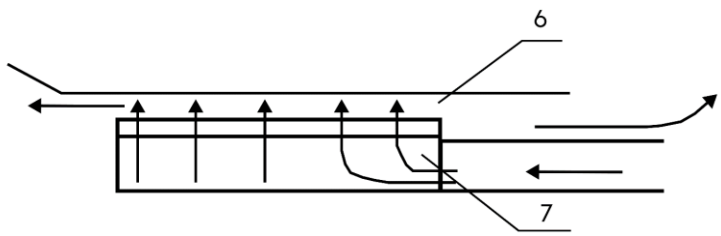

Figure 3: Nozzle (side view): 6 – cabin floor, 7 – nozzle

Structurally, the air ducts can be connected to the lower cover or to the middle part of the nozzle. The diameter and number of holes in the nozzle upper part can be different depending on the air pressure. The confuser is installed in the engine compartment's hottest part. It is possible to install two confusers at the same time. The design should allow for the confusers easy dismantling, since the operation of the device in the warm period of the year is impractical. In addition, the possibility of quick installation and dismantling of the confusers will allow easy access to some engine units (if necessary).

Experimental studies

To determine the effectiveness of the proposed automatic device, studies were conducted. They included measuring the temperature of the floor surface and of the air in the cabin of a vehicle in series production condition and of a vehicle equipped with the developed device.

Operational tests were conducted in winter on a ZIL-433360 truck. Before testing, the cabin was hermetically sealed. The outside and inside air temperature, as well as its relative humidity, were measured with an M-34M aspiration psychrometer in accordance with its operating instructions. Cabin floor temperature measurements were taken with an ETP-M (ЭТП-М) thermoelectric thermometer.

The results are presented in Figure 4.

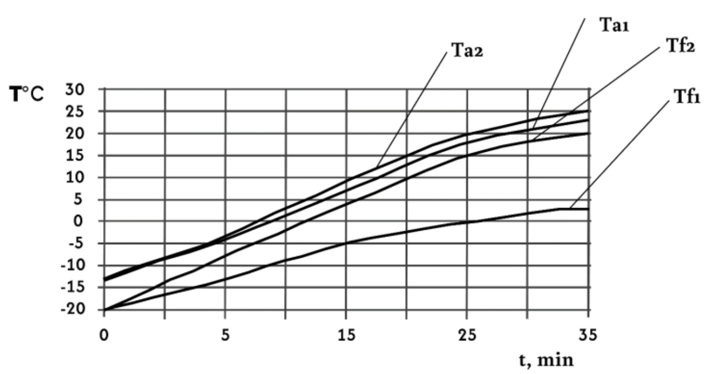

Figure 4: Change in temperature of the floor surface (T_f) and of the air (T_a) depending on the heating time (t): T_{f1}, T_{a1} – vehicle cabin in series production condition; T_{f2}, T_{a2} – cabin equipped with the developed device

CONCLUSION

Thus, the research results allow us to conclude that the use of a serial cabin heater does not allow achieving a normal floor temperature, and the proposed device is not only an effective device for heating the floor, but also helps to reduce the air at the driver's workplace warm-up time.

The developed device is distinguished by its simplicity of design and does not require electricity, since the cabin floor is heated using warm air from the engine compartment.

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