

DESIGN OF THE SYSTEM OF COOLING OF THE COMBUSTION ENGINE

Sladkova, Lubov A., Russian University of Transport, Moscow, Russia.

Nekludov, Alexey N., Russian University of Transport, Moscow, Russia.

Rozhnov, Evgeny F., Military Academy of the Strategic Missile Forces, Balashikha, Russia.

ABSTRACT

The article proposes authors' design to reduce the temperature of exhaust gases on the surface of pipelines of the resonator and the catalyst. To do so plates of various geometric shapes and sizes are arranged perpendicularly and (or) at an angle to their longitudinal axis, spaced apart from each other. The expediency of using this variant of modernization of the exhaust system of the internal combustion engine is supported by theoretical and experimental

studies, the reliability of which is confirmed with a confidence probability of 0,95. The regression dependencies obtained give grounds for recommending their own order of regulating the rate of cooling of a pipeline that removes exhaust gases, in accordance with their initial parameters and subsequent dynamics of indicators. In addition, during the experiment it was possible to reveal the physical picture of the process of heating and cooling of a pipeline along its length.

Keywords: internal combustion engine, theoretical and experimental studies, regression dependencies, cooling system, design, vehicle, temperature.

Background. The exhaust manifold allows for extraction of exhausts and the purging of cylinders from residual combustion products of fuel-air mixture. The material for its production is often heat-resistant cast iron or other heat-resistant metal. The exhaust manifold constantly interacts with hot exhaust gases and is subject to significant heating, as well as significant temperature differences during cooling after the ICE has ceased to operate.

By definition, the engine cooling system is a set of devices that provide supply of a cooling medium to heated parts and removal to the atmosphere of excess heat from them (during combustion of the working mixture, the temperature in the cylinder reaches over 2000°C). Such a supply must provide the most advantageous degree of cooling and the ability to maintain within the required limits the thermal state of the engine under various modes and operating conditions. The violation of the thermal regime leads to failure of parts and assemblies of the crank-piston engine group.

Widely used cooling devices of the exhaust system of the engine are based on natural ventilation through radiator slots and forced ventilation. The latter method includes air – by using additional engine blowing systems and a liquid one, using, for example, a water cooling jacket. The options used often lead to a reduction in engine power and occupy a significant design space in the engine's power system.

Existing electronic cooling systems for vehicle engines, even with minor engine malfunctions (power plant drop, power failures and malfunctions, and fuel system failures) often transfer the engine into an emergency mode [2].

Objective. The objective of the authors is to consider design of the system of cooling of the combustion engine.

Methods. The authors use general scientific and engineering methods, comparative analysis, evaluation approach, graph construction.

Results.

1.

Our exhaust gas cooling system includes pipelines, a resonator, a catalyst and an exhaust manifold (Pic. 1). To reduce the temperature of exhaust gases along the length of the pipeline, the design proposed by us differs from the previous ones. On the surface of the pipelines 5 located behind the exhaust manifold 2 (in front of the catalyst 3) and/or the resonator 2, perpendicularly and/or at an angle to their longitudinal axis at a distance from each other

there are plates of various geometric shapes and sizes that can alternate with each other. However, we believe that the plates can be replaced by surfaces in the form of bodies of revolution.

It is known [3] that speed of outflow of liquid (gas) along the section of the pipeline varies non-uniformly. To assess the effectiveness of the proposed improvement, theoretical studies of the change in the gas temperature over the cross section of the pipe were carried out. The initial data were [3]:

- hydraulic cross-sectional diameter for a round pipe $D_h = d/4$ (here d – diameter of a pipe, m);
- the Reynolds number by the formula

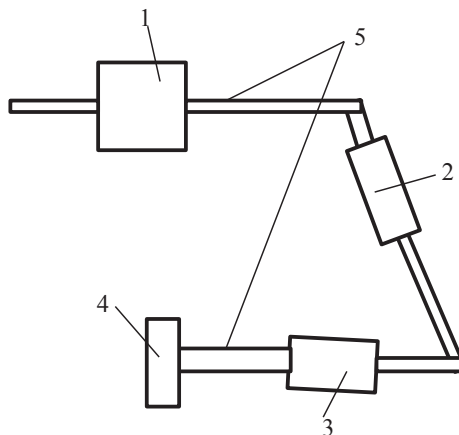
$$Re = \frac{vd}{\mu}; \quad (1)$$

- distribution of local speed v_l along the pipe section

$$v_l = \frac{dp}{4\mu l} \left(\frac{d^2}{4} - y^2 \right) = 2v \left(1 - \frac{4y^2}{d^2} \right), \quad (2)$$

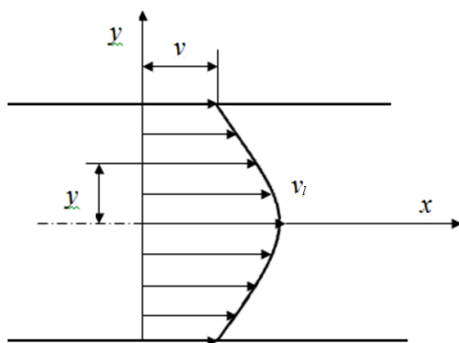
where y – current ordinate of speed along the section (see Pic. 2); v and v_l – mean and local speeds of gas outflow along the section near the pipe walls and at an arbitrary point, m/s; μ – kinematic viscosity coefficient, m²/s;

- dimensionless coefficient of frictional resistance:



Pic. 1. Exhaust gas cooling system [1]:
1 – muffler; 2 – resonator; 3 – catalyst; 4 – exhaust manifold; 5 – pipelines.





Pic. 2. Distribution of local speed v_i over the cross-section of the pipe.

$$\lambda = \frac{64}{Re}; \quad (3)$$

– loss of pressure along the length of the pipeline

$$h_{rt} = \frac{\Delta p}{\gamma} = \frac{32\mu}{g} \cdot \frac{lv}{d^2}, \quad (4)$$

where γ – specific weight of a gas (liquid); Δp – pressure in the system, Pa; l – length of the pipeline section, m; g – acceleration of gravity, m/s²; where $\gamma = g\rho$, where ρ – gas density.

The length of the initial section l_m , at which formation of a laminar flow occurs with a smooth entrance into the pipe takes place:

$$l_{in} = (0,03 \dots 0,04) d Re. \quad (5)$$

As a result of the temperature, the pressure p_i in the pipe and gas volume V_i change. This change is determined by the dependence [2]:

$$p_i = p_0 (1 + \beta t), \quad (6)$$

$$V_i = V_0 (1 + \alpha t), \quad (7)$$

$$\alpha \approx \beta \approx 0,0035 \dots 0,0037, \quad (8)$$

where α – coefficient of linear expansion, 1/deg; β – thermal coefficient of pressure, 1/deg;

2.

To determine the change in temperature for a gas flow along the length of the pipe in a laminar mode, we use the Bernoulli equation:

$$p_1 + \frac{\rho v_1^2}{2} = p_2 + \frac{\rho v_2^2}{2}. \quad (9)$$

Taking into account that the change in pressure occurs as a result of the action of temperature, we transform expression (9) with regard to (6) to the form:

$$p_1 + \frac{\rho v_1^2}{2} = p_1 (1 + \beta t) + \frac{\rho v_2^2}{2}. \quad (10)$$

Let us single out in this expression v_2 – speed of change of the flow as a result of the action of temperature:

$$\frac{\rho v_2^2}{2} = p_1 \beta t + \frac{\rho v_1^2}{2}. \quad (11)$$

It is obvious that the change in temperature from expression (11) will be equal to:

$$t = \frac{\rho(v_2^2 - v_1^2)}{2p_1\beta}. \quad (12)$$

Using expression (2), we transform the dependence (12) to the form:

$$t = \frac{\rho \left\{ \left[\frac{dp_2}{4\mu l} \left(\frac{d^2}{4} - y^2 \right) \right]^2 - \rho \left[\frac{dp_1}{4\mu l} \left(\frac{d^2}{4} - y^2 \right) \right]^2 \right\}}{2p_1\beta}. \quad (13)$$

After transformation we get:

$$t = \frac{\rho \left(\frac{d^2}{4} - y^2 \right)^2 \cdot \left(\frac{d}{4\mu l} \right)^2 \cdot [p_2^2 - p_1^2]}{2p_1\beta}. \quad (14)$$

On the other hand, speed v_2 can be represented in the form

$$v_2 = \frac{dp_2}{4\mu l} \left(\frac{d^2}{4} - y^2 \right). \quad (15)$$

We substitute (15) into the formula (14):

$$t = \frac{\rho(d^2 p_2^2 \left(\frac{d^4}{4} - y^2 \right)^2 - v_1^2)}{16\mu^2 l^2 2p_1\beta}. \quad (16)$$

Or after transformation we get:

$$t = \frac{\rho d^2 p_2^2 \left(\frac{d^4}{4} - y^2 \right)^2}{32\mu^2 l^2 p_1\beta} - \frac{\rho v_1^2}{32\mu^2 l^2 p_1\beta}. \quad (17)$$

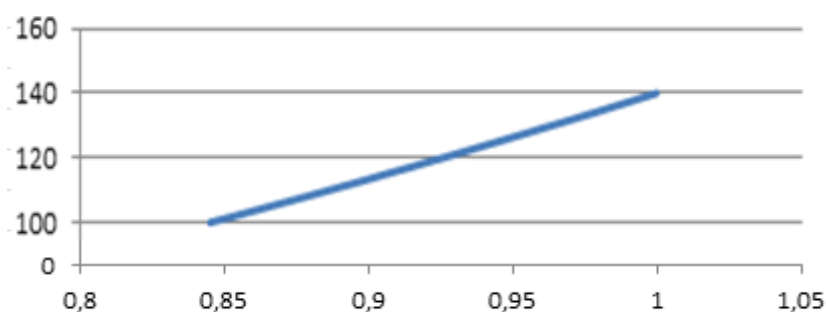
To find the temperature change along the length of the pipeline from several parameters, we define the partial derivatives of the formula (17) and find the total differential:

$$\begin{aligned} \frac{\partial t}{\partial d} &= \frac{\rho 2dp_2^2 \left(\frac{d^4}{4} - y^2 \right)^2 + \rho d^2 p_2^2 \left(\frac{4d^3}{16} - dy^2 \right)}{32\mu^2 l^2 p_1\beta} = \\ &= \frac{\rho p_2^2}{32\mu^2 l^2 p_1\beta} \left(\frac{3d^5}{8} - 2d^3 y^2 + 2dy^4 \right); \end{aligned} \quad (18)$$

Table 1

Values of the factors under the study of constructive change in the system

Parameters of plates	Thickness of a plate, δ , mm		Size of a plate, b, mm		Distance between plates, c, mm	
	X_1		X_2		X_3	
Indicator	max.	min.	max.	min.	max.	min.
Value	3	1,5	100	75	32	24



Pic. 3. Change in temperature along the length of the pipeline.

by the value y

$$\frac{\partial t}{\partial y} = \frac{\rho d^2 p_2^2 (-d^2 y + 4y^3)}{32\mu^2 l^2 p_1 \beta}; \quad (19)$$

by the value of speed v_1

$$\frac{\partial t}{\partial v_1} = \frac{2\rho v_1}{32\mu^2 l^2 p_1 \beta}. \quad (20)$$

Total differential along the length depending on the parameters under consideration will be equal to:

$$\frac{dt}{dl} = \frac{\rho p_2^2}{32\mu^2 l^2 p_1 \beta} \left[-d^4 y + 4d^2 y^3 + \left(\frac{3d^5}{8} - 2d^3 y^2 + 2dy^4 \right) \right] + \frac{2\rho v_1}{32\mu^2 l^2 p_1 \beta}. \quad (21)$$

Let's express temperature through the integral:

$$t = \frac{\rho p_2^2}{32\mu^2 l^2 p_1 \beta} \int_0^l \left[-d^4 y + 4d^2 y^3 + \left(\frac{3d^5}{8} - 2d^3 y^2 + 2dy^4 \right) \right] dl + \frac{2\rho}{32\mu^2 l^2 p_1 \beta} \int_0^l v_1 dl. \quad (22)$$

Let's determine temperature near the wall of the pipe when $y = d/2$.

After substitution of the value y , it is obvious that wall temperature will be:

$$t = \frac{\rho v_1 l}{32\mu^2 l^2 p_1 \beta}. \quad (23)$$

When $d = 0$, i. e. in the pipe center:

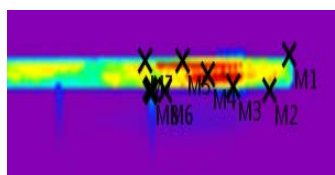
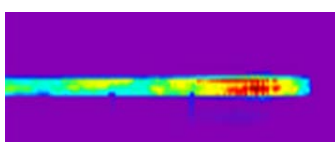
$$t = \frac{\rho}{32\mu^2 l p_1 \beta} \left(\frac{3dp_2^2}{8} + 2v_1 \right). \quad (24)$$

$$t = \frac{\rho \left(\frac{d^2}{4} - y^2 \right)^2 \cdot \left(\frac{d}{4\mu l} \right)^2 \cdot p_1^2 \beta^2 t^2}{2p_1 \beta}. \quad (25)$$

Since in the expression (25) temperature is not equal to 0, it takes the form:

$$t = \frac{2p_1}{\rho \left(\frac{d^2}{4} - y^2 \right)^2 \cdot \left(\frac{d}{4\mu l} \right)^2 \cdot p_1^2 \beta}. \quad (26)$$

Taking into account that in the center $y = 0$, from the formula (26) we get



Experiment 629:

a Выделение областей теплового изображения

№	Темп. [°C]	Излуч.	Отраж. темп. [°C]	Примечание
M1	37.3	0.24	20.0	
M2	42.0	0.24	20.0	
M3	109.9	0.24	20.0	
M4	128.5	0.24	20.0	
M5	94.1	0.24	20.0	
M6	44.2	0.24	20.0	
M7	77.7	0.24	20.0	
M8	55.6	0.24	20.0	

b

c Примечание

Pic. 4. Experimental installation: a – ready-assembled; b – thermal image; c – measured points; d – processing results.



Table 2

Regression dependencies in determining the change in the temperature of cooling of exhaust gases along the length of the pipeline

Measurement point	Regression dependence
1.	$Y = 64,60 + 8,36X1 + 7,19X1X2$
2.	$Y = 111,81 - 7,51X1 - 2,14X3$
3.	$Y = 114,87 - 9,18X1 - 3,08X3$
4.	$Y = 127,22 - 15,76X1$
5.	$Y = 131,03 - 13,82X1$
6.	$Y = 134,31 - 3,74X2 - 1,54X3 - 2,67X1X2 + 1,64X1X3$
7.	$Y = 129,85 + 8,29X1 - 5,04X2 - 3,33X1X2$
8.	$Y = 117,59 + 7,4X1 - 3,27X2$
9.	$Y = 122,34 + 2,76X1X2$
10.	$Y = 116,93 - 3,47X3$
11.	$Y = 107,5 - 3,93X1X3$
12.	$Y = 107,01 + 12,84X1 - 3,2X2 - 4,2X3 - 2,61X1X2 - 1,4X1X3$
13.	$Y = 101,30 - 3,69X3 - 2,87X1X3 - 2,81X2X3$
14.	$Y = 113,63 - 7,12X1 - 3,79X2$
15.	$Y = 111,77 - 7,55X1 - 3,99X2 - 4,48X3 - 4,05X1X2$

$$t = \frac{2p_1}{\frac{\rho d^6}{256\mu^2 l^2} \cdot p_1^2 \beta} = \frac{512\mu^2 l^2}{\rho d^6 p_1 \beta} \quad (27)$$

3.

Let's analyze the formula (27). It follows that the decrease in temperature will be facilitated by:

- increase in the diameter of the pipeline, which is not always possible taking into account the design features of the cooling system; on the other hand, this fact indicates the correctness of our improvement;
- increase in gas density, which at this stage of fuel development is unrealistic;
- increase in pressure when feeding;
- reducing the length of the pipe, which will lead to the fact that the output temperature of exhaust gases will be very high.

By varying the parameters included in the dependence (27), it is possible to change the parameters of the developed cooling unit to the desired temperature conditions.

Assuming that the exhaust gases are cooled while passing through the pipe, we take the length at the input as one. At the same time as the distance from the point of joining the pipeline to the engine, the temperature along the length l will vary. After substituting the initial data into equation (27), at $l = 1$, the average statistical pressure in the system is $p = 0,15$ MPa, $\mu = 1$, $\rho = 0,4$ and diameter $d = 0,05$ m, the temperature will be $140,034^\circ\text{C}$. Changing it later in Pic. 3.

It turns out that in the section under consideration the change in temperature can be regarded as a straight line of the form

$$t = \frac{40}{155} l + 103 = 0,258 l + 103. \quad (28)$$

Thus, the obtained dependence (27) makes it possible to estimate the temperature change of the

exhaust gases as they move along the length of the pipeline.

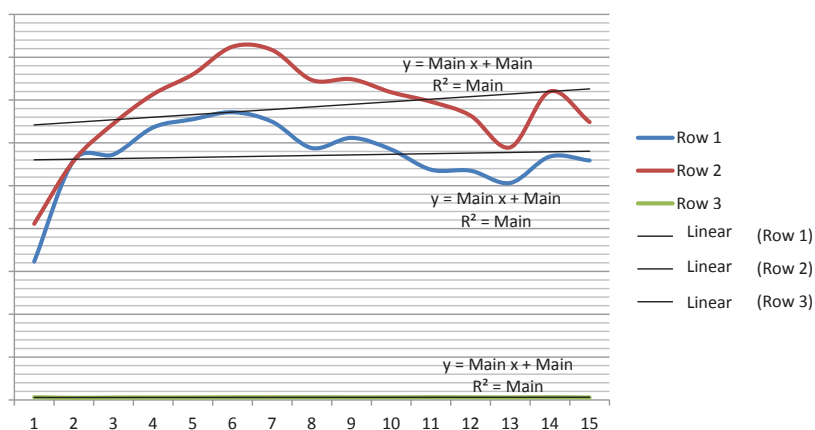
Experimental studies were carried out in accordance with the planning matrix [4] on the mounted installation, which is a pipe of $l = 1,5$ m and diameter $d = 50$ mm, made of steel 40X.

To eliminate the side effect of heat transfer to the side (support surface), the pipe was installed on supports 450 mm high above the level of the support surface. Taking into account the three-factor nature of the experiment, in order to determine the mutual influence of the factors determined by the dimensions of the heat dissipating plates of thickness δ , side b and the distance c between them, we recorded their expected values (see Table 1). The number of parallel experiments was $k = 3$. The length $l = 525$ mm corresponded to the initial length of laminar flow formation and was determined according to the dependence (5).

During the experiment, measurements were made of the change in the temperature of the pipe when it was heated to $215-220^\circ\text{C}$ (at the inlet). Room temperature – 22°C . After heating, the temperature gradient along the length of the pipe after its cooling for 3 minutes was recorded with a thermal imager.

Taking into account the uneven distribution of temperature over the cross section of the pipe, the temperature was recorded over the upper contour, center and the lower contour of the pipe through 35 mm, which in the thermal imaging will be 3,5 mm. (The outer diameter of the pipe is 50 mm, and in the thermal imaging – 5 mm). Then, at the studied length of 525 mm, it is necessary to fix the pipe temperature at $525/35 = 15$ points of section, starting from the extreme right (see Pic. 3).

All the measurements were checked for reproducibility of experiments using the Cochran test with a confidence probability of 0,95 for the number



Pic. 5. Change in temperature along the length of the pipe.

of experiments 8 and the number of degrees of freedom $f = 3 - 1 = 2$.

4.

The regression equations obtained by the method of [4] (see Table 2), taking into account the significance of each coefficient, make it possible to determine the qualitative picture of cooling of the system along the length of the pipeline. The significance of each coefficient of the regression equation was estimated by the Student's criterion with a confidence level of 0,95.

Analysis of Table 2 shows that in each section of the pipeline, deviation from the average temperature from its value is influenced by practically each of the factors considered. Of interest is point 1 (at the entrance to the cooling system), in which the proposed improvements to the cooling system of the pipeline lead to an increase in temperature. In all other cases, the improvement of the design leads to a decrease in temperature – an indication that the parameters of the plates must be made as large as possible, which correspond to the design features of the cooling system. Particularly affected is the first factor – thickness of the plate.

The proposed design solution allows to reduce the heating temperature along the length of the pipeline, the intensity of this process increasing with increasing plate thickness. The significance of each factor is not the same along the length of the plate. For example, at points 6, 12, 13 and 14, all the factors under consideration influence the cooling process. This fact suggests that in the proposed design, not only the alternation of the installed elements in terms of geometric characteristics (the thickness and size of the plate, δ and b , respectively) is needed, but also their alternation at different distances from each other.

Accepting the averaged values, for example, for the second point, we get that the cooling temperature will be $111,81 - 8,36 \cdot 0,003 - 2,14 \cdot 0,032 = 111,71^\circ\text{C}$.

Comparing with the average temperature, we determine the relative error of the experiment, which does not exceed 0,1 %.

The results of the experiment are shown in Pic. 5.

It can be seen that linearization of the obtained dependences indicates a decrease in temperature along the length of the pipeline. We choose the range of values on which the design improvement is rational: $1,2071 + 127,19 = 0,2801 + 111,7$. (29)

Hence $l = -16,61$, in fractions of 1 m.

Let's compare the results obtained with the results of calculations of the temperature according to (27) taken at the same section of the pipe of unit length (see Pic. 2 and dependence 28). The obtained dependence is well correlated with the dependences obtained theoretically (see Pic. 2 and 5).

Results. The carried out experimental researches allowed to reveal the physical picture of the process of heating and cooling the pipeline along the length. It is noted that at the maximum value of the first factor – the plate thickness, the maximum temperature is observed at point 4, and at the minimum value – at point 6.

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Information about the authors:

Sladkova, Lubov A. – D.Sc. (Eng), professor of Russian University of Transport, Moscow, Russia, rich.cat2012@yandex.ru.

Neklyudov, Alexey N. – Ph.D. (Eng), head of the department of Track, Construction Machines and Robotic Complexes of Russian University of Transport, Moscow, Russia, neklyudov.an@gmail.com.

Rozhnov, Evgeny F. – head of the laboratory of the department of power supply of missile complexes of Military Academy of the Strategic Missile Forces, Balashikha, Russia, roznov_88@mail.ru.

Article received 14.01.2018, accepted 11.03.2018.

