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MODELING OF EMERGENCY OPERATION MODE OF CAR ENGINE DUE TO COOLANT LEAK

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Annotation. A general analysis of the operation of the internal combustion engine cooling system during overheating, including in emergency mode caused by rapid coolant leak, is provided. A methodology was compiled and modeling of the thermal state of the parts with cooling failure was done. It has been determined that thermal damage to the cylinder head is possible within 10-15 seconds after a cooling failure, while the piston heats up more slowly and can be damaged only in the upper part and over a much longer period of time.

By calculation, it was found that in the coolant's absence, the temperature sensor, if located on the outlet pipe of the cylinder head, did not show an increase in temperature until the engine failed.

The calculated data is confirmed by real expert studies of engine failures due to overheating. Based on the results of the study, it was concluded that in the event of an emergency coolant leak, the driver does not have the technical ability to see an increase in temperature. This may be important when investigating the causes of engine failures due to overheating.

Keywords: Internal combustion engine, cooling system, coolant leak, modeling, overheating, thermal damage.

Introduction. It is known that various damage and failures can occur in various systems and components at all stages of engine operation [1, 2]. In this case, we are talking about the peculiarities of engine operation in the event of a failure in the cooling system, while in well-known studies practically no attention is paid to this emergency mode [3, 4].

The emergency operating mode of a cooling system with a small coolant level in the system differs significantly from “normal” overheating at the full coolant amount [5, 6]. One of the main differences is the dependence of the part temperature state on the operating time under conditions of impaired cooling and non-stationary heating from hot gases.

Obviously, when the significant coolant loss, the system elements located at the upper points of the system (Fig. 2), including the sensitive element of the temperature sensor, will be exposed (that is, they will be left without liquid, or its supply will not be continuous) [7].

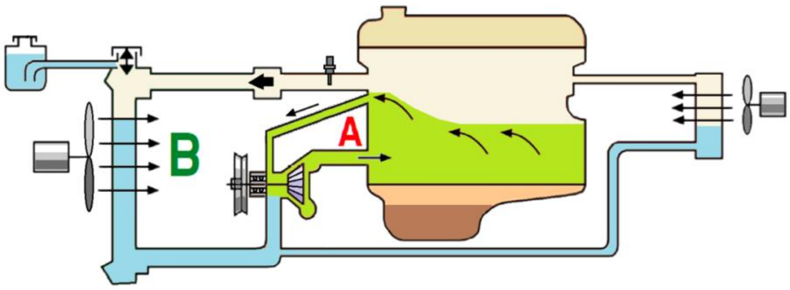

Fig. 1. Scheme of the cooling system operation during coolant leak with continued circulation in a small circle

Aim. The purpose of the work is to determine the relationship between the heating of parts and sensor readings in emergency operation mode of the cooling system. To achieve the purpose, it is necessary to solve the task of determining the change in temperature of the elements over time, i.e. find a solution to the problem of unsteady heat transfer for the elements under consideration under the condition that their cooling is broken.

Materials and methods. Let us assume that when operating in a steady state, part cooling suddenly disappears as a result of breakage in the coolant circulation (we neglect heat removal with steam to the 1st approximation).

To approximately solve the problem of heating an element when cooling is broken, we will use the heat balance equation written for the selected element [2, 7] under the condition that there is no cooling (Fig. 2):

$$q\ F\ d\tau = C_w\ M\ dT, \qquad (1)$$

where F is the surface area of contact with the working medium, C_w is the specific heat capacity of the metal, M is the mass of the element, $d\tau$ is the period of time during which the temperature of the element T_w increases by the amount dT.

Next, from equation (1) it is easy to obtain the differential equation for temperature of the element:

$$dT_w = \frac{\alpha_1\ F}{C_w\ M}\left(T_1 - T_w\right)d\tau\ . \qquad (2)$$

Equation (2) is solved with initial conditions and approximately describes the process of the temperature element changing over time after an abrupt disruption of its cooling due to a rapid coolant leak.

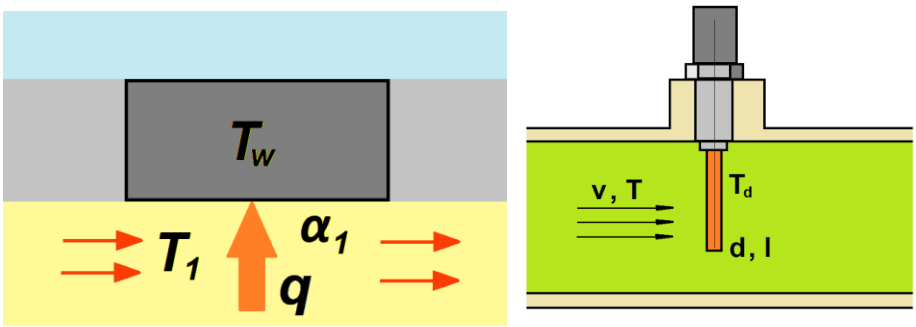

Fig. 2. Calculation diagram of the engine element (left) and the coolant temperature sensor installation (right)

First, let's consider the temperature sensor. Its sensitive part is a cylinder with diameter d installed in the coolant flow (Fig. 2). The heat exchange of the cylinder with the flow is quite reliably described by the empirical formula [8, 9]:

$$Nu = C\ Re^m\ Pr^{0,33}, \qquad (3)$$

where: Nu is Nusselt criterion (number), which shows how heat transfer by liquid flow is more than heat transfer by thermal conductivity, and it is proportional to heat transfer coefficient α ($Nu = \alpha\, d/\lambda$), λ is medium thermal conductivity coefficient, Re is Reynolds number, C and m are empirical coefficients that depend on the type of working medium and the mode of change [10].

For the combustion chamber wall, the gas heat transfer coefficient given in equation (2) can be approximately calculated using the Eichelberg formula [11]. To calculate the unsteady heating of the piston in the cylinder after the cylinder cooling is broken, equation (2) can also be applied. The heat transfer coefficient α_c is calculated in each combustion group. However, thermal expansion must be taken into account for the piston.

The gap between the piston and the cylinder in the zone of the piston head at normal temperature T_0= 20^{0}C is usually 0.50 mm. If the piston is heated to temperature T_w, diameter D_0 will increase in accordance with thermal expansion [7]:

$$T_w = T_0 + \frac{\delta_0}{D_0\,\alpha_a - D_{0c}\,\alpha_c}\,. \qquad (4)$$

where α_a, α_c are the coefficients of thermal expansion of aluminum alloy and cast iron (α_a =20·10^{-6} deg^{-1}, α_c =10·10^{-6} deg^{-1}), D_{0c} initial diameter of the cylinder at temperature T_0.

Results and discussion. Overheating is modeled by specifying a change in the temperature of the medium, which increases abruptly from 90^{0}C to 120^{0}C, i.e. by 30^0. After substituting all values into formula (5), we obtain the value of the heat transfer coefficient for the case of liquid and steam flowing around the sensor: for liquid α_f = 1,45·10^4 W/m^{2}K, for steam α_v = 40,7 W/m^{2}K.

Next, from equation (2) we obtain that the sensor, being in the liquid, will monitor its temperature with a delay of no more than 1-2 seconds (the temperature of the sensor in the liquid increases by 30^0 per about 1 second).

At the same time, the delay in the temperature sensor readings for steam will be extremely long – approximately 0,3^0 per 1 second or only 18^0 per minute (Fig. 3).

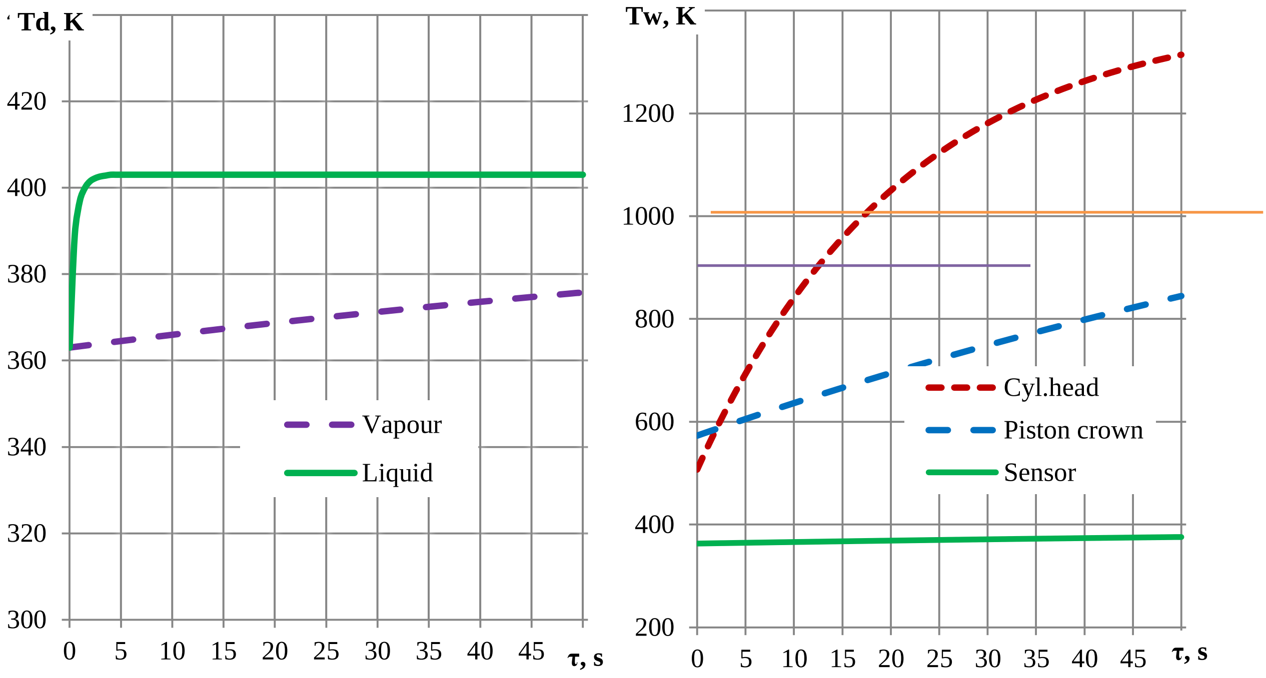

Fig. 3. Change in the temperature of the sensitive element of the temperature sensor, cylinder head and piston head over time from the moment of cooling failure, subject to instantaneous leak of coolant

This result shows that with an abnormally rapid decrease in the coolant level or its loss and exposure of the sensor, its inertia increases approximately 100 times. In this case, the sensor may not be able to track the temperature increase when the entire overheating process due to loss of liquid can be measured in seconds.

Similarly, the change in temperature of the cylinder head element and the top of the piston can be calculated over time from the cooling stops. As follows from the calculation results (Fig. 3), in the event of a sudden and complete cooling failure, the chamber wall will begin to melt after approximately 10-15 seconds of engine operation.

Heating of the piston when the cooling of the cylinder is disrupted occurs much more slowly, and scuffing on the piston top should be expected at a time that is several times longer than the time of damage to the combustion chamber wall (Fig. 3).

Fig. 4. A combustion chamber with traces of the wall melting between the exhaust valve seats (left) and a case of seats falling out due to overheating when the engine is running in place (right)

Fig. 5. Seizures on the piston head (left) and cylinder (right) of a gasoline engine due to emergency coolant leak

Let us substitute the values of the diameter of the piston upper part D_0 = 0,09 m, the initial gap $\delta_0 = D_{0c} - D_0$ = 0,5 mm and the initial temperature T_0 =293K into expression (4). Then we can obtain the maximum temperature of the piston in the cylinder, at which scuffing begin, of T_w = 848K (t_w = 575^{0}C), , and this temperature practically coincides with the beginning of melting of the piston material.

It is of interest to compare the obtained calculation results with real expert studies of the causes of engine failures in operation during an emergency rapid coolant leak due to damage to the cooling radiator by various foreign objects from the road [2, 7]. In Fig.4, the combustion chamber of a gasoline engine is shown with melting traces of the wall between the exhaust seats. At the same time, minimal damage to the cylinders and pistons was found, only in the upper part, where, due to the thermal expansion of the bottom, the piston can jam in the cylinder with characteristic marks of scuffing (Fig. 5). Similar damage is possible in diesel engines.

Conclusions. The automobile internal combustion engines with traditional cooling systems with a one-way thermostat and a bypass channel have a peculiarity: a rapid emergency drop in the liquid level causes the cessation of its circulation in the system. In this case, the combustion chambers can receive extremely serious damage in the form of melting walls and/or falling off the seats in about 10-15 seconds after cooling failure. At the same time, the pistons in the cylinders receive minor thermal damage and only after a much longer time from the start of the combustion chamber destruction. If the temperature sensor is installed on the outlet pipe of the cylinder head, then due to its inertia during rapid coolant leak, it does not indicate not only engine overheating, but even a simple increase in temperature. As a result, the driver does not have the technical ability to see the temperature increase in the system until the engine fails.

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