Mathematical efficiency model of the block-module cooling system of automotive vehicles and tractors

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Abstract. As related to other heat exchange systems, the operation of a heat exchanger should be based on the quality analysis of the heat carrier flows. One of these quality characteristics is the uneven distribution of temperature and air flow velocity ahead of the heat exchanger. To obtain more accurate performance indicators, it is necessary to build mathematical models of thermal processes in the radiator taking into account the unevenness of the air flow. The improvement of cooling systems is one of the priorities for the development of motor vehicles, as the temperature and dynamic loads in the engines are increasing due to the requirements that are becoming more stringent every year. First of all, this relates to environmental friendliness and fuel efficiency parameters, and secondly, it is service maintenance and labor safety, etc. Given this trend, it is necessary to pay attention to such important issues as improving the design of cooling systems, influencing the efficiency of heat balance distribution in the internal combustion engine. When developing new heat exchangers, a thermal engineering design should be analyzed to determine the heat exchange surface area that ensures the transfer of a given amount of heat from one heat carrier to another.

1. Introduction
Modern methods of designing any system are based on detailed knowledge of the processes occurring in the systems under consideration. This knowledge is represented by a mathematical model and a description of the system. Modeling the system is especially important, as it is faster and cheaper than conducting a physical experiment. The results obtained in the course of mathematical modeling can be used to optimize the system and to determine the operating modes and the causes of possible failures.

2. Conditions, materials and methods
For efficient operation of an internal combustion engine (ICE), it is necessary to ensure stable maintenance of its thermal condition, which saves fuel, prevents a drop in power, and reduces the wear of the cylinder-piston group parts. In other words, stabilized temperature of an internal combustion engine improves its efficiency and increases its reliability and durability. The internal combustion engine temperature is stabilized by the cooling system. A radiator fan is a necessary element of the cooling system [1-4].
3. Results and discussion
To assess the heat dissipation capacity of radiators of the block-module cooling system used in a motor vehicle engine, an indicator of the ratio between the actual and expected values of the specific thermal efficiencies of the heat exchange equipment used in motor vehicles was chosen [5]:

\[
\varepsilon_\Sigma = \frac{K_a F_a}{K_e F_e} \tag{1}
\]

where the indices “a” and “e” correspond to the values of the actual (obtained by interpretation of the test data) and expected values of the parameters; \( K \) is the coefficient of heat transfer from the coolant to the air, reduced to the mean log temperature difference, \( \frac{W}{m^2 K} \); \( F \) – heat exchange surface blown by air, \( m^2 \).

A decrease in the efficiency of the cooling devices inevitably leads to the risk of overheating of the heat carrier in diesel engines. The higher the ambient air temperature, the higher the engine load, and the lower the \( \varepsilon \) value, therefore, the higher the probability of such an event is.

The economic losses from this event are great and should be prevented in advance. In addition, a decrease in the heat dissipation capacity of cooling devices constantly leads to an increase in power consumption of a diesel generator set to drive fan installations of cooling devices and, consequently, to excessive fuel consumption [6, 7].

Formulas for assessing a specific factor affecting a decrease in the heat dissipation ability of the heat exchanger of the block-module cooling system used in a motor vehicle engine have been obtained:

\[
\varepsilon_\Sigma = \prod_{i=1}^{n_f} \varepsilon_{ind_i} = \varepsilon_1 \cdot \varepsilon_2 \cdot \varepsilon_{7317} \cdot \varepsilon_{pt} \cdot \varepsilon_{rep} \cdot \varepsilon_{cf} \cdot \varepsilon_{sh} \cdot \varepsilon_{ecbp} \cdot \varepsilon_{bl} \cdot \varepsilon_{p} \cdot \varepsilon_{fi} \tag{2}
\]

where \( n_f \) is the number of factors that reduce the heat dissipation capacity of cooling devices, pcs.;

\( i \) – serial numbers of each factor;

\( ind \) – index of the \( i \)-th factor;

\( \varepsilon_{ind} \) – the value of the decrease in the relative heat dissipation capacity of the cooling devices due to the influence of the factor \( ind \).

The following significant factors were identified from this formula:

\( \varepsilon_1 \) – contamination of the inner surfaces of the radiator tubes;

\( \varepsilon_2 \) – contamination of the outer surfaces of the radiator cooling fins and tubes;

\( \varepsilon_{7317} \) – replacement of the estimated type of radiator sections No. 1 with radiator sections No. 7317 with a reduced heat dissipation capacity;

\( \varepsilon_{pt} \) – exclusion of part of the sections from the cooling circuit (plugged) due to their depressurization or another reason;

\( \varepsilon_{rep} \) – the use of sections of the estimated type, but which have been repaired, the collectors being removed;

\( \varepsilon_{cf} \) – jamming of cooling fins in individual sections of radiators;

\( \varepsilon_{sh} \) – absence of fittings designed to exclude air flow past the radiators when installing the radiator unit in the engine compartment;

\( \varepsilon_{sh} \) – defects in the shutters control linkage, which does not ensure their complete opening;

\( \varepsilon_{ecbp} \) – operation of a vehicle with an open circuit or the presence of an abnormal inter-circuit bypass (hereinafter ICBP) in warm months;

\( \varepsilon_{bl} \) – the presence of insulation blinds, which must be dismantled in warm months;

\( \varepsilon_{p} \) – a decrease in the efficiency of the water pump;

\( \varepsilon_{fi} \) – deterioration in the fan installation operation relative to the design parameters.

Variables of the heat exchanger are divided into dimensionless and dimensional ones.

For a conventional heat exchanger through which two streams pass, the following parameters characterizing the heat transfer process are essential:

\( k \) – the total heat transfer coefficient, \( \frac{KW}{m^2 K} \).
\[ F \] – heat exchange surface, \( \text{m}^2 \) to which the total heat transfer coefficient belongs;

\[ \tau_{h1}, \tau_{h2} \] - temperature of the hot heat carrier, \( \text{°C} \);

\[ \tau_{c1}, \tau_{c2} \] - temperature of the cold heat carrier, \( \text{°C} \);

\[ W_h = (\omega_m c_p) h \] - water equivalent of hot heat carrier, \( \frac{kW}{m^2 K} \);

\[ W_c = (\omega_m c_p) c \] - water equivalent of cold heat carrier, \( \frac{kW}{m^2 K} \).

The values of all these parameters, with the exception of the total heat transfer coefficient \( k \), are obvious. The meaning of the general heat transfer coefficient, combining heat transfer by convection and heat conduction, is seen from the general heat transfer equation [8]:

\[ \frac{dq}{dF} = \kappa (\tau_h - \tau_c) \]  

As can be seen from the formula \( k \) is the total thermal conductivity related to the temperature potential \( t_g - t_x \) and to the unit of heat exchange surface.

The value opposite to \( k \) is the total thermal resistance, which includes the following components:

- The convection component on the side of the hot flow, taking into account the actual efficiency of the developed surface or the surface of the finning on this side.
- The component associated with the thermal conductivity of the wall.
- The convection component on the side of the cold flow, taking into account the actual efficiency of the developed surface.
- The component associated with the presence of a layer of contaminants on both sides of the heat exchange surface.

For simplicity, neglecting the influence of layers of contaminants, the equation expressing the total thermal resistance can be presented in the following form:

\[ \frac{1}{k_h} = \frac{1}{n_{or} a_h} + \frac{\alpha}{F_h} + \frac{1}{F_h n_{ox}} \]  

\[ \frac{1}{k_c} = \frac{1}{n_{ox} a_c} + \frac{\alpha}{F_c} + \frac{1}{F_c n_{or}} \]  

where \( k_c \) corresponds to the unit of total heat transfer surface on the hot stream side (including fins or any developed surface); \( k_h \) – to the unit of the total heat exchange surface on the side of the cold flow; \( F \) corresponds to the average size of the main (primary) surface; \( n_{or}, n_{ox} \) – efficiency of the total heat exchange surface \( F_h \) or \( F_c \), respectively.

The efficiency of the heat exchanger is calculated by the formula:

\[ \varepsilon = \frac{q}{q_{max}} = \frac{W_h (\tau_{h1} - \tau_{h2})}{W_{min} (\tau_{c1} - \tau_{c2})} = \frac{W_c (\tau_{c1} - \tau_{c2})}{W_{min} (\tau_{c1} - \tau_{c2})} \]  

where \( W_{min} \) – the lowest value of \( W_h \) and \( W_c \).

The number of heat transfer has the formula:

\[ NTU = \frac{\kappa F}{W_{min}} = \frac{1}{W_{min}} \int_0^F \kappa dF \]  

where \( F \) – heat transfer surface that is used to determine the heat transfer coefficient. While calculating, the heat transfer coefficient \( k \) can usually be taken constant.

The efficiency of the heat exchanger of the block-module cooling system used in a motor vehicle engine can be presented in a complete algebraic formula [9, 10]:

\[ \varepsilon = \frac{NTU}{1 - e^{-NTU}} \left( \frac{W_{min}/W_{max}}{NTU} \right) \frac{NTU}{1 - e^{-NTU}} \left( \frac{W_{min}/W_{max}}{NTU} \right) - 1 \]
4. Conclusions
The systems of modern energy-intensive vehicles experience high mechanical and thermal loads, which are accompanied by the release of heat, which must be discharged into the environment. To assess the efficiency of the parameters of a transport unit, it is necessary to know the temperature-dynamic criteria of the cooling system, as well as their relationship with the operating conditions and driving mode.

A modern vehicle must be considered as a multi-circuit source of heat radiation, in which 35–40% of the heat received during fuel combustion is used to perform useful work. There are power losses in power and auxiliary units, which also increase the heat intensity.

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