The use of information technologies in diagnosing heat exchangers of transportation equipment in operation

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Abstract. The problems of determining the technical condition of transport equipment heat exchangers in operation are considered. A method is proposed enabling to diagnose radiators with simulated heat load at a specialized stand, which allows determining the current value of the most important characteristic of a heat exchanger - heat transfer, which characterizes the degree of operability of heat transfer surfaces in specific operating conditions.

1. Introduction
In vehicle structures, recuperative and regenerative (surface) heat exchangers are widely used, where heat transfer is carried out through the interaction of heat carriers with a solid wall. The presence of such an element inevitably leads to a decrease in the reliability of heat transfer due to a change in the qualitative state of the wall surface during operation. In heat exchangers of the recuperative type, the dividing solid wall changes its qualitative state, both from the side of the hot heat carrier and from the side of the cold one [1, 2]. The intensity of these changes is different. In real operating conditions, the process of changing the qualitative state leads to a deterioration in heat transfer conditions, the regularity of the change in which has been little studied.

Nevertheless, the need to assess the actual heat transfer of heat exchangers in operation is associated with the determination of the actual technical condition to justify the frequency and scope of work on their maintenance. Such an assessment is carried out, as a rule, by indirect indicators and mainly subjective. With regard to radiators of internal combustion engine cooling systems, as a particular case of heat exchangers, indirect signs of a deterioration in the heat transfer capacity of heat exchange surfaces are: engine overheating, power loss, increased fuel consumption (by an average of 5-6%), increased oil burnout [3]. The consequence of engine overheating is increased wear of the CPG elements, violation of the metal structure, the appearance of thermal fatigue cracks, intensive aging of sealing parts, etc. [4].

2. Mathematical description of the heat exchange process
The working process of heat exchange is mathematically described by the following basic equations [1, 5]:

- heat transfer equation

\[ Q = kF \Delta t_{\text{log}}, \]  

(1)
where \( k \) is the current value of the heat transfer coefficient, \( W/(m^2 \cdot °C) \); \( F \) is the heat exchange area, \( m^2 \); \( \Delta t_{log} \) - average logarithmic temperature head, \( °C \);

- the heat balance equation

\[
\Delta Q = Q_1 - Q_2 ,
\]

where \( \Delta Q \) is the heat released into the environment; \( Q_1 \) - the amount of heat given off by the hot heat carrier, \( W \); \( Q_2 \) - the amount of heat received by the cold heat carrier, \( W \).

In real operating conditions, the heat transfer coefficient \( k \) changes, as a result of which the total amount of heat transferred through the heat exchange surfaces changes. It is difficult to accurately take into account the influence of all factors on the heat transfer coefficient \( k \) encountered in real operating conditions, therefore, in practice, the basic design equation in general form is as follows:

\[
k = 1/[1/\alpha_W + (\delta/\lambda + 1/\alpha_L) \cdot \psi] ,
\]

where \( \alpha_W, \alpha_L \) are the coefficients of heat transfer from the liquid and air side, respectively, \( W/(m^2 \cdot °C) \); \( \psi \) - coefficient of ribbing; \( \delta \) — wall thickness of the cooling element (tube), \( m \); \( \lambda \) - coefficient of thermal conductivity of the tube material, \( W/(m^2 \cdot °C) \).

When considering the working process in a dirty heat exchanger, it is assumed that a decrease in the value of the heat transfer coefficient \( k \) is due to the following reasons:

- deposition of a layer of pollution with high thermal resistance on the inner and outer surfaces;
- decrease in the speed of the coolant (air or liquid), and sometimes even the termination of its flow into certain channels of the heat exchanger due to their complete blockage (most often in the initial section);
- change in the nature of the flow through the channels of the cooling surface due to local (local) deposits of pollutants.

The listed reasons most often manifest themselves in aggregate, causing an integral negative effect. Analytical determination of the change in the heat transfer coefficient for a contaminated heat exchanger becomes more complicated, since contamination is unevenly distributed over the working surfaces. Distribution of contaminants to finned outer surfaces is a complex and poorly understood process [6].

**Figure 1.** Heat transfer diagram of clean (a) and dirty (b) radiator walls.
Fine-structured pollution (road-soil dust, etc.) form centers of local thermal resistance, depending on the shape of the ribbing plates, their orientation in the gravitational field, and some other factors. Figure 1 shows the heat transfer diagrams of a clean (a) and a dirty surface of the wall of a tube-plate radiator.

For a wall with operational contamination, the heat transfer conditions become more complicated. Considering that \( k_t = R_t^{-1} \), where \( R_t \) is the total thermal resistance to heat transfer, \( m^2 \cdot ^\circ C / W \), for a radiator with operating time \( \tau \) in the interval \( 0 < \tau < T \), where \( T \) is the operating period, we have:

\[
\lambda R_t = \frac{1}{\alpha_w} + \left( \frac{\delta_{cm, \tau}}{\lambda_{cm, \tau}} + 1 \right) \psi = \frac{1}{\alpha_w} + \left[ \left( \frac{\xi \delta_{ext,c}}{\lambda_{ext,c}} + \frac{\delta_{int,c}}{\lambda_{int,c}} + \frac{\delta_{cm}}{\lambda_{cm}} \right) + 1 \right] \psi, \tag{4}
\]

where \( \delta_{ext,c}, \delta_{int,c}, \delta_{cm}. \) - thickness of the layer of internal and external pollution and wall material; \( \lambda_{ext,c}, \lambda_{int,c}, \lambda_{cm} \) - coefficients of thermal conductivity of layers of external and internal contaminants, and, accordingly, wall material; \( \xi \) - fins contamination factor.

Using expression (1) and (4), after simple transformations, we obtain the heat transfer equation for any current value of the operating time \( \tau \) at the operation stage in an expanded form convenient for analysis:

\[
Q_{\tau} = F \cdot \bar{A}_{t\log, \tau} \left[ \frac{1}{\alpha_w} + \psi \cdot \xi \cdot \delta_{ext,c} / \lambda_{ext,c} + \delta_{int,c} / \lambda_{int,c} \cdot \psi \cdot \delta_{cm} / \lambda_{cm} + \psi \cdot \alpha_L^{-1} \right]. \tag{5}
\]

Further transformations (5) of the total thermal resistance \( R_t \) through local thermal resistances

\[
R_t = R_{W_T} + R_{L_T} + R_{CT_T}, \tag{6}
\]

where \( R_{W_T}, R_{CT_T}, R_{L_T} \) - respectively, the current values of local thermal resistances from the liquid to the wall, the wall itself and from the wall to the air, result:

\[
Q_{\tau} = F \cdot \bar{A}_{t\log, \tau} / (R_{W_T} + \psi \cdot \xi \cdot R_{ext,c} + R_{int,c} + R_{CT_T} + \psi \cdot R_{L_T}). \tag{7}
\]

When using antifreezes in the cooling system of the internal combustion engine as a coolant and following the recommendations for their operation (timely replacement), the increment of the local thermal resistance \( R_{int,c} \) can be neglected. The use of materials with high thermal conductivity and small wall thickness for cooling tubes (in the case of stability of the properties of the wall material in the absence of corrosion) makes it possible to consider the effect of \( R_{CT_T} \) on the change in the total thermal resistance to be negligible [1]. As a result, expression (7), which is a universal mathematical model of the heat transfer process of a radiator during the operation of transport equipment, will take the form:

\[
Q_{\tau} = F \cdot \bar{A}_{t\log, \tau} / [R_{W_T} + (\xi \cdot R_{ext,c} + R_{L_T}) \cdot \psi]. \tag{8}
\]

Figure 2. Graphical interpretation of changes in heat transfer from a radiator during operation.
The resulting additional thermal resistance of the contaminant layer after a given period of time:

\[ \Delta R_\tau = \frac{1}{k_\tau} - \frac{1}{k_0}, \]

where \( \Delta R_\tau \) is the additional thermal resistance; \( k_\tau, k_0 \) are the heat transfer coefficients of the dirty and clean surface.

Here: \( Q_{p0}, Q_{pt} \) - initial and current value of heat transfer from the radiator, \( W \); \( Q_{eng,\ max} \) - maximum value of engine heat transfer, \( W \); \( \Delta Q_{p0}, \Delta Q_{pt} \) is the heat transfer reserve of the new and operating radiator, \( W \); \( \tau_i \) is the operating time of the radiator to the corresponding impact, thousand km (m-h).

The general nature of the regularity of changes in thermal resistance in operation with operating time \( \tau \) was established [3]:

\[ R_\tau = R_{\tau max} (1 - e^{-B\tau}), \]

where \( R_{\tau max} \) is the maximum thermal resistance to which contamination curves tend to asymptotically approach over time (at the maximum possible deposit thickness); \( B \) is the constant of pollution intensity, determined experimentally.

In the absence of contamination: \( R_\tau = 0; k_\tau = k_0 \).

In addition, along with an increase in thermal resistance with an increase in the layer of pollution during operation, a reverse process (cleaning) is possible under natural or forced exposure to moisture, road dust, temperature drops, etc. Figure 2 shows a graphical interpretation of the pollution process - cleaning an autotractor radiator and the change in its heat transfer during operation.

3. Experimental method for determining the thermal characteristics of heat exchangers

Along with the calculation and analytical methods for a more accurate determination of the thermal characteristics of heat exchangers, experimental methods are used based on calorimetric measurements of thermo physical parameters under conditions of stationary heat transfer.

The temperature and dynamic characteristics of the internal combustion engine cooling systems are determined in specialized laboratories in which full-scale tests are performed with imitation of road and climatic conditions. These laboratories make it possible to reduce the time required to master new technology and to improve the quality of scientific research with regard to the choice of design and technological solutions for cooling systems, their optimal match to power plants in various operating conditions.

Such tests increase the reliability of information about the operating processes of heat exchangers, but they require a significant amount of time, labor and energy, since the system must enter thermal equilibrium, i.e. all elements of the complex and cumbersome structure of the stand and heat carriers must have a certain temperature.

The development of a simple and reliable experimental method for quantifying the state of the operating characteristics of heat exchangers, as well as diagnostic tools for its implementation, is relevant, since this makes it possible to predict the residual resource of heat exchangers, as well as to plan the scope and content of work to restore the working state of cooling systems.

Orenburg State University scientists have created an express method and equipment that implements for diagnosing heat exchangers at the stage of operation by the criterion of heat transfer [7]. The diagnostic stand, equipped with a hardware-software, measuring and computing complex (MCC) is shown schematically in figure 3, and the structure of the MCC is shown in figure 4 [8, 9].

The calculated value of the heat transfer coefficient is compared with the value of this coefficient for a reference, clean surface of the heat exchanger, obtained under the same test conditions.

Diagnostics of heat exchangers by the proposed method makes it possible to detect deviations of operating characteristics from the passport ones and to choose the optimal variant of preventive actions with subsequent control of their results [8].

Figure 5 shows a polygram for registering the heat transfer process of a heat exchanger.

Diagnostics makes it possible to establish not only the degree of deviation of heat transfer from the heat exchanger from the initial state, but also to establish the reason for its decrease. In the case of an
increase in the hydraulic resistance of the coolant due to blockage (most often in the initial section) of the channels of the cooling pipes, the nature of the graphs changes.

![Figure 3](image3.png)

**Figure 3.** Scheme of the stand for diagnosing the performance of radiators. 1 - radiator, 2 - measuring steam generator, 3 - pump, 4 - fan, 5 - control cabinet, 6 - MCC, 7 - computer, 8 - expansion tank, 9 - mass air flow sensor, 10 - flow meter, 11 – thermocouple.

![Figure 4](image4.png)

**Figure 4.** Block diagram of the MCC diagnostic bench.

For example, a change in the heat flow graph towards a decrease (subject to preliminary cleaning of the outer surfaces before testing) will indicate an increase in hydraulic resistance from contamination of the inner channels of the tube sheet. Moreover, an unambiguous conclusion can be made about the validity of the conclusion on the fact of recording the pressure drop at the inlet and outlet of the heat
exchanger. If this difference is not significant, then the decrease in heat transfer must be associated with
the increased thermal resistance of the inner surfaces of the tubes.

The reliability of the analysis of the reasons for the decrease in heat transfer of heat exchangers can
be increased by including an optical pyrometer in the diagnostic complex, and for research tasks - a
thermal imager. For example, to compare the nature of contamination distribution, the temperature field
of a new radiator and a radiator with operating time was studied.

\[\textbf{Figure 5.} \text{ The resulting polygram of testing the heat exchanger on the diagnostic bench.}\]

The measurement was carried out using a Thermo imager MOD Ray TI30XXEU/9 in (X; Y)
coordinates relative to the geometric center of the radiator. The irregularity of the temperature field for
the new radiator, taking into account the device error, was X (± 1.7°C); Y (± 1.3°C), for a radiator with
operational pollution - X (± 3.0°C); Y (± 2.75°C). By the nature of the irregularity of the temperature
field, it is possible to recommend the most optimal option for cleaning the heat exchanger, namely:
physical and chemical (without disassembly) or mechanical (with disassembly).

4. Conclusion
The developed method and the diagnostic stand in operation allow:

- to determine, without disassembling heat exchangers, the current quantitative value of the most
  important characteristic - heat transfer, which characterizes the degree of performance of heat
  transfer surfaces;
- to predict and determine the residual life of heat exchangers in specific operating conditions,
  which, in turn, makes it possible to build a scientifically based strategy for maintaining their
  performance.
- to determine the actual need and content of work when performing cleaning operations of heat
  exchange surfaces, thereby significantly reducing the cost of maintenance and repair.

The results of the work are planned to be used in diagnosing the condition and monitoring the
maintenance operations and repairing heat exchangers of transport equipment: cooling radiators, interior
heaters, charge air coolers, air conditioners.
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