Assessment of the technical condition of intercoolers for turbocharged internal combustion engines

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Abstract. The presented work considers the analysis of methods and means for assessing the technical condition of charge air coolers in vehicles in operation. Metallographic studies of the fragments of samples, identified local sections of the heat exchanger, have been carried out. Various defects of the internal heat transfer surface, caused by the influence of operational factors, have been revealed. The article also touches upon the problem of imperfection of methods and means of instrumental control of the operating parameters of the heat exchange equipment of road transport. It is proposed to carry out diagnostics of the technical condition of heat exchangers at specialized stands equipped with an instrumentation and apparatus complex. The prospects of new developments in the field of diagnostic equipment for determining the operating characteristics of heat exchangers with the ability to measure the most important parameter - heat transfer are noted. An important addition, confirming the relevance of the chosen direction of research, is the substantiation of the value of the described developments not only as a tool for measuring the parameters of the state of heat exchangers, but also to solve the problem of predicting their residual resource. The results of the conducted research are presented. Using the method of physical modeling, an algorithm has been developed for diagnosing the technical condition of the charge air cooler in operation. Issues of provision with methods and means of diagnosing parameters of heat exchangers of vehicles in operation and repair are considered.

1. Introduction

Turbocharging units are increasingly used in the design of internal combustion engines of modern vehicles. Basically, their use causes an increase in engine power as a result of increased air density and fuel combustion efficiency. One of the important elements in the cooling systems of units of internal combustion engines is an intercooler, or charge air cooler [1, 2].

On some vehicles, plate-tube air heat exchangers are used in the charge air cooling system. The charge air moves inside the flat oval tubes, and the atmospheric air enters the core thanks to the oncoming flow and the fan with mechanical drive of the blades from the engine.

During operation, the cooling capacity of the heat exchanger decreases due to contamination of the working surfaces with dust, oil and soot deposits, as well as polymerization products, which create additional thermal resistances that affect the efficiency of the heat transfer process. This, in turn, affects the power, reliability, environmental safety and efficiency of combustion engines. To detect malfunctions of the charge air cooler heat exchanger, it is necessary to diagnose it. However, the
analysis of sources on the topic under study allows us to conclude that reliable and acceptable in operation methods and tools for diagnosing charge air coolers have not yet been developed. Thus, the development of diagnostic software for determining the technical condition of the charge air cooler heat exchangers in operation is relevant.

The aim of the work is to implement new diagnostic tools for monitoring and determining the technical condition of the charge air cooler at the operational stage, as well as assessing the post-operational state of the internal heat transfer surfaces of the heat exchanger.

2. Materials and methods

Samples made from a charge air cooler of a Volvo car with a mileage of 280,000 km were used as material for studies to assess the post-operational state of the internal heat transfer surfaces of the heat exchanger. The heat exchanger was made of 3003 aluminum alloy, the chemical composition of which according to EN 573-3 is presented in the table 1.

Table 1. Chemical composition of alloy 3003 according to EN 573-3 (except aluminum).

| Chemical composition, % | Others |
|-------------------------|--------|
| Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Ni  | Zn  | As supplements | Total |
| 0.6 | 0.7 | 0.05-0.2 | 1.0-1.5 | 0.05 | - | - | 0.10 | 0.05 | 0.15 |

The studies were carried out by the method of destructive testing with a sample of the most characteristic local sections of the heat exchanger.

For the manufacture of thin sections, three samples were cut out, the following local areas: at the air inlet to the charge air cooler, in the central part and in the area before leaving the heat exchanger.

To preserve the structure of layers of operational pollution in various phase states, namely:
- soot, dust, oxide films, etc. (solid phase):
- oil film, resins, etc. (liquid phase).

The samples were filled with a polymer composition based on epoxy resin. This technique made it possible to preserve the shape of the internal partitions. The samples prepared in this way were subjected to mechanical grinding and polishing. The obtained thin sections were examined in an un-etched form on a Carl Zeiss 1 metallographic microscope at a magnification of 100 and 200 times.

For the research and development of algorithms and diagnostic tools, a physical modeling method was selected that allows full-scale tests with full-scale samples of the charge air cooler.

The most important characteristics of the charge air cooler, the definition of which is necessary to simulate the workflow, are: heat transfer (heat flow); costs of cold and hot heat carriers; temperatures of cold and hot heat carriers at the inlet to the heat exchanger; temperatures of cold and hot coolant at the outlet of the heat exchanger or their temperature drops; pressure of cold and hot heat carriers at the inlet to the heat exchanger; pressure of cold and hot heat carriers at the outlet of the heat exchanger.

Requirements for technical equipment, selection of parameters and test method for heat exchangers of vehicles are set out in GOST R 53832-2010. The control of the charge air cooler heat exchangers, for compliance with the functional indicators, must be carried out at a stand of the «Thermal wind tunnel» type.

The Orenburg State University has a stand for monitoring the technical condition of car radiators, which allows testing water-air heat exchangers. The stand is equipped with a hardware and software measuring and computational complex that allows you to measure, register and calculate the thermal parameters of the heat transfer process.
3. Results and discussion

3.1 Investigation of the post-operational state of the internal heat transfer surfaces of the heat exchanger

At the stage of operation, the products are exposed to various operational factors that ultimately change the numerical value of heat transfer, as an integral criterion for the performance of the charge air cooler. A change, or more precisely, a decrease in heat transfer, leads to a violation of the parameters of the working process not so much of the cooler itself, as an element of the turbocharging system, but also of the internal combustion engine. In this case, the nominal discharge air temperature shifts upwards, and the engine power decreases. The most common reason for the disruption of the working process of the cooler is the change in the resistance of the cooler on the side of the cold heat carrier due to the deposition of fine and coarse-structured impurities on the outer cooling surface of the frame. It can be dust, soil and other deposits, as well as foliage, fluff, insect remains, and so on.

As a rule, these deposits are associated with moisture, oil and fuel drips, which makes them resistant to physical and mechanical effects when cleaning the heat exchanger with water and compressed air. In fig. 1 shows external operational contamination and charge air cooler faults.

![Figure 1. External operational pollution and charge air cooler violations.](image)

The considered contamination and deposits of the heat exchanger contribute to the formation on the inner surfaces of the cooler of a layer of an oxide film with a high thermal resistance to heat transfer (fig. 2). Fig. 2 shows that the rate of scale formation is different even within the same heat exchanger.

![Figure 2. Fragment of a layer of operational deposits on the inner wall of the charge air cooler.](image)

The metallographic method of analysis, in addition to operational deposits on the inner walls of the cooler, revealed the following defects: delamination of the base metal; destruction of the cladding layer; traces of operational pollution; the formation of an oxide layer on the outside and inside of the tubes; mechanical destruction of the junction.

Aluminum oxide films consist of two parts: an inner and an outer layer (fig. 3). The inner layer is pure alumina, while the outer layer contains impurities of various ions. The maximum thickness of the barrier type aluminum oxide film is approximately 1 micron.

According to [2], the thickness of the natural oxide film on aluminum at normal temperature does not exceed \(0.01\,\mu\text{m}\). Even when heated close to the melting point of the metal, it cannot reach a thickness of more than \(0.2\,\mu\text{m}\). After the formation of a natural oxide film on the metal, its further growth can occur only when the oxidation process is activated by some external factor, for example,
heating or an electric field. As a result, the natural oxide film already present on the aluminum surface is artificially thickened, which happens during long-term operation of the charge air cooler.

These data allow us to state that contamination and oxide deposits are present throughout the entire volume of the charge air cooler. In addition, the destruction of the tubes and partitions of the cooler was revealed. It can be assumed that it was the combination of external and internal defects that led to the failure of the investigated unit [2].

Figure 3. Oxide layer.

3.2 Development of diagnostic software to determine the technical condition of the charge air cooler heat exchangers during operation

The further direction of research on the role of defects in the internal heat transfer surface in changing the technical state of the charge air cooler will be associated with a heat engineering experiment to determine the operating parameters of the heat exchanger with operating time. For these studies, a modernization of the test bench for heat exchange equipment was carried out [3-10]. The need to change the design of the stand is associated with the design features of the charge air cooler, which is an air-to-air type of heat exchangers.

The principle of operation of the developed stand is that the heat from a hot coolant circulating through a heat exchanger with a certain initial temperature, maintained by heating from an external source, is removed to a cold coolant with a constant initial temperature. A heater with continuously variable power control carries out heat supply to the charge air. Cooling air supply through test charge air cooler heat exchanger provided by a variable speed fan. When testing the heat exchangers of the charge air cooler, compressed air from the compressor station is used as a hot coolant.

During the tests of the charge air cooler, the following was determined:
- cooling air mass velocity \( \rho W \) kg \( / (m^2 \times c) \), which is calculated by the formula (1)

\[
\rho W = \frac{G_x}{F_x}
\]

where \( G_x \) - mass air flow, kg \( /c \); \( F_x \) - heat exchanger frame front area, \( m^2 \);
- heat transfer (heat flux) of the heat exchanger \( Q \), \( W \), determined by bench tests and calculated by the formula (2)

\[
Q = G_r \cdot c_{pr} \cdot (t_{r1} - t_{r2});
\]

- reduced heat transfer \( Q_{pr} \) according to the formula (3)

\[
Q_{pr} = Q \cdot \frac{t_{xpr} - t_{xpr}}{t_{r1} - t_{x1}}
\]

where \( t_{r1} \) и \( t_{xpr} \) - reference temperatures, \( ^\circ C \), take charge air cooling – \( t_{r1} = 120 \ ^\circ C \), \( t_{xpr} = 20 \ ^\circ C \);
- resistance of the heat exchanger on the side of the cold heat carrier, \( kPa \) according to the formula (4)

\[
\Delta p_x = p_{x1} - p_{x2};
\]
- resistance of the heat exchanger from the side of the hot coolant according to the formula (5), kPa

\[ \Delta p_r = p_{r1} - p_{r2}. \]  

(5)

The main result of bench tests and mathematical modeling was the implementation of a new diagnostic algorithm for the charge air cooler heat exchangers. A fragment of the algorithm is shown in figure 4.

**Figure 4.** Fragment of the algorithm for diagnosing the technical condition of the charge air cooler in operation.

Using the capabilities of the developed diagnostic software algorithm, in turn, will make it possible to predict the residual life of the charge air cooler heat exchangers, as well as to determine the volume and content of work to restore their operability.

4. Summary

Forcing internal combustion engines without changing the overall and weight characteristics in order to increase power is achieved by burning a larger portion of the air-fuel mixture in the cylinders in one working cycle. The solution to this problem required, first of all, the supply of more air, that is, an increase in the amount of fresh charge. With a constant working volume of internal combustion
engines, this became possible due to an increase in the charge density as a result of preliminary compression with mandatory subsequent cooling.

One of the additional structural elements of the vehicle in this case becomes an intercooler, or charge air cooler. Thus, it is fair to assume that charge air cooling is one of the progressive directions of increasing the power and efficiency of internal combustion engines.

For the manufacture of thin sections, three samples were cut out, the following local areas: at the air inlet to the charge air cooler, in the central part and in the area before leaving the heat exchanger.

To preserve the structure of the layers of operational contaminants in various phase states, the samples were filled with a polymer composition based on epoxy resin. This technique made it possible to preserve the shape of the internal partitions. The samples prepared in this way were subjected to mechanical grinding and polishing. The obtained thin sections were examined in an un-etched form on a metallographic microscope.

For the research and development of the algorithm and diagnostic tools, a physical modeling method has been chosen that allows full-scale tests with full-scale samples of the charge air cooler.

In connection with the relevance of the problem under consideration, the main result of the work should be the implementation of new tools and algorithms for the diagnostic support of CAC heat exchangers. This will allow monitoring and diagnosing the technical condition of heat exchangers at the stage of their operation with the possibility of quantitatively assessing the main performance characteristics.

Using the capabilities of the developed diagnostic software, in turn, will make it possible to predict the residual life of the charge air cooler heat exchangers, as well as to determine the volume and content of work to restore their operability.

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The method for quantifying the heat transfer of the charge air cooler as an integral evaluation criterion of operability is based on technical solutions according to RF patents Nos. 2279605, 2352925, 2544365, 2621569, where the problem of measuring the heat flow is solved by modeling the parameters of the heat load on the heat exchanger.