Improvement of heat transfer of liquid-oil heat exchangers for internal combustion engines

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Abstract. Removing heat from an internal combustion engine is one of the most promising areas for the development of vehicles and heavy vehicles, especially. The article studies the influence of various parameters of the coolant and the parameters of the heat exchanger on the efficiency of heat transfer when removing heat from an internal combustion engine by an oil-liquid heat exchanger. The influence of "diffuser-confusor effect" on flow turbulization is considered. Literature analysis was carried out during the study. It raised such issues as: the issues of the efficiency of heat transfer from liquid to the wall under various conditions of the flow of the medium, the issues of changing the hydraulic regimes depending on the parameters of the medium, the issues of changing the parameters of the medium from the determining and secondary factors of heat transfer. The data on the influence of the temperature of various oils on their viscosity and density are presented. The influence of the state of the refrigerant on the efficiency of heat transfer is generalized. As a result of the analysis, a number of solutions have been proposed to the safe intensification of heat removal from the internal combustion engine. These solutions can be used for efficient oil cooling in diesel engines, mainly in engine design.

1. Introduction

Internal combustion engines are constantly exposed to thermal effects from the processes occurring in them. Engines are also associated with a variety of equipment that are most efficient in certain temperature ranges. Every engine in a modern engineering unit is equipped with turbochargers that cannot operate beyond a certain temperature range. Diesel fuel becomes thicker when operating temperatures drop significantly, and this fact complicates both starting the engine itself and the engine operation in general. Therefore, the thermal stability of the engine is an important component of its performance. Thermal stability of the engine is ensured by oil cooling systems. Figure 1 shows an oil-liquid heat exchanger used in a number of engines to solve cooling issues.

The oil-liquid heat exchanger is integrated into the lubrication system as an additional element. Its purpose is to provide oil cooling. It is important to do so as engine oil overheating leads to serious problems: the oil viscosity changes, the intensity of its burnout and decomposition increases, and engine performance decreases. Overheated oil cannot provide sufficient quality lubrication of rubbing parts and complicates engine cooling. Moreover, insufficient cooling can result in a variety of damage to the power unit (up to jamming). Oil cooling systems are especially developed on uprated engines, because such engines are subject to significant overheating.
There are several approaches to cooling automotive oil. The method of cooling the lubricating oil by means of an oil heat exchanger is discussed in the books [1, 2]. This approach is based on the removal of heat from the heat exchanger due to the flow of coolant circulating in the cooling system of the power unit. As a result of the study, the following indicators were achieved [2]: reduction in overall performance and weight of the lubrication system, ensuring intensive heating of the oil after starting the engine, reducing wear of parts, protection from hypothermia during winter operation.

Also, the advantages should be noted [1]: installation of a heat exchanger in any convenient place and needless of long pipelines and many connections. The oil temperature in such a heat exchanger does not drop below the coolant temperature, as a result of which the engine operates in the best temperature mode. The disadvantages of the solution include a malfunction of the lubrication system in case of leakage, a complex design and the need for maintenance. In the conclusion, it is confirmed that the results obtained will increase the resource of the engine and oil, due to operation in a more stable temperature regime. This cooling system is widely used on both diesel engines and gasoline [2].

At present, this approach to oil cooling is widely used on domestic KAMAZ and YaMZ engines [1].

An alternative to a liquid-oil heat exchanger is the use of an air cooler, also called an intercooler. The use of an intercooler for cooling the internal combustion engine is considered in [3]. The disadvantages of using an intercooler include its significant dimensions and mechanical fragility. The intercooler housing is made of aluminum and is easily damaged by the hit of small stones or an easy road accident, and its repair is expensive.

One of the modifications of the liquid-oil heat exchanger for cooling high-power diesel units was presented in the patent [4]. The liquid-to-oil heat exchanger has been modified to eliminate the poor flushing efficiency of the coolant surfaces of the oil heat exchanger inside the radiator coolant manifold, which depends mainly on the performance of the water and oil pumps of the internal combustion engine. Liquid-and-oil heat exchanger includes tube bundle arranged inside cylindrical shell which connects reservoirs provided with branch pipes and partitions mounted perpendicularly relative to tubes; these partitions divide inner space of heat exchanger into cavities and provide for flow of heat transfer agent from one chamber to another.
After the modification, the heat exchanger started to work as follows. When the rotor rotates from an electric motor in a liquid-oil heat exchanger for internal combustion engines of vehicles, a forced pumping effect of pumping both coolants in countercurrent directions is created. This effect is achieved due to the fact that the liquid-oil heat exchanger for internal combustion engines of vehicles is equipped with pump blades on the inner and outer cylinders of the end parts on the coolant side of the combustion engine. As a result, there was an increase in the level of stability of the oil temperature and a high level of thermal equivalents of coolants at the most severe operating conditions of the internal combustion engine, which do not depend on the crankshaft speed.

2. Scientific novelty
There are two significant advantages of liquid-oil heat exchanger use. Firstly, the oil temperature in the liquid-oil heat exchanger does not fall below the coolant temperature [5]. This means that fewer stresses arise in the engine parts that come into contact with the oil at the same time; so the engine operates in a better temperature condition. Secondly, the heat exchanger can be installed in any convenient place on the engine. This eliminates the need for long pipelines and multiple connections. Disadvantages of a liquid-oil heat exchanger include complex design and the need for maintenance and repair [6].

These problems can be solved by reducing the weight and size of the heat exchanger. To reduce the size of the heat exchanger while maintaining the amount of heat transferred through it, it is necessary to increase the heat exchanger performance [7]. The most promising way to achieve that is to intensify heat transfer [8]. This is an important part of the development of internal combustion engines.

This article discusses the methodology for calculating the optimal flow rate of heat transfer intensification and the most effective design solution when choosing a heat exchanger. This can be achieved by improving the heat transfer coefficient, using a more efficient flow rate of the coolant and improved geometric characteristics of the channel.

3. Results
The key indicator of the efficiency of the heat transfer process is the heat transfer coefficient \( k \), which can be calculated by the formula (1). This is a proportionality constant between the heat flux (the amount of heat passing through a unit area) and the temperature difference (the one between a solid surface and the surrounding fluid), which characterizes the intensity of heat transfer on the surface of a solid body [9].

\[
k = \frac{1}{\frac{1}{\alpha_1} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_2}}
\]  

where \( \alpha_1 \) is a heat convection coefficient from the side of fluid to be cooled [W/(m\(^2\)·K)]; \( \alpha_2 \) is a heat convection coefficient from the side of fluid to be heated [W/(m\(^2\)·K)]; \( \sum \frac{\delta_i}{\lambda_i} \) is the total value of the thermal resistance of the wall and contamination [m\(^2\)·K/W].

We consider a heated wall or surface being in contact with a fluid flow. When the fluid flows within alternating channels of different cross-sections, a periodic separation of the boundary layer from the surface of the corrugations occurs. This phenomenon is called «diffuser-confusor effect» shown in Figure 2 [10].

The laminar boundary layer grows on the impermeable channel wall within the convergence area due to the viscosity forces. The thickness of the laminar boundary layer is determined by the type of fluid flow and the curvature of the streamlined surface (i.e. corrugation geometric characteristics). When the fluid flows through the diffuser, its velocity decreases, while the pressure increases. The pressure gradient increasing against the flow prevents the longitudinal movement of the fluid in the boundary layer. This backpressure, combined with viscous friction on the wall, slows down the boundary layer. The layer is detached from the surface and begins to flow in the opposite direction at
some distance from the protrusion. The backflow appears in the shape of vortex. The combination of these two complex flows results in increased fluid flow turbulence of the fluid flow in the plate heat exchanger flow channel. Turbulent flow is the most efficient flow type for heat exchangers operation.

Figure 2. The channel concentration field

It is known that a developed turbulent flow for a stationary isothermal fluid flow in a pipe with a circular profile appears when Reynolds numbers reach \( Re = 1000 \). In the flow channels of plate heat exchangers this effect is observed at Reynolds numbers reaching \( Re = 50-100 \) [11]. This indicates that the turbulent flow in the plate heat exchanger will develop at lower speeds (as compared to the shell-and-tube heat exchanger under the same conditions). The heat transfer coefficient in the flow path of the plate heat exchanger exceeds the heat transfer coefficient in the tubes of the shell-and-tube heat exchanger about 10 times [12]. This means that a more turbulized flow type will be observed in a plate heat exchanger at the same values of the coolant flow rate. As a consequence, this leads to a higher intensity of the heat transfer process between the channel wall and the moving coolant in a plate-type heat exchanger.

The Reynolds number characterizes the ratio of inertial forces to viscous friction forces in viscous liquids and gases. It is also a similarity criterion for the viscous fluid flow [13]. The Reynolds number can be determined by formula:

\[
Re = \frac{p \cdot v \cdot D_h}{\eta} = \frac{Q \cdot D_h}{v \cdot A}
\]  

where \( p \) is a fluid density \([\text{kg/m}^3]\); \( v \) is a fluid velocity \([\text{m/s}]\); \( D_h \) is a hydraulic diameter \([\text{m}]\); \( Q \) is a volume flow rate \([\text{m}^3/\text{s}]\); \( v \) is a kinematic viscosity coefficient \([\text{m}^2/\text{s}]\); \( \eta \) is a dynamic viscosity coefficient \([\text{Pa}\cdot\text{s}]\).

It is necessary to refer to the concept of the hydraulic diameter for further transformations. It characterizes the measure of the fluid flow passage efficiency by the channel. The hydraulic diameter can be determined by the formula:

\[
D_h = \frac{4 \cdot A}{P}
\]  

where \( A \) is a cross-sectional area of fluid flow \([\text{m}^2]\); \( P \) is a wetted perimeter of the flow cross section \([\text{m}]\).

For rectangular channels, the hydraulic diameter can be determined by the formula:

\[
D_h = \frac{4 \cdot a \cdot b}{2 \cdot (a + b)}
\]  

where \( a \) is a channel fill level \([\text{m}]\); \( b \) is a channel width \([\text{m}]\).

The Reynolds number for a plate heat exchanger can be expressed using the geometric characteristics of the channel and the flow rate of the heat transfer fluid according to formula:

\[
Re = \frac{Q \cdot 4 \cdot a \cdot b}{v \cdot a \cdot b} = \frac{4 \cdot Q}{2 \cdot (a + b) \cdot v} = \frac{4 \cdot Q}{P \cdot v}
\]  

where \( P \) is a channel perimeter \([\text{m}]\).

The resulting dependence relates the Reynolds number to the volumetric flow rate of the liquid (which flows through the cross section of the fluid flow per unit time), as well as to the channel perimeter and kinematic viscosity.
Kinematic and dynamic viscosities are related to each other according to the formula:
\[ \nu = \frac{\eta}{\rho} \]  
(6)
where \( \rho \) is a fluid density [kg/m\(^3\)].

The dependences of the dynamic and kinematic viscosity of water on temperature and pressure are presented in Figure 3 [14].

![Figure 3](image)

**Figure 3.** The dependence of engine oil viscosity on temperature: 1 - Aviation oil MK-22; 2 - Autotractor oil "AK-Yu"; 3 - Automobile oil "AC-5"; 4 - Motor oil "AKZp-6"

For a more accurate determination of the density, the American scientist, Doctor of Natural Sciences James Dewey Watson introduced the empirical dimensionless value of \( \omega' \) [15]. According to Watson, the dependence of \( \omega' \) on the given parameters is a universal function that is valid for most liquids. The diagram is shown in Figure 4 [15]. The diagram makes it possible to calculate the value of the liquid density for any temperature and pressure. In this case, the critical constants of the fluid and one value of density must be known at arbitrary values of temperature and pressure. The following expression is valid for the data obtained from the Watson diagram:

\[ \frac{\rho_1}{\rho_2} = \frac{\omega'_{1}}{\omega'_{2}} \]  
(7)
where indices 1 and 2 characterize the state of the liquid for various parameters of the fluid.

Formula (5) demonstrates ways to more efficiently use a plate heat exchanger in a lubrication system. As it follows from it, the turbulization of the flow increases with an increase in the volume flow rate, but decreases with an increase in the kinematic viscosity of the liquid or the wetted perimeter. Figure 3 shows that the viscosity of oils drops significantly with increasing temperature. Thus, significant cooling of the coolant complicates turbulization of the flow. Therefore, it is necessary to avoid overcooling the oil when removing heat from the internal combustion engine.

Maximization of turbulence occurs at a smaller wetted perimeter. Therefore, to increase the efficiency of the heat exchanger and the engine, preference should be given to the device whose channels have a smaller wetted perimeter when choosing between two devices with an equal heating surface area. A heat exchanger whose plates have a smaller width at the same channel height.
4. Conclusion
The article discusses methods for flow turbulence intensification, which can improve the conditions for heat transfer and indirectly affect the heat transfer coefficient.

The following solutions are presented:
1. reduction of the wetted perimeter of the heat exchanger channel;
2. avoidance of oil overcooling when organizing heat removal from the engine.

These solutions can be used for efficient oil cooling on diesel engines. The use of a plate heat exchanger will simplify the design, maintenance and repair of the heat exchanger. Also, liquid-oil heat exchangers have a long service life, and with regular maintenance and timely flushing and repair, this part will not cause problems, providing effective oil cooling at all engine operating modes. Currently, they are widely used on domestic KAMAZ and YAMZ engines, and liquid metal products have also found application in many modern trucks of foreign production and even in compact passenger car engines.

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