Development of cooling systems for internal combustion engines in the light of the requirements of modern drive systems

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Abstract. In the article was held a critical discussion on the challenges facing the cooling system of thermal engines in the light of modern requirements. These issues are directly related to new tendencies in the construction of internal combustion engines, including those concerning increasing unit power, application of the Atkinson and Miller theoretical cycles, and cooperation of heat engines with electric machines.

1. Introduction

The task of the cooling system of the internal combustion engine is removing the heat flow from the elements exposed directly to the high temperature, preventing local overheating. At the same time, he is responsible for maintaining the optimal operating temperature of the internal combustion engine, which is one of the key elements necessary to ensure work with the highest possible thermal efficiency.

Heat flux discharged must be large enough to guarantee correct cooperation of all construction elements taking into account the properties of the construction material, and in particular its thermal expansion. Deviations from this rule may lead to a reduction of clearance in the fits, for example in the piston, ring and cylinder system, which may result in excessive wear or seizure of these elements. Locally exceeding the maximum temperature of specific engine components may result in boundary or dry friction, which in a short time leads to the destruction of cooperating elements. This is due to significant changes in the viscosity of the lubricating oil along with the temperature change of the lubricated elements. The key issue here is to guarantee an adequate heat flux discharged from the combustion system, which is the most thermally loaded element of the engine. Any deviation from the adopted thermodynamic parameters may cause, on the one hand, combustion anomalies when working at too high temperature, and on the other hand, excessive emission of incomplete combustion products resulting from insufficient process temperature. Usually in internal combustion engines, it is a very difficult task to maintain optimal conditions for the cooperation of all construction elements from the point of view of the lubricating oil function in relation to the high inertia of currently used cooling systems. Usually, they cause the averaging of thermal loads of individual units and use the lack of a quick response to the changing conditions of thermal load. In modern constructions of internal combustion engines, due to the safety of the structure, the heat discharge streams are usually
oversized, which has a significant impact on the efficiency of energy conversion and the emission of toxic exhaust components.

2. Analysis of modern cooling systems

Ensuring the proper operation of the internal combustion engine is not possible without the use of a cooling system that will ensure the discharge of excess heat from elements exposed to overheating. According to the theoretical basis for the work of internal combustion engines, heat dissipation through the cooling system causes losses, reducing the efficiency of the cycle.

In modern constructions of combustion engines, are used both air and liquid cooling systems. They differ significantly in the medium used, as well as in the construction and adjustment possibilities. The simplest structure of all so far used cooling systems is characterized by an air cooling system. In this type of cooling systems, heat exchange occurs between the finned surface and the air flowing around it. No need to use an external heat exchanger, coolant pump and mechanical components makes this system maintenance-free, which reduces operating costs. Internal combustion engines with the air cooling system emit more noise than engines where is a liquid cooling system. This is due to the lack of damping of vibrations by the cooling liquid and the resonating effect of the finning of the cylinder head and the engine block. In order to improve the air flow, which significantly affects the efficiency of the cooling system, are used individual cylinders and heads. This solution increases the dimensions and weight of the motor and significantly reduces the stiffness of the structure. Due to the simple design of the air cooling system, it has many limitations and disadvantages. In this type of construction heat exchange takes place only on external surfaces, therefore there is no possibility of optimal cooling internal components of the internal combustion engine. This has an adverse effect on the uniformity of the temperature distribution, which may lead to the occurrence of areas exposed to local overheating, which is conducive to rapid wear of components of the internal combustion engine. The efficiency of the air cooling system is largely dependent on the air flow speed and the heat exchange surface. Obtaining a sufficient heat exchange of the internal combustion engine necessary for correct operation forces the use of technical solutions that will ensure the appropriate amount of heat transfer medium delivered. The lack of thermal stabilization of the engine negatively affects the lubricating properties of the engine oil, whose viscosity changes as the operating temperature of the internal combustion engine changes. Deterioration of lubricating properties of engine oil can lead to damage to engine components. Due to the design and principle of operation of such systems, limited is the possibility of regulating heat exchange. Due to the above limitations, air cooling systems are only applicable to low power traction motors or those operating under constant load conditions. In internal combustion engines with high unit power in conditions of work with high load at low speed, the required air flow may be insufficient, which may lead to overheating of the engine and as a result the occurrence of combustion anomalies. Despite the many disadvantages of air cooling systems, the important advantage is the rate of heating individual elements. Very quickly achievement of the internal combustion engines operating temperature improves the overall efficiency and durability of the associated engine components. Internal combustion engines with air cooling system, due to their simple construction, are characterized by lower self-weight compared to liquid-cooled engines. The lack of a heat exchanger and expensive mechanical components, such as: a coolant pump, a thermostat, and coolant hoses, significantly reduce the production costs of reducing the mass and dimensions of the engine with this type of system.

Continuous development of internal combustion engines, which results in increasing efficiency and obtaining more and more unit power, air cooling systems are insufficient. In this type of constructions, the liquid cooling system becomes the standard. Internal combustion engines with a liquid cooling system are characterized by a more complex construction. They are equipped with many external elements, such as: heat exchanger, heater, thermostat, mechanical water pump, fan, cooling liquid lines, which are necessary to ensure correct operation of the entire system. Such an amount of peripheral elements increases the complexity of the system and the cost of production and exploitation of the internal combustion engine. In addition, liquid-cooled internal combustion engines generate less
noise and vibrations than air-cooled engines. It is caused by filling the channels of the cylinder head and engine with cooling liquid, which ensures noise and vibration damping. When using such a cooling system, the stiffness of the head and hull is increased. High stability and uniformity of heat collection is possible due to the filling of channels located in the head and the hull by the cooling liquid. In contrast to air cooling systems, in liquid cooling systems it is possible to collect heat from internal construction nodes of an internal combustion engine. The above features allow you to maintain the correct operating temperature of the internal combustion engine, regardless of the ambient conditions and the engine's operating condition. The large volume of cooling liquid and the inability to control the operation of the mechanical liquid pump, which is usually coupled to the crankshaft, will prolong the heating time of the engine. This is a disadvantage both from the ecological point of view as well as the durability of the team. Extended heating time results in increased emission of toxic exhaust components (mainly HC, CO, PM). Too long heating of the engine may cause penetration of the lubricated fuel into the lubricating oil, changing its lubricating properties, which in turn causes faster wear of the mechanical components of the internal combustion engine. The inability to control the operation of the coolant pump significantly reduces the heat exchange. When operating an internal combustion engine with maximum load and low speed, the pump output may be too small to ensure optimal heat exchange conditions. This situation adversely affects the overall efficiency of the engine and can lead to its destruction. In transient states and when the engine is operated with low load and high speed, unnecessary mechanical losses due to the resistance of the coolant flow are generated.

Modern internal combustion engines are made of many different materials with different physical and chemical properties, including thermal expansion. This solution improves the operating parameters of internal combustion engines. The use of a liquid cooling system in modern combustion engines also requires analysis of the interaction between the cooling medium and various types of construction materials, because there is a possibility of chemical reactions occurring in them. Increasingly, the cooling systems of internal combustion engines are equipped with an additional support system whose task is to maintain the circulation of the cooling liquid, preventing its overheating when the engine stops.

In liquid cooling systems of an internal combustion engine, the element responsible for ensuring the flow of cooling medium is usually a centrifugal pump. It is characterized by high efficiency and a very simple and compact construction. The calculation of the water pump is made on the basis of the amount of energy flow which should be removed from the internal combustion engine. Usually, it ranges from 25 to 35% of the heat generated from the combustion of fuel. The amount of heat discharged per unit of time by the coolant is:

\[ Q = \frac{(0.25-0.35)}{\eta_0} N_e \text{, [kW]} \]  

\( N_e \) – effective power  
\( \eta_0 \) – general efficiency

The pump capacity can be determined by the formula:

\[ M_w = \frac{Q}{c_w \Delta t_w} \text{, [kg/s]} \]  

\( c_w \) – specific heat of the cooling liquid [kcal/kg·°C]  
\( \Delta t_w \) – reducing the liquid temperature in the radiator [°C]

In commonly used forced cooling systems, the coolant is kept under pressure during operation. This solution allows to increase the boiling point of the cooling liquid. In these systems the pressure accumulation should be:

\[ \Delta p = 45\sim120 \text{ [kN/m}^2 \text{]} \]
The power required to drive the coolant pump can be specified by the formula:

\[ N_{pw} = \frac{M_w \cdot \Delta p}{\rho \cdot \eta_w}, \text{[kW]} \]  

(3)

\( M_w \) – specific mass of the cooling liquid
\( \eta_w \) – general efficiency of the pump [1]

Technological progress and continuous technical development of internal combustion engines leading to increasing the overall efficiency, forces the constructors to apply innovative solutions that will ensure optimal cooling conditions. Due to the variable operating conditions of combustion engines, the cooling system cannot allow both overcooling and overheating of the engine. Overcooling will increase the emission of toxic exhaust components, increase fuel consumption and wear of cooperating elements. Overheating the engine will damage it. The biggest disadvantage of currently used mechanical coolant pumps is the lack of controllability of the flow rate. Research shows that due to the dependence of the coolant pump parameters on the engine crankshaft speed, usually used pumps guarantee an optimal flow to the load conditions for only 5% of the service life under variable conditions. Usually, the pump's efficiency is selected based on the criterion of the maximum thermal load of the structural components of the engine [2].

The ongoing work on improving cooling systems focuses on the ability to regulate the flow of cooling liquid depending on the engine's operating status. The latest solution is to replace traditional pumps with mechanically driven electrically driven pumps. They allow regulating the flow of refrigerant regardless of the engine speed. This solution allows to reduce the power consumption during operation of the engine with partial load, shorten the time of heating the engine and reduce the amount of toxic components of the exhaust during the heating phase.

These pumps are standard equipment for internal combustion engines used in modern hybrid drive systems. The independent operation of the coolant pump allows it to function even when the engine is not running. In the traditional solution with a mechanical liquid pump, when the engine stops, the flow of cooling liquid stops, which may lead to overheating and accelerated wear or damage to the engine components. The use of electrically driven coolant pumps allows to completely eliminate the above disadvantage of the cooling system. It is also possible to shorten the heating time by using a heat accumulator by starting the pump before starting the engine.

Based on research conducted by Loughborough University [2], it appears that replacing a mechanically driven pump with an electrically driven pump will increase the value of the engine's operating parameters. The results obtained are shown in Fig.1.
Based on the above tests carried out [2], it may be considered appropriate to use electrically driven pumps in the cooling systems of the internal combustion engine. This solution affects both the improvement of the operating parameters of the internal combustion engine and the increase of its durability by thermal stabilization.

The system of active coolant control is an extension of the liquid cooling system. Research on this type of system was carried out by Automotive and Tractors Engineering, Faculty of Engineering, Helwan University [7]. In their work, the authors presented the concept of the system, where the classic, mechanically driven coolant pump was replaced with an electrically driven pump and used an "intelligent" thermostat with the possibility to regulate its opening by means of electronic control independent of the temperature of the coolant. This solution gave the possibility of a smooth adjustment of the pump output regardless of the rotational speed of the crankshaft of the internal combustion engine and the degree of thermostat opening. Based on the laboratory tests carried out, it was found that the use of the above system allowed to reduce the heating time of the engine by approx. 30%. The use of an advanced cooling system allows to increase the thermal stability of the internal combustion engine [7]. The obtained results are presented in the diagrams below.

**Figure 1.** Engine performance with the mechanical and electric pumps.[2].

**Figure 2.** Engine temperature with mechanical pump[7]

**Figure 3.** Engine temperature with electrical pump[7]
The use of electric pumps enables better use of heat accumulators in the cold start phase. A heat accumulator is a device whose task is to stop some of the energy lost in the cooling system. The principle of operation of previously used heat accumulators was based on the phase change (clotting heat) of PCM material (phase change material). The PCM material in the heat accumulator under the influence of the heat flux emitted by the cooling system melted, thus remaining in the liquid state, it stored thermal energy in this way. In the solidification process, the previously stored heat was transferred [3]. Currently, only heat accumulators can be used that store part of the hot coolant. The use of thermal energy, which is usually lost, improves the heat balance of the internal combustion engine. The use of thermal energy stored in the heat accumulator during the cold start phase of the engine and in the heating phase leads to an improvement in the combustion process, shortening the time of heating the engine and reducing the emission of toxic exhaust components. The use of heat energy accumulated in the heat accumulator contributes to the increase of engine durability [4].

With a classic pump, the circulation of refrigerant through the heat accumulator takes place simultaneously with starting the engine using an electric pump, it is possible before starting the engine.

Research on heat exchange in the cooling systems of internal combustion engines contributed to their significant development and increased efficiency. Over the last decade, there have been many technical solutions that improve the work of these systems. The properties of the medium used have a significant influence on the efficiency of heat exchange in liquid cooling systems. Currently, the most commonly used cooling agent in this type of systems is the ethylene glycol water solution. Research on the application of nanoliquids in cooling systems of internal combustion engines has shown that the use of nanoparticles of metallic or non-metallic materials can lead to 15-40% increase in heat exchange in cooling systems of internal combustion engines [5]. Based on numerical simulation carried out in the Department of Mechanical Engineering Institute of Technology-BHU [6], the authors have shown that the addition of copper oxide nanoparticles to the ethylene glycol based cooling medium leads to an increase in the heat exchange coefficient in the cooling system of the internal combustion engine. Based on numerical data, an increase in the maximum engine power was observed of 5% and a reduction of energy consumed by the pump drive by 88%. The obtained results are presented in Table 1. and Tab.2. [6].
Table 1. Increased engine heat rejection with Nanofluids[6]

| Coolant | Base Fluid (50/50 ethylene glycol/water mixture) | Nanofluid-1 (ϕ = 2% CuO in base fluid) | Nanofluid-2 (ϕ = 4% CuO in base fluid) |
|---------|-----------------------------------------------|----------------------------------------|----------------------------------------|
| Engine Heat Rejection to Coolant Circuit | 400 HP                                      | 410 HP                                  | 420 HP                                  |

Table 2. Reduced pump speed with nanofluid[6]

| Pump Speed | Pump Power |
|------------|------------|
| RPM        | kW         |
| 1600       | 0.75       |
| 1150       | 0.386      |
| 800        | 0.09       |

3. The cooling system concept for modern drive systems

The cooling system features mentioned in the above chapters do not meet the modern expectations of a rational thermal management of the vehicle. In many aspects, there are heat losses that reduce the overall efficiency of the entire drive system.

For these reasons, the authors considered it expedient to develop a new concept of a universal cooling system that would reduce thermal and mechanical losses generated in the cooling system and improve the scope of heat exchange regulation by using a new method of generating flow while using nanoliquids.

At the Institute of Automobiles and Internal Combustion Engines at Cracow University of Technology, work is underway to improve the operation of cooling systems, through the use of a new type of refrigerant transport, as well as the use of a new type of coolant characterized by an increased coefficient of thermal conductivity. The results of this work can bring benefits in the form of:

- reducing the weight and dimensions of the engine;
- improvement of heat management control both in the engine itself as well as in peripheral devices (heating of the vehicle interior, cooling of electric current batteries, cooling of automatic transmissions);
- reduction of the cold start and heating time;
- increase in mechanical efficiency;
- increase in general fitness;
- reduction of toxic components emissions (especially during the cold start and heating phase).

The developed system with the use of liquid pumps with the drive independent of the engine operation conditions, shortens the time of heating the engine and reduces mechanical losses. The new system will be universal, possible to be used in various vehicle drive configurations. The primary function will be to cool the heat engine components, while it will be possible to extend its functions. It is also expected to be able to use some of the solutions of this system to work with a "clean" electric or hybrid drive system, using excess heat for heating or cooling. This system will also be suitable for servicing heat management in a fuel cell drive system.

Some of the developed system components are in the preparation phase of the patent application.

4. Summary

The dynamic development of drive systems with thermal engines forces designers to reach for newer technical solutions in the field of cooling and maintaining thermal equilibrium. In the current form, cooling systems for heat engines no longer meet the requirements set by modern vehicle drive systems. Therefore, it is necessary to develop new, universal solutions that will have wider application both for cooling thermally loaded structural elements and for the implementation of the entire thermal management in the vehicle. In this direction work undertaken at the Institute of Automobiles and Internal Combustion Engines at Cracow University of Technology.
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