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The concept of a new refrigerant in combustion engines in aspect of the requirements of modern drive systems

The article presents currently applied construction solutions for currently used cooling systems for internal combustion engines. There were presented their defects and possible development directions were indicated. On this basis the concept of a cooling system which will enable the improvement of heat exchange in the internal combustion engine has been proposed.

Key words: *combustion engine, engine cooling system, electromagnetic pump*

1. Introduction

The internal combustion engine is a thermal machine in which there is a need to remove heat from elements subject to high temperature. This function is performed by the cooling system, which is also responsible for maintaining the correct operating temperature having a significant effect on thermodynamic efficiency. Therefore, there is a need to ensure a strictly determined temperature value of individual structural elements of the engine, at which the assumed thermodynamic efficiency is achieved, and at the same time the correct cooperation of individual structural elements is guaranteed [1].

Running the process of heat emission in an internal combustion engine on the one hand is limited by the effects of combustion anomalies, which in a short time lead to destruction of the engine, and on the other, the exploitation of the engine at too low temperature results in reduced efficiency, increased emission of incomplete combustion products and accelerated consumption of cooperating construction elements.

Due to the conditions imposed on contemporary sources of vehicle and machine propulsion, aspects related to energy efficiency and impact on the environment are currently the main priorities. For this reason, there is an urgent need for development research, also in the area of cooling systems for thermal machines which results from a significant impact on the listed conditions, including an efficient cooling system for internal combustion engines. This is all the more important as there are still significant development reserves in this area of technology. Therefore, undertaking scientific research on the development of cooling systems for internal combustion engines is justified in all respects, and the results of this type of work are in great demand in the sphere of technical practice.

2. Currently used cooling systems for internal combustion engines

Requirements for cooling systems of thermal machines are very complex. As already mentioned in the introduction, conducting the process of heat production at high temperature is beneficial due to thermodynamic efficiency, but too high thermal load of cooperating structural elements of an internal combustion engine can cause operational problems. This is mainly due to changes in the assembly clearances and lubricating oil operating conditions. The effect is usually accelerated consumption or destruction of cooperating surfaces. Even temporary, local exceeding of the admissible temperature of the elements of the internal combustion engine may cause extreme or dry friction resulting from the lack of adequate lubrication.

As a result, an important task of the cooling system is to discharge the corresponding heat flux from each structural element of the motor which is thermally loaded.

Due to the engine's operational safety, heat dissipation streams from individual structural elements are usually oversized and are not suited to real needs. The modern development of technology, especially in the field of regulation and control, allows the development of a cooling system in which the most appropriate thermal conditions for the work of individual components can be obtained. Therefore, it is advisable to undertake development works in the field of cooling systems, which will have wider application to the implementation of the entire thermal management in a vehicle.

In the current designs of internal combustion engines, both air and liquid cooling systems are used. The air cooling systems are characterized by a simple construction, because the basic heat exchange takes place without an intermediate medium, between the surface of the internal combustion engine and the environment. Due to the construction of such a cooling system it is maintenance-free and does not generate additional operating costs [2].

However, it should be emphasized that the lack of vibration damping by the cooling liquid and the resonant effect of the surface of the ribbed heat exchange surface causes that the motors using the air cooling system generate more noise than the motors with the liquid cooling system. The guarantee of correct heat exchange is also often the need to use ribs of individual cylinders and heads, which results in increased dimensions and weight of the engine.

In air-cooled heat engines, the basic heat transfer takes place only on the external surface, while the internal components are not cooled, which may lead to local temperature rise above the limit values, overheating of these elements and their irreversible damage. In air cooling systems, its efficiency depends on the air flow rate and the heat exchange surface. There is a significantly limited control over the thermal load of individual engine components. Usually in this type of constructions the combustion process is carried out at a higher temperature, which results in the necessity of using fuels with higher anti-knock resistance and oils with greater thermal stabilization. Due to the features mentioned, the air cooling systems have a limited application, mainly in engines with low unit power or stationary motors.

Limits of emissions of toxic exhaust components and the tendency to increase the unit power of internal combustion engines, forces the constructors to reach for new, often more complex solutions of cooling systems. In engines with a liquid cooling system, a number of additional components are required that make for a more complex construction compared to engines equipped with an air-cooling system. These are various types of elements, such as: heat exchanger, mechanically driven coolant pump, expansion tank, heater, thermostat, fan, coolant supply pipes, which significantly complicate the structure, increase weight and dimensions, and increase the production and operation costs of the engine. A better feature of the liquid cooling system is better vibration and noise damping thanks to filling the hull and the cylinder head with cooling liquid [3].

In addition, in this type of cooling system it is possible to cool the internal structural nodes of the engine and to achieve greater thermal stabilization, preventing the local formation of areas with unfavourable thermal features. The design and features of the liquid cooling system also allow maintaining a stable temperature of the internal combustion engine regardless of the operating status and ambient conditions. Usually however, the coolant pump is mechanically coupled to the crankshaft of the internal combustion engine, which prevents independent control of its, flow rate suited to current needs. One of the disadvantageous effects is for example, the prolongation of the heating time of the engine, which affects the durability of components and increased emission of toxic exhaust components.

Nowadays, for marketing reasons, motor vehicles with very high nominal power are used in motor vehicles, whereas under real operating conditions the engine usually operates in low or medium load conditions, not exceeding typically 20–40% of nominal value and the full load is used sporadically. In this case, the role of the constructor is to design such a cooling system for a reciprocating internal combustion engine, which after many hours of operation in urban traffic with a low load guarantees optimum cooling conditions also during operation with maximum load, e.g. during highway traffic.

This is a difficult task, because the thermal inertia of the coolant and the speed of cooling liquid displacement in the system significantly limit the possibility of regulating the heat pickup in the rapidly changing thermal conditions of the engine. The effect of this is increased fuel consumption, increased emission of toxic exhaust components and reduced durability of cooperating construction elements. In the few new designs, the mechanical coolant pump is assisted or replaced by an electric pump. This solution, to a limited extent, creates the possibility of controlling the heat reception, this type of regulation being global, limited to controlling the average temperature of the cooling medium, not always suitable for all local engine components [4].

Since heat exchange between the cooled walls of the motor and the cooling medium is strongly dependent on the flow rate of the refrigerant, cavitation may occur in some of the nodes. This is particularly true for areas with a variable cross-section, in which there is a significant change in the speed of the cooling agent. The appearance of cavitation is related to the disruption of the continuity of the flowing liquid and the formation of embryos in the form of cavitation bubbles.

Cavitation bubbles collapse, and often violently implode, creating a local shockwave. Its speed may be sufficient to create wear of the erosive surface of the engine components. The basic symptom of cavitation on the components of a reciprocating internal combustion engine is the progressive loss of material, which after degradation of the primary structure is dispersed in the liquid in the form of fine grains. Therefore, cavitation is a source of impurities in the cooling liquid, leading to a change in its properties. The complex geometry of the liquid channels of the reciprocating internal combustion engine, as well as other components, make the liquid cooling systems a place of occurrence of the phenomenon of cavitation. Usually elements such as: thermostat, coolant pump rotor, coolant ducts and cylinder liners are subject to erosive damage. Fig. 1 shows a brand new coolant pump at the factory, while Fig. 2 shows a coolant pump destroyed by the erosive effect of cavitation [5].

Fig. 1. Brand new, mechanical coolant pump

Fig. 2. A mechanical coolant pump destroyed by the erosive action of cavitation

Considering the features of modern systems for cooling internal combustion engines with air or liquid, in order to improve their efficiency, various types of support devices are used.

One of such systems, supporting the heat exchange in a piston combustion engine, is the lubricating oil cooling system. The oil circulating in the lubrication system of the internal combustion engine, in addition to the lubrication function of the cooperating surfaces, also acts as a coolant. Therefore, for example in engines with high unit power, as well as in industrial engines, engine oil is used as a cooling medium for pistons, supporting the basic cooling system.

3. A new concept for the cooling system of the internal combustion engine

Considering insufficient possibilities of matching air and liquid cooling systems of piston combustion engines to the requirements of modern internal combustion engines, it is necessary to find new solutions in this area. The cooling system of modern internal combustion engines should provide cooling conditions adequate to the state of the engine operation, with particular emphasis on the efficiency of energy conversion and the emission of toxic exhaust components. This is possible by using a coolant with a greater heat transfer capability and another coolant transport strategy.

The most important feature of the developed concept of a modern cooling system for a reciprocating internal combustion engine is the use of a new type of coolant in the form of a ferromagnetic liquid with good heat transfer properties.

It also results from the possibility of using a new type of pump, responsible for the movement of the coolant in individual cross-sections of the cooling system. This type of pump, using an electromagnetic field for transporting a ferromagnetic liquid, is characterized by a simple construction as well as a wide possibility of regulating the flow of the medium. By using an electronic controller, it is possible to control the flow of refrigerant in the piston cooling system of the internal combustion engine, independent of the engine crankshaft speed.

The proposed cooling system is universal, possible to be used not only in piston combustion engines, but also in other types of thermal machines, where there are specific conditions regarding the thermal state of individual structural elements. This type of cooling system also allows the development of an individual cooling strategy for selected construction nodes by forming independent refrigerant circuits inside the entire cooling system structure of a given machine. This enables individual adaptation of the cooling agent's speed in the given nodes, controlled by additional electromagnetic pumps. The entire system can be centrally controlled based on signals from temperature sensors placed in the cooled machine structure.

The proposed cooling system concept can bring the following effects:

- increase in general efficiency;
- increase in mechanical efficiency;
- improvement of thermal stabilization of the internal combustion engine and shortening the heating time;
- reduction of toxic components emissions;
- better management of heat exchange in the combustion engine and other peripheral devices of the vehicle, such as: interior heating system, vehicle ventilation system, drive transmission system, and in hybrid drive systems: cooling of the inverter, batteries and electrical machines.

This cooling system is a liquid heat exchange system operating in a closed circuit. In the conceptual design, the centrifugal mechanical pump was replaced by an electromagnetic pump for the coolant. This type of pump is made of a solenoid wound on a casing made of a diamagnetic material. In the discussed solution, the coil carcass simultaneously functions as the pump body together with connection stubs. The diagram of the construction of an electromagnetic pump for a coolant composed of one and many solenoids is depicted in Fig. 3 and Fig. 4. The presented concept of the cooling medium pump causes its movement due to the magnetic field created by the electric current flowing through a solenoid or a set of solenoids. The phenomena of magnetism were used to create the motion of the cooling agent. The cooling agent used nanoparticles of ferromagnetics suspended in a liquid, commonly known as "ferrofluid". When the electromagnetic pump is activated, a very large current flows through the solenoid, resulting in a strong magnetic pulse. Ferromagnetic nanoparticles suspended in the liquid at one end of the coil (or even some distance away) are pulled into the pump body, where they begin to accelerate rapidly. The acceleration force stops working around the centre of the coil. The magnetic pump should be designed so that the current in the coil stops flowing from the moment when the stream of nanoparticles of ferromagnetic suspended in the liquid reaches the area around the centre of the coil - otherwise it will be braked on further movement.

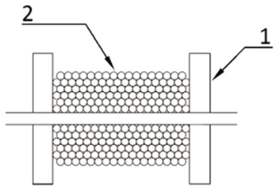

Fig. 3. The design of the electromagnetic pump: 1 – core of the coil, 2 – coil

Fig. 4. Prototype of electromagnetic pump

Figure 5 shows a model test stand, where the prototype pump has been installed. Preliminary tests of the electromagnetic liquid cooling pump were carried out in the presented position. During the tests, it was found that the magnetic field produced by the coil causes the flow of ferrofluid. It has also been shown that by changing the length of the control pulse or changing its frequency, it is possible to change the flow rate of the cooling liquid.

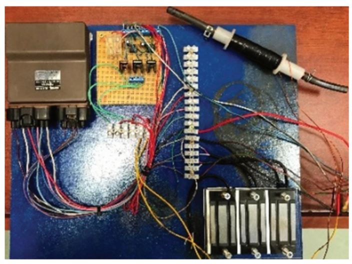

Fig. 5. A model test stand for an electromagnetic pump

In Institute of Vehicles and Internal Combustion Engines at Cracow University of Technology there were developed various concepts of cooling systems using an electromagnetic pump and a cooling agent consisting of ferromagnetic nanoparticles forming a suspension in a liquid. The presented systems differ from each other by the construction of a coolant pump.

Figure 6 shows a cooling system consisting of an electromagnetic one-stage ferromagnetic liquid pump which, if necessary, generates flow in the system from the combustion engine to the heat exchanger. The electronic controller is responsible for the correct operation of the electromagnetic ferromagnetic fluid pump. It simultaneously controls the value of time intervals and the maximum current flowing through the coil, based on electrical signals from such sensors as engine temperature sensor, coolant temperature, oil temperature, crankshaft speed, throttle angle or fuel injection time. After processing in the control unit, they allow precise control of the algorithm and procedures based on the rotational speed of the crankshaft. This method of control also allows complete shutdown of the refrigerant flow, resulting in a shorter heating time for the internal combustion engine. However, due to the rapidly changing processes in the internal combustion engine, the total shutdown of the coolant flow can be risky and lead to engine damage. To implement such a solution, it is necessary to conduct long-term durability tests on many types of engines. The reduction of the heating time of an internal combustion engine can be received by using an additional coolant circuit with low flow rate.

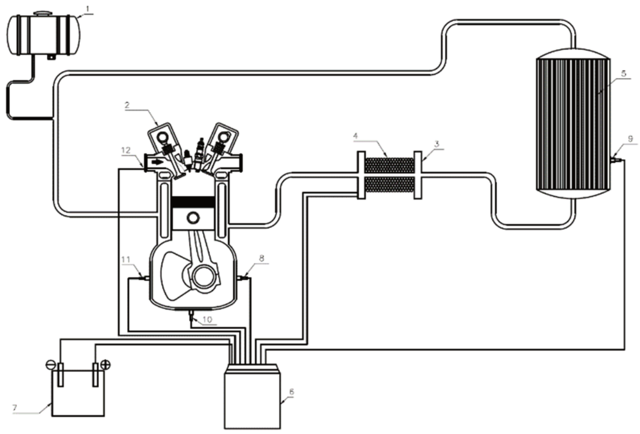

Fig. 6. Diagram of the piston cooling system of an internal combustion engine with an electromagnetic pump: 1 – compensating tank, 2 – combustion engine, 3 – coil core, 4 – coil, 5 – heat exchanger, 6 – electronic controller, 7 – supply source, 8 – temperature sensor, 9 – coolant temperature sensor, 10 – oil temperature sensor, 11 – crankshaft speed sensor, 12 – throttle angle sensor

This solution of the cooling system together with the control system allows obtaining the required cooling liquid flow, regardless of the crankshaft rotational speed. The possibility of such a control of the cooling system significantly improves the heat exchange regulation range. In conventional cooling systems of the internal combustion engine, the lack of control over the cooling agent flow significantly limits the heat exchange control range. When operating an internal combustion engine with maximum load and low speed, the coolant flow must be sufficient to ensure correct heat exchange conditions. This situation adversely affects the overall efficiency of the engine in other work states. In transient states, and when the engine is operated with low load and high speed, unnecessary mechanical losses are generated due to the resistance of the coolant flow. The possibility of controlling the electromagnetic pump can significantly reduce the consumption of energy lost on the drive of the refrigerant pump and eliminates the possibility of cavitation, which can lead to destruction of the pump impeller, and consequent damage to the engine.

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.

It is necessary to find new, universal solutions that would allow a rational heat exchange economy, not only in the internal combustion engine, but in the whole vehicle drive system.

The use of a cooling system in an internal combustion engine in which an electromagnetic pump was used to create the flow rate and as a cooling agent used ferromagnetic nanoparticles suspended in a liquid can bring benefits related to heat exchange. Depending on the results obtained, it will be possible to assess the applicability of the cooling system in question not only in the internal combustion engine, but also in other elements of the vehicle's drive system that require cooling and other industries.

It is necessary to conduct experimental tests using an internal combustion engine as a test object, which will aim to determine whether it is possible to produce controlled movement of a ferromagnetic fluid by using a pump that uses a magnetic field of sufficient intensity to operate.

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