Prospects for development of high-temperature evaporative cooling systems of internal combustion engines with increased temperatures of the cooling body

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Abstract. The article deals with issues related to the development of the high-temperature evaporative cooling (HTEC) systems of internal combustion engines (ICE). These systems can transfer the proportion of heat that flows to the ICE into the cooling system. HTEC systems are usually part of the integrated heat recovery (IHR) systems based on large-piston ICES. It is proposed to improve the efficiency of the operation of the HTEC systems, as well the IHR systems on their basis, by a significant increase in the temperature of the cooling body in the cooling jacket up to 200°C and even 350°C. The increased coolant temperature causes a decrease in the power of the heat fluxes from the heated surfaces thus causing the engine overheat. This reduction can be compensated by increasing the area of the cooled surfaces of the sleeves and cylinder heads. To test the theoretical proposals, a working ICE model equipped with the HTEC-based IHR system was developed. The results of its bed tests are provided. During the experiments, the temperature of the coolant in the cooling jacket reached 204°C, with the engine performance remaining stable.

Keywords: The high-temperature evaporative cooling systems of internal combustion engines

1. Introduction
This paper considers the issues related to the prospects for the development of integrated heat recovery (IHR) systems of the main engines, based on high-temperature evaporative cooling (HTEC) with significantly increased operating parameters (temperature and pressure) as compared to the current operating parameters. Use of secondary heat is an effective way to increase the efficiency of power plants of almost all types, including those based on piston internal combustion engines. Nevertheless, the efficient heat recovery on power plants based on piston ICES faces a number of obstacles. For example, in gas turbine installations (GTIs), all the heat released into the environment is the residual enthalpy of exhaust gases, and the major part of the secondary heat of the ICES, almost in equal proportions, is lost both with exhaust gases and through the cooling system. Therefore, additional heat exchangers are required to recover the secondary heat released by the gas turbine, but to do the same with ICES it certain steps should be taken to recover both the heat lost with the exhaust gases and the heat diverted to the cooling system.

2. High-temperature evaporative cooling systems of internal combustion engine
The method of high-temperature cooling (HTC) of ICES can be implemented in classical closed-type liquid cooling systems with pressures in the cooling circuit exceeding the ambient pressure. The increased pressure in the cooling circuit makes it possible for the coolant to overheat to higher temperatures without boiling. The coolant temperatures in such systems are maintained above 115–120°C. The temperatures of coolant overheating to 115–120°C can be obtained in conventional cooling systems. The upper limit of temperatures in the HTC systems rarely exceeds 135°C, although there is information about ICE installations with HTC systems in which the water temperature reaches 180°C. High-temperature cooling with a phase of overheated coolant transiting to vapor is commonly
referred to as high-temperature evaporative cooling (HTEC). Both high-temperature and high-temperature evaporative systems are widely distributed (large vessels, ICE diesel and fixed installations). In a pure form, the HTC and HTEC being used for ICE cooling, they have a rather limited, but important advantages, if compared to conventional cooling systems. First, they provide increased mechanical efficiency of the HT based ICE due to the lower viscosity of the oil at a higher temperature. More intensive heat exchange with the environment and a higher temperature of the cooling body allow, for a given heat flux, to somewhat reduce the surface of the heat exchangers. The high temperature of the walls of the cylinders does not allow moisture to condense on them and ensures their higher corrosion resistance, more stable thermal state of the engine parts, etc.

However, various HTEC-based schemes are mostly used in the integrated heat recovery systems of power plants based on piston ICES. The use of a piston ICE as a basic one in a combined power plant causes a number of specific difficulties associated with the issues of secondary heat recovery released into the environment. Two ways to divert the secondary heat of a piston engine into the environment make it necessary to take a number of measures to recover both the heat released with the exhaust gases and the part of the heat lost through the cooling system.

While the recovery of heat of ICE exhaust gases is possible, as at GTIs, through the use of additional heat exchangers, effective recovery of the heat of the cooling system requires significant modification of the existing facilities. To ensure effective recovery of heat diverted to the cooling system of the engine is a rather complicated task. The key problem is that in conventional liquid cooling systems, the coolant (water, air) has, from the point of view of thermodynamics, very low parameters and cannot be used as a working body in the recovery cycle. The temperature of the coolant (water, antifreeze) in the cooling circuit does not usually exceed 85–95°C which is below the boiling point for water at zero level, i.e. the cooling body does not undergo phase transformations which provide the opportunity to use vapors of the cooling agent as the working body for the recovery cycle. The use of hot water is limited to heat supply and technological purposes. From the point of view of the possibilities of efficient conversion of heat into process, the working medium should feature a gaseous form and have the highest possible temperature at the expansion stage. The use of high-temperature evaporative cooling simultaneously solves two problems: to provide effective cooling of the engine and to recover heat that is lost at the same time. The possibility to increase the pressure in the cooling jacket of the engine allows the coolant overheating to higher temperatures. The temperatures of the beginning of vaporization are determined by the degree of pressure increase, and the saturated vapor obtained can already be used as a working fluid. Thus, for the water temperature of 135°C, the corresponding saturated water vapor pressure is 0.3 MPa, and for the water temperature of 180°C, it is 1.0 MPa. It is also worth striving to further increase the temperature of the coolant and the vapor pressure in the HTEC systems. Increase of the coolant temperature reduces the proportion of heat leaving the cylinders in the cooling system and increases the ICE thermal efficiency. Higher parameters of steam produced in HTEC systems with increased operating temperature make it possible to reduce the weight and dimensions and increase the efficiency of various heat engineering and steam power equipment. This is due to an increased temperature difference in the heat exchangers, as well increased initial temperature and pressure of the working processes in steam expansion machines. The relatively low temperature of the cooling body in the ICE cooling systems is not an accidental factor. Regardless of the type and kind, the cooling system primarily serves to remove heat, from the main, most heat-loaded engine parts to the environment. Under all conditions, this system must ensure a stable temperature state of the cylinder-piston group (CPG) parts which corresponds to the most advantageous combination of energy characteristics with minimal wear of the parts. The temperature of the cooling body is selected taking into account the provision of both the specified optimum thermal regime of the engine and the prevention of the boiling and evaporation of the cooling body in the circulation circuits in order to avoid the development of steam congestion and pump surging. When converting conventional cooling systems to the HTEC ones, these conditions are seen as the key factor limiting the maximum coolant temperature. Without taking a number of special measures, increase of the coolant temperature in conventional cooling systems, even without taking
into account the pressure increase would cause thermal overstrain of the engine components, primarily the CPG, and premature engine failure. Rather accurate representation of the stress-strain state of the main, most heat-stressed parts of the engine, and a forecast of their performance, can be made only with temperature fields of these parts available. Preliminary assessment of the reliability of heat-stressed parts is usually performed using the temperatures at individual points or zones of parts.

The temperature limits at the CPG characteristic points are determined taking into account the material of the parts, the conditions of their operation, the grade of fuel and lubricants, the requirements for the engine, etc. At the same time, the possibility of deviations of the temperatures measured from standstill temperatures, from the temperatures that occur during the engine performance under operating conditions, is taken into account. Considering Russian and Western experience in the operation of engines of various types, the following temperature values can be accepted as limit ones. Maximum temperatures of aluminum alloy parts should not exceed 250–350°C, of cast iron of different types – 400–450 °C, of steel – 450–500°C, and of heat-resistant steels – 600–650°C. Excess of these temperatures causes a change in the structure of the material, worsens its physical and mechanical properties, and leads to a sharp decrease in the strength and reliability of the parts.

Interesting variants of the further development of HTEC systems for ICE were proposed in the following works [1-3]. We would attempt to evaluate the main proposals outlined in above mentioned works. Having analyzed the operating conditions of the existing cooling systems and assessed the prospects for the development of high-temperature systems, the authors conclude that it is possible to achieve the temperatures of the cooling body in the cooling jacket of the cooling body up to 300°C and higher accompanied by reaching the corresponding pressures (up to 16.5 MPa for saturated water). However, the achievement of new parameters of high-temperature evaporative cooling systems necessitates a different degree of modification of the ICE existing designs and the maintenance of certain technological conditions relating to the cooling process.

Considering the data cited by the authors, we would summarize them:
1. Cooling each part of the cooling surface of the cylinder and head with a limited volume of the cooling body (liquid or vapor), the temperature of which is less or equal to the most optimal temperature for the corresponding cooled section.
2. The limitation of heat transfer, mainly convective, between the layers of the cooling body and the direction of displacement of the coolant mass, caused by evaporation of its part and the supply of an appropriate compensating quantity, from cooling zones with a lower temperature, to areas with a higher temperature.
3. The engine is positioned relative to the ground so that the head of the cylinder lies higher or on a level with the cylinder base
4. Increase of the surface area of the cooling surfaces of the cylinder and the cylinder head to the values that provide the necessary heat transfer to the cooling medium with a preset temperature. The specific degree of increase is determined based on a special calculation.
5. Additional measures to ensure the operation of the HTEC system with increased parameters: thermal insulation of surfaces, installation of control and safety equipment, etc.

The engine design shown in Pic. 1a, b was developed taking into account the above recommendations. The initial value for the calculation of the elements of the cooling system is the amount of heat \( Q \) kJ / h, which must be diverted from the engine to the cold-producing medium. The value of \( Q \) can be determined both through the specific amount of heat of cooling \( q_{cool} \) J / kWh and the engine output \( N_e \) kWh and through the total (heat transfer from the wall by convection) and special (heat transfer through the wall) cases of writing the Newton-Richman equation:

\[
Q = q_{cool} \cdot N_e = \alpha_{F} \cdot F_{cool} \cdot ( t_c - t_{cool} ),
\]

where \( \alpha_{F} \) and \( \alpha_{F} \) – average for the time of heat exchange, heat transfer coefficients, from gases to the heated wall and from the wall to the cooling body, W / m²·K; \( F_h \) and \( F_{cool} \) – the average area of the heated and cooled surfaces, respectively, m²; \( t_c \) and \( t_{cool} \) – average temperatures of gases and a cooling body, respectively, °C; \( \lambda \) – the average coefficient of thermal conductivity of the material of the wall,
W / m·K; δ – wall thickness, m.

It can be seen from the equation that the amount of heat Q transmitted through the walls of the cylinder and the engine head depends on their size and material (influence of \( F_h \), \( F_{cool} \), \( \lambda \) and \( \delta \)), engine workflow (influence of \( \alpha_1 \) and \( t_h \)) and on cooling parameters - \( t_{cool} \), \( \alpha_2 \).

These equations can be jointly solved as relative to the temperature of the cooling body, i.e. calculate it with the other known parameters, and relative to the area of the cooled surfaces:

\[
F_{cool} = \frac{q_{cool} \cdot N_\varepsilon \cdot \lambda \cdot \alpha_1}{\alpha_2 \cdot (\alpha_1 \cdot \lambda \cdot F_h \cdot (t_h - t_{cool}) - \lambda \cdot N_\varepsilon \cdot q - \alpha_1 \cdot \delta \cdot N_\varepsilon \cdot q)}
\]

i.e. to obtain the required value of the area of cooled surfaces with the other known or specified parameters.

**Figure 1.** Schemes of the construction of cavities of the cooling jacket of a piston engine operating with increased parameters of the cooling body: a) with divided cooling zones (jacket-casing 4) and evaporation (steam separator 5) and inclined finning; b) with a combined cooling and evaporation zone (jacket-casing 4) and vertical finning;

1 - cylinder; 2 - cylinder head; 3 - cooling fins; 4 - jacket-casing; 5 - steam separator; 6 - heat-insulating and shielding layers; 7 - the automatic power supply; 8 - level of a cooling liquid; 9 - manometer; 10 - safety valve; 11 - steam main; 12 - feed water supply line.

**3. HTEC system experimental analysis**

In addition to the theoretical aspects of the HTEC system development, the results of test of the HTEC-based working model are presented in [1, 2]: “for practical evaluation of the possibility of a significant increase in the temperature of the coolant in the ICE cooling systems and the degree of its impact on the efficiency of secondary heat recovery systems, technological methods and constructive improvements, the IHR working model was developed which ensures both the use of heat from exhaust gases and the cooling system.” The works considered being little known, the experimental model of the operating installation is described below. The steam generating part is made according to the classical scheme and is represented by three corresponding devices: economizer (water heater), evaporator boiler and superheater. The model was developed based on a low-power, two-stroke ICE transferred to the HTEC with increased parameters. The basic engine is a single-cylinder, carburetor type with air-cooling and a cylinder capacity of 50 cm³. The rated effective power is 0.75 kW at 4500
rpm. The actual compression ratio is 6.4. The transfer to the HTEC system implied that, with considerable preservation of the edges of the air cooling surfaces, the engine cylinder and the head were enclosed in a steel, sealed, heat-insulated casing. In the engine heat-insulated exhaust system, a steam superheater and a feed water heater (economizer) wounded from copper tubes were installed. Together with the casing they make up a steam generating part of the recovery system. The feedwater supply to the system is carried out by an autonomous electrically-driven pump. One of the first versions of the working model, and its final design are shown in figures 2 and 3.

![Figure 2. The initial version of the engine design for operation with increased parameters of the coolant.](image)

![Figure 3. The main version of the HTEC-based working model.](image)

Integrated experimental studies of this ICE model with secondary heat recovery were conducted on a small-sized motor test bed equipped with a balancing DC machine. The test bed is designed for testing low-power ICEs (up to 2 kW) and is equipped with the main units and equipment necessary for conducting standard engine tests of ICEs, including the indicating system and gas analyzer, and for testing individual elements and the entire heat recovery system of the compound engine as a whole. In addition to the already mentioned water pump, it has a steam condenser, steam meter, stand-alone
water boiler-evaporator and superheater with gas heating, thermometry system, various control and shut-off valves. The purpose of the research is the experimental verification of theoretical assumptions about the possibility to achieve higher temperatures of the cooling body in HTC systems and an evaluation of the engine performance under such cooling conditions. The second part is comprehensive assessment of the impact of elevated temperatures in the HTC and HTEC systems on the efficiency of integrated heat recovery systems developed on their basis. The main tasks are to record the standard speed characteristics of the engine, and to make up a heat balance both of the recovery system and of the engine as a whole, at various coolant temperatures (in the experiments, the coolant is water).

4. Results of HTEC system experimental analysis
Summarizing up, we can assume that the results of the experiments provided a positive result. Compared to the air-cooling system, the HTEC-based engine was capable to operate at coolant temperatures up to 204°C in the cooling jacket. However, it should be noted that the HTEC-based engine completely lost its efficiency and died under a sharp narrowing of the stable area, compared to a temperature of 180°C for the basic air-cooled engine. When working with the temperatures of the cooling surfaces above 150-160°C, the serial air-cooled engine generates only 50% of the rated power, while the HTEC-based engine loses only 10-15% of the power when heated, even to the maximum temperatures, but with a decrease in the zone of stable regimes, which nevertheless indicates a partial engine overheat.

When compared with the water cooling system, the HTEC-based heat recovery system allows obtaining water vapor, using for this purpose about 65-80% of the heat diverted to the cooling system and lost with the exhaust gases. Further use of the steam received should ensure an overall increase of the IHR system efficiency. Graphs that demonstrate the effect of coolant temperature on the external speed characteristics of the experimental engine are shown in figure 4.

Figure 4. External speed characteristic of the engine.
Also presented the approximation equations of the experimental graphs of the external speed characteristic of the engine in the coolant temperature range 82–183°C (Table 1). The accuracy of the approximation (polynomial of the second degree) is characterized by the multiple correlation coefficient \( R^2 = 0.901-0.999 \).

**Table 1.** Approximation equations of the experimental characteristics of the engine.

| \( T_{coo \text{av}} \) °C | \( M_e = f(n) \) N·m | \( N_e = f(n) \) kw | \( g_e = f(n) \) g/kWh | \( \alpha = f(n) \) |
|----------------|------------------|-----------------|-------------------|------------------|
| 82 (min) | \(-3E-07n^2 + 0.0015n - 0.0526\) | \(-1E-07\cdot n - 0.7789\) | \(+2069.9\) | \(+0.7646\) |
| 183 (max) | \(-5E-07n^2 + 0.0029n - 2.6708\) | \(-2E-07n + 1.5733\) | \(+0.0035n + 0.4047\) | \(+0.0005n + 0.4047\) |

\( n \) – crankshaft rotation speed r / min; \( \alpha \) – excess air ratio

5. Conclusion

Despite a significant amount of experimental data, testing only one engine equipped with the proposed HTEC-based IHR system will not give a complete answer to all questions related to the development, test and operation of HTEC systems with increased parameters. However, the fundamental problem of the possibility of development and wide implementation of this system type was solved. Considering the studies conducted, it is already possible to draw conclusions about the main dependencies and characteristic values of various parameters inherent in these cooling systems, both separately and in combination with recovery systems. Depending on the proposed type or mode of operation of the HTEC-based power plant, it is possible to select modes and system adjustments that would ensure increased efficiency of the entire power plant. Experimental analysis of the engine working with the increased parameters of the working fluid in the cooling system fully confirmed the possibility of achieving the declared parameters, and the proposed HTEC systems can be used both independently and in combination with the recovery systems. Further research is needed to conduct more in-depth analysis, to obtain more accurate dependencies, to use more rational design schemes and solutions and, ultimately, to create more efficient cooling systems than those used in ICEs now. One article is enough to provide a detailed description of neither the calculations of the HTEC system, nor the design of the current model, nor the results of the tests. It can be briefly said that the theoretical background of the development of the HTEC systems with increased parameters has been fully confirmed and the possibility of developing and operating such systems has been proved. In the experiments, the coolant temperature in the engine cooling jacket up to 200°C was reached.

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