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EXPERIMENTAL RESEARCH, MATHEMATICAL MODELING AND ENGINEERING OPTIMIZATION OF THE AIRCRAFT ENGINE COOLING SYSTEM

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Abstract

This paper presents the results of a study aimed at improving the air-cooling system on aircraft engines and validating the relevant methodologies. It includes experimental studies and develops a methodology of heat engineering research using a full-size aircraft piston engine in test-bench conditions with detailed thermometering of cylinder and piston assembly parts. A part of the work focuses on heat transfer from gas to combustion chamber walls and within the cooling system.

Introduction

Air-cooled aircraft engines endure significant thermal stress and their time between overhauls is restricted. Increasing aircraft engine power requires, all else being equal, efficient cooling of the cylinder and piston assembly (CPA) that works under high thermal and mechanical loads. Reliability and durability of the engine depend, to a large extent, on the temperature levels of the CPA parts. Due to this fact, defining the cylinder

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head and barrel temperature fields and finding ways to improve their thermal condition are very important. Along with specific power increase, the quantity of heat passed to the walls grows. If heat removal is inadequate, then wall temperatures of the parts forming the operating volume of the cylinder may reach a level that can threaten engine reliability. Keeping the temperature within a range that guarantees reliable operation of the engine requires proper heat removal arrangements at the cooled surfaces [1].

Creating efficient cooling systems remains a top priority task for engine designers and manufacturers. The most important facet of this task is developing engineering solutions for improving and predicting the efficiency of such systems.

Objective

The main goal of the research at hand was to develop scientific approaches and to implement R&D measures to ensure more intensive heat transfer within the cooling system and thermal stress reduction in modern aircraft engines [2].

One of the tasks that arose from the stated objective was theoretical and experimental research into heat transfer at the edges of the parts forming the combustion chamber [3].

The results of the CPA thermal processes study shall serve as a basis for improving the air-cooling system in aircraft engines and further experimental testing of their efficiency.

Experimental Studies and Mathematical Modeling of Heat Transfer

The thermal condition of the parts forming the combustion chamber (CC) and the local heat transfer to CC walls and within the air-cooling system [4] were studied on the example of the M-14P aircraft engine.

The experimental studies concentrated on the following tasks:

1. Gathering data on the temperature condition of the CPA parts

(cylinder pistons, barrels and heads) during bench and flight testing of the M-14P aircraft engine.

2. Defining the heat flows from gas to CC walls both via direct measurement by special sensors and via thermocouples spaced according to the wall thickness during bench tests covering the entire range of engine speeds and load conditions.

3. Gathering data on the cylinder head fin thermal field and monitoring the thermodynamic parameters of the air in the cooling system interfin channel.

4. Compiling a set of experimental data to define time-averaged local coefficients of heat transfer from gas to CC walls and in the air-cooling system interfin channel.

5. Studying the influence of operation and regulation parameters on the level and nature of changes in the temperature conditions and heat transfer from gas to the CC walls and within the air-cooling system.

6. Formulating a methodology for experimental studies of the thermal condition and heat transfer from gas to CC walls and within the air-cooling system for a given class of engines.

Experimental research was carried out for the entire range of operation and regulation parameters. It included:

- a detailed definition of the cylinder head and barrel temperature fields with the help of a large number of thermocouples;

- a definition of the piston temperature fields through maximum temperature sensors;

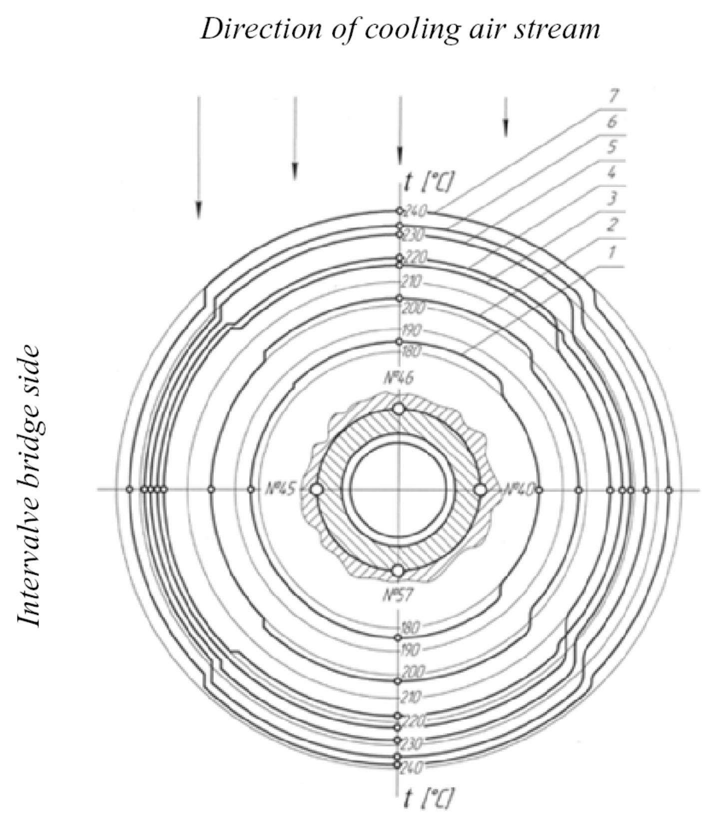
- a definition of time-average local specific heat flows to the CC walls via thermocouples spaced depending on the depth of their embedding;

- measurements of time-average local specific heat flows to the CC walls immediately by heat flow sensors;

- measurements of standard operation parameters: crankshaft revolution rate, torque at the outlet shaft, the fuel flow rate, supercharging pressure, inlet and outlet oil temperatures, air temperature at the engine inlet and at the supercharger outlet, the cooling air temperature, cylinder head temperatures, using standard thermocouples (under the back spark plug);

- thermometering of the vertical fin of the most thermally stressed cylinder head area;

- measuring the temperatures and velocities of cooling air flow at the cylinder head interfin channel inlet and outlet.



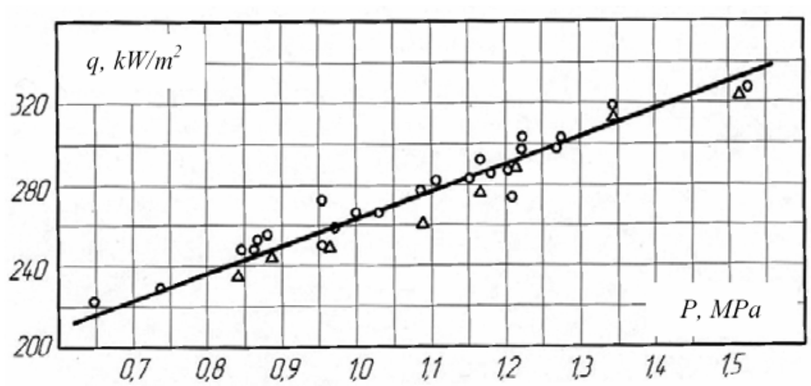
1…7 - testing modes, ○ - places of thermocouples location

Figure 1. Distribution of temperature along M-14 engine cylinder exhaust valve seat depending on the operation mode.

The test-bench simulated in-flight operation of the engine within the entire range of its nominal operating parameters that define its thermal condition. The study has shown that the temperature fields of the cylinder heads are significantly uneven, especially in the planes perpendicular to the cooling air flow. A maximum temperature drop in the central section of the head at the intake and exhaust valves is within the 70…90°C range. The temperature drop in the cooling air flow ranges from 40 to 60°C. Figure 1 shows the cylinder #1 exhaust valve seat temperature field depending on the engine load (the cooling air velocity at the front of the engine was between 19 and 35m/s).

The maximum exhaust valve seat temperatures stand at 260…275°C, and the temperature drop at the seat perimeter stays within 40…60°C range.

Measurements of heat flows at the cylinder head show that their variation in different conditions corresponds to the variation of the temperatures of the metal used to make the head [5]. Figure 2 illustrates the dependence of heat flows at the cylinder head on the indicated mean pressure during a cycle.



○, Δ - M-14P engine cylinder piston head and bottom,
q - specific heat flow rate, *P* - pressure

Figure 2. Dependence of the average heat flow density at the CC walls during a cycle on the indicated mean pressure.

Within the operational engine power range (108...265kW), the growth of the heat flow is practically linear, from $250 \cdot 10^3 W/m^2$ to $355 \cdot 10^3 W/m^2$. The heat flow values are averaged for the entire spherical surface of the head and along the piston bottom. The heat flow going to the exhaust pipe wall at the nominal operation mode (effective power $Ne = 207$ kW, crankshaft rotation speed $n = 2{,}300$rpm) is $\sim 450 \cdot 10^3 W/m^2$. The temperature of the metal making up the head in this area reaches the maximum value of 235°C [6]. A generalized relationship between the operation parameters and the piston temperature is shown in Figure 3.

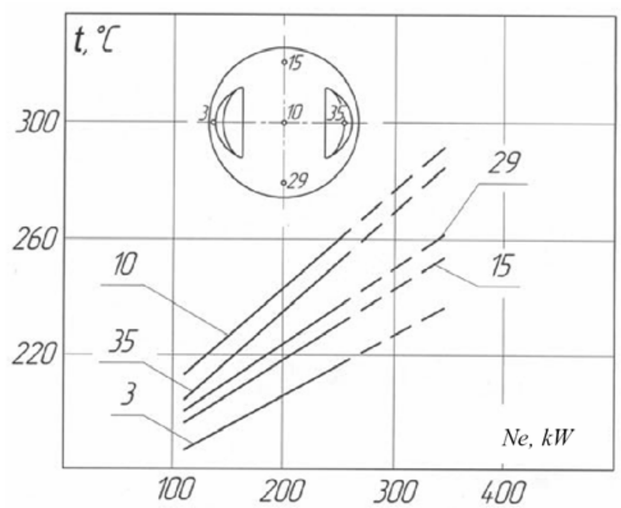


Figure 3. Variation of piston bottom surface temperature relative to the effective power of the M-14P engine.

These dependences were approximated by empirical formulas:

- for the bottom center (thermocouple (t.c.) #10)

$$t_{10} = 215 + 0{,}2368(Ne - 145{,}5), \tag{1}$$

- for thermocouple locations:

29 –

$$t_{29} = 201 + 0{,}1827(Ne - 145{,}5), \tag{2}$$

15 –

$$t_{15} = 195 + 0{,}2014(Ne - 145{,}5), \tag{3}$$

35 –

$$t_{35} = 210 + 0{,}2405(Ne - 145{,}5), \tag{4}$$

3 –

$$t_{3} = 186 + 0{,}1773(Ne - 145{,}5), \tag{5}$$

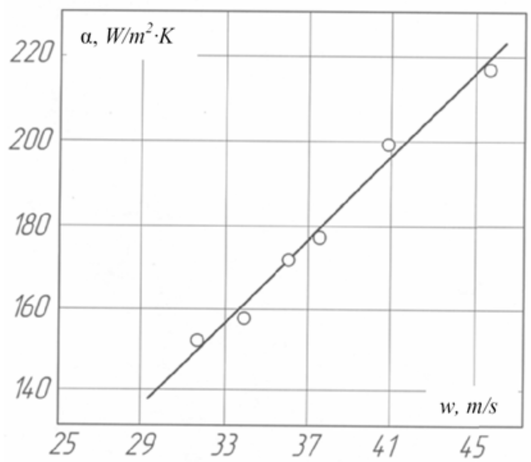
- for the upper groove (UG):

$$t_{UG} = 188 + 0{,}1967(Ne - 145{,}5). \tag{6}$$

Engine power growth leads to a practically linear temperature growth in different areas of the piston, with certain variations in the dynamics of their increase. The reason for this is relative growth of specific heat flows in those areas. Changes in the engine power from 125 to 265kW cause the temperature at the center of the piston bottom to increase from 220 to 270°C. Established dependences of the growth in specific local temperatures on the power output open up a possibility to predict the temperature condition of the CC parts during future aircraft engine development and modification of the existing ones [7]. The data obtained during the study define a set of heat exchange boundary conditions at the head cooling fins with an eye on attaining a permissible level of temperatures and their gradients along the cooled surface.

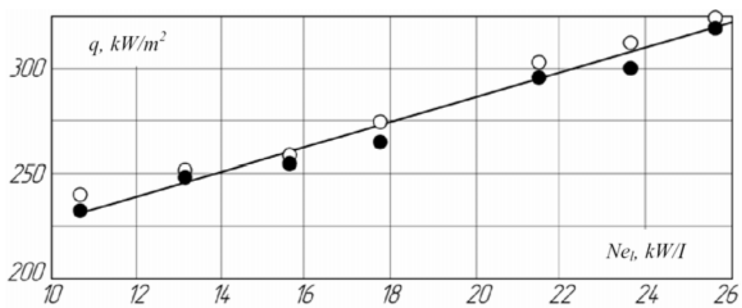
Figure 4 illustrates the dependence of the average fin surface heat transfer coefficients in the mean section of the entire channel length (80…110mm from its beginning or $(12...16)\,x/d$) in a stabilized area of the flow at different cooling air velocities corresponding to the engine operating conditions.

Direct measurement of the time-averaged local heat flow $\overline{q}$ from gases to a CC wall by a heat flow sensor and the flow analysis based on cooling fin temperature field measurements at the head's outer wall where the density of the heat flow slightly changes during a cycle, reveal a satisfactory match between the results obtained with the help of both methods (Figure 5). An insignificant 3…5% discrepancy is caused by the presence of minor heat dissipation along the interfin channel bases and by a multidimensional nature of the heat flow through the fin body.



α - the heat transfer coefficient, *w* - the average speed of gas flow

Figure 4. Average cylinder head interfin channels heat transfer in the M-14 engine depending on the cooling air velocity at different levels of engine performance.



○ - measured by the heat flow sensor;

● - defined by the fin temperature field

Figure 5. Dependence of the average specific heat flow going to the M-14P engine cylinder head wall on the power-per-litre.

The cylinder diameter was used as a linear dimension characteristic in similarity criteria. The determinant temperature was defined as a thermodynamic temperature calculated as an equation of state based on the indicator diagrams compiled experimentally at all of the studied engine operation modes.

Based on the information above, the heat exchange in the chambers of aircraft piston engines was described by a similarity equation used to calculate the intensity of heat exchange between gas and the piston bottom:

$$\overline{Nu} = 0{,}018k(S/d)^{2/3}(1 + \exp(-0{,}038Re^{0{,}38}))Re^{0{,}8}, \tag{7}$$

where *Nu* is the Nusselt number; *k* is the coefficient defining the relationship between the charge expansion at the cylinder intake and the heat transfer intensity; *S* is piston stroke; *d* is the cylinder head diameter; and *Re* is the Reynolds number.

In order to generalize the established dependence even further, we calculated the average heat transfer to CC walls for the most popular engines. Similarities were defined through a comparative analysis of the CPA part geometry, their thermal condition and basic operation parameters.

The heat transfer study links the surface-average and local parameters whereby the established dependences of average heat transfer to CC walls become usable in a wider range of applications.

Based on the research results, we defined the qualitative and quantitative specifics of the engine operation and the relationship between control parameters and the intensity of heat transfer to the CC walls. The effective power of the engine was considered as an integral parameter defining the intensity of heat transfer to the CC walls. The research served as a basis for defining a functional dependence of the heat transfer coefficient on the engine operation parameters:

$$\alpha = C_1 N_i^{0{,}8} D^{-1{,}8} (S/D)^{2/3} \overline{T}_G^{\,-0{,}67}, \tag{8}$$

where C_1 - basic engine constants; N_i - indicated power; D - cylinder diameter; T_G - average temperature of gas in a cycle.

Known engine characteristics were used as a starting point for thermal analysis. The validity of the established mathematical dependences is confirmed by a satisfactory (5…7 degrees) convergence of experimental temperature values at the control points and our calculations of the cylinder temperature fields using the third type boundary conditions.

In order to confirm the validity of boundary conditions and solve the heat conductivity problem, we used the finite-element method to develop a three-dimensional model of the piston (see Figure 6).

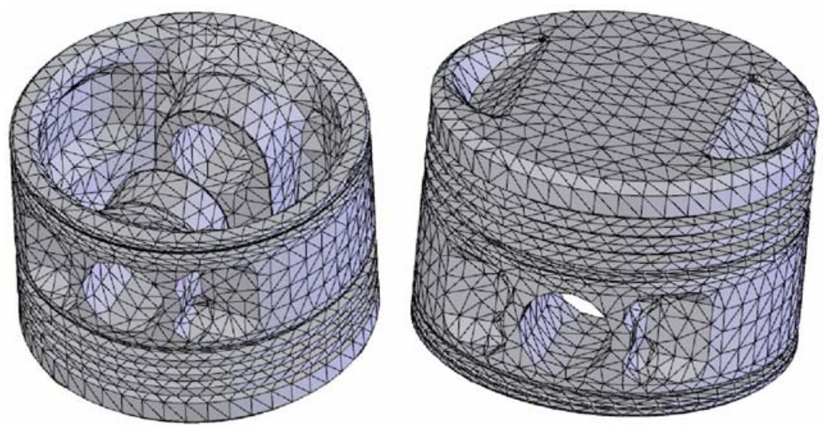


Figure 6. Three-dimensional design model of the piston.

We found a stationary solution to the problem of calculating the parameters of the piston temperature field using boundary conditions of the third kind. A solution of the three-dimensional stationary heat conductivity problem was obtained with the aid of the CosmosWorks design module of the SolidWorks engineering analysis system. The correctness of heat exchange boundary conditions at the outer borders of the piston model, especially along the bottom and in the area of the two upper piston rings, was a crucial factor in getting an accurate solution.

The values of local heat transfer coefficients and their distribution along bottom surface of the piston (Figure 7) come from the experimental studies described.

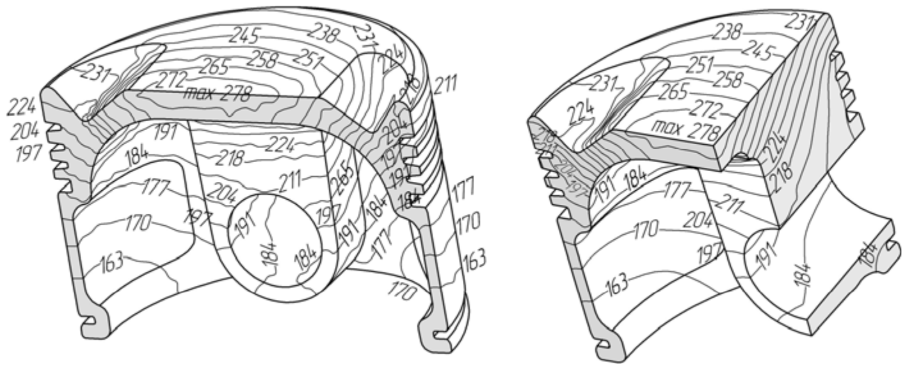


Figure 7. Piston temperature field at take-off operation mode.

The boundary conditions were adjusted by solving variant direct conductivity problems until a good (up to 3…5°C) convergence with experimentally obtained values of the temperatures in key control areas was achieved.

The selection and adjustment of boundary conditions at maximum load allowed for establishing the coefficients of heat transfer and the temperatures of heat-releasing and heat-absorbing mediums at the outer borders of the piston.

Optimization of the Cooling System

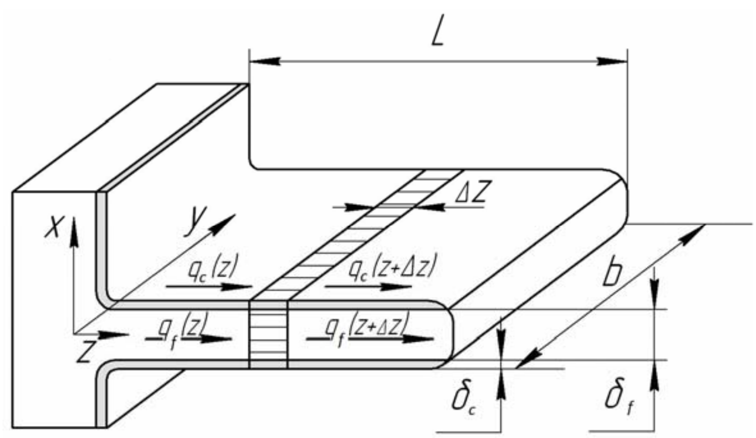
The gas and finned surface heat exchange boundary conditions obtained experimentally served as the basic data for solving the heat conductivity problems related to the cooling system elements. This, in turn, gave us an opportunity to determine the temperature status of the engine parts.

The cooling system of an aircraft piston engine (APE) consists of a fan and the finning of the cylinder barrels and heads encased in deflectors. It consumes from 10 to 20% of the engine’s effective power. For the most part, power loss is caused by drag in the finning grid channels. That is why optimizing the finning to reduce the amount of power needed to move the heat-carrying agent is a good way to upgrade both the cooling system and the whole engine.

An engineering solution for adequate fining dimensions and appropriate air flow in the cooling grid that guarantees minimal power losses and a desired heat removal rate is based on theoretical and experimental research of heat exchange and hydrodynamics in turbulent air flows around longitudinal fins with a rectangular cross-section.

One of the best ways to improve a cooling system is to increase the efficiency of the fins. This becomes especially important when further development of the finning surface at the expense of its geometry does not lead to a reduction in the temperature levels.

Efficiency of the steel fins on the cylinder barrel for different high-conductivity coating materials and thicknesses was established as an analytical solution of a one-dimensional heat conductivity equation for a rectangular composite fin, taking into account the contact thermal resistance between the fin and the coating materials (Figure 8).



x, y, z - coordinates; *L* - geometrical dimension

Figure 8. Heat conductivity in a coated fin.

Heat conductivity of fin and coating materials along the fin height λ_f and λ_c - constant; heat transfer between the fin and the coating occurs as defined by the heat transfer coefficient of $\kappa = 1/(\delta_c/2\lambda_c + R + \delta_f/2\lambda_f)$, where R is the coefficient of contact thermal resistance between the fin and the coating; δ_c and δ_f are coating and fin thicknesses; temperatures of fin T_f and coating T_c change only along the fin's height (along the z axis); the heat flow density is determined by the following formula: $q = \alpha(T_c - T_{cool})$, where α is the coefficient of heat transfer from the side surfaces of the fins and T_{cool} is the coolant temperature.

In general, it was established that a 0.1mm copper coating provides an approximately 15% increase of the barrel fin efficiency.

An analysis of the results obtained during the thermal and stressed condition study of the cylinder heads suggested further modifications of the cooling system around the cylinder heads. In order to improve the efficiency of aircraft engines and to reduce the temperatures of the CPA parts, a new cylinder head with an enlarged heat removing surface has been designed and manufactured based on the above mentioned solutions (Figure 9).

(a) (b)

Figure 9. Cylinders of the M-14 family engines: a serial production cylinder (a) and a cylinder with an experimental head (b).

In order to evaluate the experimental head efficiency in test-bench conditions, a comparative thermometering of a serial production cylinder and a cylinder with the experimental head was conducted.

For metal temperature measurements, the studied cylinders were outfitted with 0.2mm chromel-copel thermocouples. Each of the cylinders had 35 thermocouples: 12 of them were located on the cylinder barrel, by 4 in each of the three sections; 4 thermocouples were located in the exhaust valve seat, and the rest of them along the cylinder head. The schematic of thermocouple locations around the cylinder perimeter is shown in Figure 10.

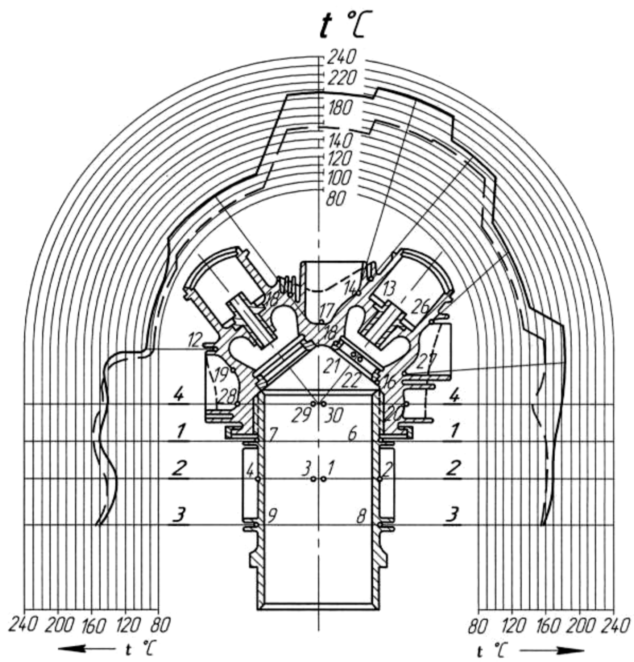


Figure 10. Temperatures distribution around the perimeter of the experimental (----) and original (—) cylinders. Mode: $Ne = 216\,\text{kW}$; $n = 2400\,\text{rpm}$; supercharging pressure $P\kappa = 115\,\text{kPa}$.

The thermal condition of the cylinders was characterized by the actual temperature value and by temperature drops at different cooling surface areas. The measurements were conducted in steady-state thermal conditions in a wide range of loads and crankshaft rpm's.

The results were presented in the form of temperature fields along the contour of cylinders and other characteristic sections, and were divided into groups depending on the cooling air flow rates.

Figure 8 also shows variation in the heat condition along the serial production and experimental cylinder contours at the nominal operation mode, in the 10…19m/s range of cooling air velocities at the engine front.

Experimental data analysis shows that the temperature levels of the experimental head were significantly reduced: at the exhaust valve side, it decreased by 35…45 degrees, and at the intake valve side, it went down by 20…25 degrees; in the intervalve bridge area at the exhaust valve side, in maximum power conditions, the temperature decreased by 38 degrees, from 225°C to 187°C, and at the intake valve side by 18 degrees, from 118°C to 100°C.

The barrel temperature of the cylinder with the experimental head decreased by 5…15°C at the exhaust valve side and increased by 3…10°C at the intake valve side, depending on the engine operation mode. The temperature drop between the back side and the cooling air flow side increased by 10°C, from 5…15°C on the serial head to 15…25°C on the experimental head. The temperature drop between the intake and exhaust valve sides was from 40…48°C on the serial head to 0…10°C on the experimental head. This provided a more even temperature field along the cylindrical belt of the experimental head.

The general level of the experimental head exhaust valve seat temperatures decreased by 20…60°C, depending on the engine operation mode. Distribution of temperatures along the seat perimeter became 4-6°C less uneven.

Minimum-to-maximum increase of cooling air flow rate for cylinders blow-off reduces the metal temperature in the most heat-stressed areas of the cylinder with the experimental head by 5…10°C, depending on the engine operation mode; in the same places of the serial cylinder, the temperatures drop by 3…5°C.

On the whole, the experiment results have shown that using a larger surface and composite head finning leads to a reduction in the cylinder temperature levels. Compared to the cylinder with the serial production head, the general temperature level of the cylinder with the experimental head was lower by 20°C on average. The temperature reduction is especially significant at the exhaust valve seat - by 20…60°C, and in the area of the exhaust valve - by 30…50°C, depending on the engine operation mode.

A significant decrease of the exhaust valve seat and cylinder head exhaust area temperature levels will ensure more reliable operation of the valve unit and the cylinder in general.

Conclusion

Modification of the APE CPA parts with a classic geometry is subject to serious design, technological and economic limitations. Therefore, step-by-step optimization of the temperature condition based on a comparative analysis of temperature field variant calculations is, as of now, the core approach to thermal stress reduction in the CPA parts.

The experimental data, as well as the generalizing equations and dependences, engineering solutions and mathematical models were used to test the methods and design solutions efficiency in process of creating a standardized cylinder for a number of modern highly uprated APEs. In particular, our study has shown that cylinder heads with composite finning may lead to a significant improvement of their cooling systems.

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References

[1] D. D. Broze, Sgoranije v porshnevikh dvigateliah (Combustion in Piston Engines), Mashinostroenie, Moscow, 1986, p. 247.

[2] D. Kern and A. Kraus, Razvitije poverkhnosti teploobmena (Developed Heat-Exchange Surfaces), Energia, Moscow, 1977, p. 462.

[3] N. D. Chainov, V. G. Zarenbin and N. A. Ivaschenko, Teplomechani-cheskaya napryazhennost detalei dvigatelei (Thermomechanical Stress in Engine Parts), Mashinostroenie, Moscow, 1977, p. 151.

[4] M. D. Nikitin, A. Ya. Kulik and N. I. Zakharov, Teplozaschitnie i iznosostoikie pokrytija detalei dizelja (Heat-resistant and Wear-resistant Coatings of Diesel Parts), Mashinostroenie, Leningrad, 1977, p. 164.

[5] A. F. Kosjak, Metod rascheta konvektivnogo teploobmena v tsilindre porshnevogo dvigatelja (The method of analysis of convective heat transfer in the piston engine cylinder), Dvigatelestrojenije 1 (1985), 17-20.

[6] H. R. Ricardo, The High Speed Internal Combustion Engine, State Scientific and Technical Press, Moscow, 1980, p. 410 (in Russian).

[7] R. M. Petrichenko, Physicheskije osnovy vnutritsylindrovykh processov v dvigateljakh vnutrennego sgoranija (Physical Foundations of Intracylinder Processes in Internal Combustion Engines), Mashinostroenie, Leningrad, 1983, p. 194.