Study of the influence of thermodynamic processes on the parameters of the technical condition of power plants

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Abstract. The article substantiates the need to consider the dependence of the external characteristics of transport power plants on the parameters of thermodynamic processes in the combustion chambers of heat engines. The results of theoretical and experimental studies are presented. They prove the influence of the technical condition on the thermodynamic parameters of diesel internal combustion engines. Expressions are presented that describe the thermodynamic processes of power plants from the point of view of the relationship between the mechanical and thermodynamic components of torque. It is shown that the temperature of the working surfaces of a diesel engine is an important characteristic of its technical condition. The results of experimental studies of the influence of the temperature of the cylinder liner wall, which determines the rate of evaporation of the oil film between the piston and the cylinder liner, on the amount of engine oil consumption for waste under various technical conditions of the diesel engine are presented. It has been shown that reducing engine temperature can help reduce oil consumption in internal combustion engines.

1 Introduction

When analyzing the reasons for changes in the technical and economic characteristics of transport power plants during operation, it is necessary to take into account their dependence on the parameters of thermodynamic processes occurring in the combustion chambers of heat engines. In relation to diesel power plants, this, first of all, implies taking into account the relationships between fuel supply parameters, fuel combustion kinetics and output parameters of the internal combustion engine (ICE). To ensure the improvement of the designs of power plants and increase the efficiency of their operation, a more accurate understanding of the flow of intra-cylinder fuel combustion processes and the development of operational methods for monitoring the thermal state of diesel engines are required. Such studies are especially important in the practical implementation of technical measures for the use of alternative fuels, improving the environmental characteristics of power plants, ensuring the optimization of intra-cylinder processes and the dynamic performance of diesel internal combustion engines [1, 2, 3]. The purpose of this work is to study the influence of the characteristics of thermodynamic processes on the parameters of the technical condition of diesel power plants and the possibility of assessing and predicting their changes during operation.

Thermodynamic processes of diesel power plants are functions of continuous changes in the effective pressure and temperature of the working fluid depending on time or the angle of rotation of the crankshaft. The performance of these functions largely depends on the homogeneity of the working mixture in the combustion chamber, the injection advance angle and the rate of fuel combustion, etc. as a consequence, the rate of change in the volume of the working fluid in the internal combustion engine cylinders. Any change in the qualitative or quantitative composition of diesel fuel or the air-fuel mixture, as well as a change in temperature or humidity of the fuel, leads to a change in the ignition delay value of the diesel engine and, ultimately, to a change in the current values of the piston speed. Traditional ideas about changes in the state parameters of the working fluid during fuel combustion do not provide a real picture of the dynamics of qualitative and quantitative characteristics of heat exchange in diesel power plants, which have a significant impact on their efficiency, durability and environmental friendliness. The adiabatic processes of fuel combustion in the cylinders of an internal combustion engine, which are usually described by the well-known thermodynamic equation $pV^n = const$, are largely approximate. It is usually assumed that the piston speed is constant or equal to the average value throughout the adiabatic process. In fact, the piston speed, the value of the expansion polytrope and the nature of the engine indicator diagram are influenced by a combination of a number of factors, such as the quantity and quality of fuel entering the cylinders, the nature of the processes of flame propagation throughout the volume of the combustion chamber and the deviation of the fuel ignition delay period from the nominal values due to changes in technical condition.

The temperature conditions of the cylinder group also determine the parameters of the thermal stress of the power plant parts, which in some cases are the cause of emergency wear and destruction of critical parts of internal combustion engines. The relevance of finding ways to solve this problem is confirmed by a large number of modern scientific studies devoted to the optimization of the characteristics of thermal stress of units and assemblies of power plants and methods of preventing the negative consequences of their deviation from nominal values [4, 5, 6, 7]. Such optimization measures are necessary to analyze the thermal state of individual engine elements, including from the point of view of preventing the achievement of critical values of temperature loads [8, 9, 10]. It is also necessary to evaluate the elimination of the negative consequences of starting the engine in conditions of low ambient temperatures and its operation when the coolant of the cooling system does not reach the required temperature range.

When ensuring optimal temperature conditions for the operation of power plants, a variety of scientific approaches can be used, including a comprehensive analysis of hydrodynamic and thermodynamic processes. In relation to ship power plants, optimizing the temperature regime also means justifying the use of a flow-through or closed-loop engine cooling system. Particular attention, in our opinion, should be paid to the study of heat transfer processes in oil films formed in the contact areas of piston rings and cylinder liners of diesel engines. This is due to the fact that the characteristics of the processes of heating and evaporation of the oil film are closely related to the parameters of the operating processes of power plants and affect the mechanical load of the elements of the crank mechanism and the reliability of the internal combustion engine [11].

The purpose of the paper is theoretical and experimental research that proves the need to take into account the parameters of thermodynamic processes on the operational characteristics of diesel power plants.

2 Materials and methods

The oil film in an internal combustion engine is an important element of the power plant. providing not only lubrication, but also protection of the critical parts of the piston group, since it is a thermal and dynamic damper when changing the direction of movement and moving the piston at top dead center. The parameters of thermal and mechanical loading of the oil film should be considered from the point of view of their total dynamic stress, which is the sum of interrelated thermal and mechanical stresses. When analyzing such complex technical systems, it is preferable to be guided by the principles of equal importance of all components. Let's imagine a diesel power plant as a single technical system designed to obtain effective power and torque and consisting of separate subsystems that are conditionally equal in their degree of influence on the efficiency of its operation, namely: the mechanical part, the thermodynamic part, the fuel supply system and the automatic frequency control system rotation. This representation corresponds to the definition of the effective efficiency of a power plant as a characteristic of the total impact of the processes of converting the chemical energy of fuel into mechanical energy. Modern research in the field of improving the modeling of fuel supply and patterns of fuel combustion in internal combustion engines also indicates the need to take into account the influence of the relationship between the dynamics of combustion processes and the dynamics of other work processes.

Qualitative and quantitative characteristics of heat exchange largely determine the efficiency, durability and even environmental friendliness of power plants. This fully applies to internal combustion engines, where the values of the indicator and average effective pressure in the cylinders represent universal criteria for the calorific value and technical condition of the engine. The temperature conditions of the cylinder group also determine the thermal stress of engine parts, that is, the absolute temperature values on the surface of the walls of the cylinder liners, as well as the temperature stresses arising due to temperature unevenness at different points of the parts.

Based on the assumption of equal importance of the mechanical and thermodynamic components of the power function of a diesel power plant for its efficient operation, let us present expressions that describe the processes occurring simultaneously in these systems, which are essentially heterogeneous from a physical point of view. The characteristics of the mechanical system of a diesel engine are primarily the geometric parameters of the crank mechanism, and the concept of the thermodynamic component in this case should include the combination of fuel combustion processes and expansion of combustion products. The thermodynamic processes occurring in the cylinders of an internal combustion engine and directly related compression processes (filling diesel cylinders with fresh charge, compressing the charge and cleaning the cylinders) ultimately generate a total force function characterized by the magnitude of the torque T_i, discretely distributed along the length of the crankshaft.

Using the dimensionless characteristics of the thermodynamic $Q(\varphi)$ and compression $K(\varphi)$ components of the force function T_i can be described for a single diesel cylinder by the following expression:

$$T_i(\varphi) = V_h\left[p_c K(\varphi) + p_i Q(\varphi)\right]; \tag{1}$$

where V_h – cylinder displacement; p_c and p_i – functions of gas pressure in the cylinder, which determine the speed and load conditions of the engine.

In relation to a multi-cylinder diesel engine with j cylinders, the total force function can be represented by a set of j force functions T_i acting on the corresponding sections of the crankshaft, the distances between which are determined by the distances between the individual cranks of the engine:

$$T_i = \sum_0^{j-1} V_h \left[p_c K(\varphi - \beta) + p_i Q(\varphi - \beta) \right], \tag{2}$$

where β – crankshaft rotation angle between flashes in the *j*-th and first cylinders.

The components p_c and p_i included in expressions (1) and (2) are also functions of the angular velocity of the crankshaft ω, the instantaneous values of which, in turn, depend on the speed of movement of the piston and the degree of insensitivity of the speed controller. The power function of each engine cylinder depends on the coordinate of the fuel supply control ψ_i, especially in modern fuel supply systems with electronically controlled multiphase fuel injection. As a result, the regulatory effect at time τ, which ensures the necessary change in the value of the cyclic fuel supply, is carried out with some delay:

$$\psi_i = \psi(\tau_k - \tau), \tag{3}$$

where τ_κ – the previous moment in time at which the coordinate change occurs ψ (k = 1, 2, … n).

In general, the torque from one diesel cylinder can be represented as: $T_{ij} = T_K + T_Q$. In this case, the average effective torque of an internal combustion engine T_{em} is determined by the well-known expression:

$$T_{em} = \frac{jV_h}{2\pi s}, \tag{4}$$

where *s* – engine stroke; *j* – number of internal combustion engine cylinders.

Taking into account expressions (1) and (4), the thermodynamic mathematical expression of the engine torque generator can be represented in the following form:

$$T_Q'(\varphi, \psi) = V_z Q(\varphi) \frac{\partial p_i}{\partial T_{em}} T_{em} \cdot \tag{5}$$

Let us present the values of the indicator pressure in a diesel cylinder as a sum:

$$p_i = p_0 + \Delta p_Q + \Delta p_\psi; \tag{6}$$

where p_0 – air-fuel mixture compression pressure; Δp_Q – pressure increase from fuel combustion and subsequent expansion of the working mixture; Δp_ψ – change in pressure compared to what is required at the current value of the crankshaft rotation angle φ due to untimely or poor-quality operation of fuel control systems.

Based on the dependence of the temperature t_i in the cylinders on pressure (Mendeleev-Clapeyron equation), it is possible to transform equation (5):

$$T_Q'(\varphi, \psi) = V_z Q(\varphi) \frac{\partial (mRT_i / V_h)}{\partial T_{em}} T_{em}; \tag{7}$$

where *m* – number of moles of gas mixture; *R* – gas constant.

Thus, it is shown that the value of the thermodynamic generatrix and, accordingly, the value of the total torque are functions of the fuel combustion temperature in the diesel cylinders. Consequently, the temperature of the engine working surfaces, as one of the most important characteristics of thermodynamic processes, is a functional dependence on the current torque values determined by a set of operating conditions and the technical condition of the power plant: $t_i = f(T_e)$. Since in a diesel cylinder there is not only a proportional change in temperature and pressure in accordance with known physical laws, but also stochastic processes of fuel combustion, the dynamics of the working processes of the power plant from the standpoint of changes in the operating temperature in the diesel cylinders, by analogy with expression (6), can also be represented in as the sum of the following components:

$$t_i = t_0 + \Delta t_Q + \Delta t_\psi. \tag{8}$$

The expressions presented in the article can serve as an approximate description of the thermodynamics of diesel power plants from the point of view of the relationship between the mechanical and thermodynamic components of torque. If we neglect the discreteness of angular velocity control, the description and possible solutions of the equations for the dynamics of internal combustion engine operating processes are significantly simplified. However, it is precisely the control of changes in the functional dependencies of the temperature of the working fluid on the angle of rotation and angular velocity of the crankshaft due to all the most likely causes of deviations of the indicator pressure from the optimal values (the amount of cyclic fuel supply, the qualitative composition of the fuel; the technical condition of the cylinder-piston group, gas distribution mechanism, fuel supply systems and automatic speed control) can in practice help improve the operating efficiency of power plants based on the analysis and improvement of thermodynamic processes.

3 Results

A mathematical description of the change in heat and mass transfer of an oil film of initial thickness δ_{oil} under the influence of temperature and the total component of gas and inertial forces can be presented in the form of energy and mass balance equations [11]:

$$C_{oil}\rho_{oil}V\frac{dt_{oil}}{d\tau}+\rho_{oil}\Delta H+f\left[q-\left(q_c+\frac{f_m}{f}q_r\right)\right]=0, \tag{9}$$

$$\rho_{oil}\frac{dV}{d\tau}+f\rho\alpha Z=0; \tag{10}$$

where C_{oil} and ρ_{oil} are the heat capacity and density of the oil, respectively; q – total heat flux density from the oil to the cylinder wall; q_r and q_c– radiation and convection components of heat transfer; V – oil film volume; ΔH – difference in enthalpies of oil in gaseous and liquid states; t_{oil} – oil temperature; f – surface area of the oil film; f_p – radiative heat exchange area; f_m is the density of the mixture of vapor and air on the surface of the film; Z is the dimensionless mass concentration of oil vapor on the film surface; α is the coefficient of mass exchange between the oil film and the engine cylinder displacement; τ – current process time.

One of the most powerful factors influencing oil loss in an internal combustion engine and the quality of the oil film in its cylinders is the cylinder liner wall temperature t_c, which determines the rate of evaporation of the oil film. The value of this temperature, in turn, affects the value of the oil temperature $t_м$. As the temperature of the oil decreases, its viscosity increases accordingly, which helps to reduce oil throw into the combustion chamber and, therefore, should theoretically reduce oil consumption due to waste.

To confirm this theoretical hypothesis, practical tests were carried out on various diesel engines. The first test was carried out on a ship's power plant of a Project 428 vessel with two G70 engines (Table 1). The power of each engine was 833 kW at a nominal crankshaft speed of 375 rpm. The tests were carried out at a speed slightly below the nominal value of 370 min^{-1}. During the experiments, diesel fuel of grade "L" (GOST 305-2015) and motor oil $M10B_2$ (GOST 8581-2021) were used. To measure oil consumption, containers with glass calibration scales with a division value of 10 kg were used, which, to increase accuracy, were additionally divided into 10 parts with a division value of 1 kg. Tests showed consistency with factory data. To increase the accuracy of measurements, the duration of each measurement in different operating modes was at least 24 hours.

Table 1. Results of practical tests on G70 engines.

Test #	Coolant temperature leaving the system, ^{0}C	Experiment duration, h	Oil consumption, kg
1 2	37.5 37.5	24 24	74 73
Average oil consumption			73.5
3	61.0	24	97.0

4	61.0	24	96.5
Average oil consumption			96.75
5	70.0	24	117.0
6	70.0	24	117.5
Average oil consumption			117.25

The second test was carried out on a Project 292 vessel equipped with two G60 main engines with a power of 662 kW each at a nominal speed of 375 min^{-1}. The tests were carried out at a constant crankshaft speed of 370 min^{-1}. Also, as in the previous case, “L” grade fuel and M10B2 engine oil were used. Oil consumption for waste was measured using the same method as in the first set of tests on G70 engines. The test results are shown in Table 2.

Table 2. Results of practical tests on G60 engines.

Test #	Coolant temperature leaving the system, ^{0}C	Experiment duration, h	Oil consumption, kg
1	40.0	24	43.6
2	40.0	24	40.4
Average oil consumption			42.0
3	70.0	24	70.0
4	70.0	24	68.6
Average oil consumption			69.3

Based on the results of the experiments given in Tables 1 and 2, we can conclude that lowering the temperature of the coolant in the cooling system is a fairly effective way to reduce oil consumption due to waste in internal combustion engines. In this case, the experiments were carried out on operating ship power plants with flow-through systems for cooling engines with sea water. This confirms the need to take into account the influence of thermodynamic processes on the parameters of the technical condition of power plants.

With the obtained external positive effect, it should also be taken into account that, according to the theory of internal combustion engines, a decrease in the temperature of the coolant can also lead to negative consequences:

– due to the expected increase in oil viscosity, there is an increase in mechanical losses to overcome friction;

– an increase in heat losses into the cooling system can lead to a decrease in the thermal efficiency and, accordingly, the indicator and effective;

– due to increased processes of moisture condensation in the engine cylinders, an increase in the corrosive effect on the cylinder liner, cylinder cover and piston is possible.

To study the possible negative consequences that may arise when the coolant temperature decreases, in order to reduce oil consumption due to waste, an experimental installation based on a two-cylinder diesel engine was designed and manufactured. To eliminate losses during the pumping strokes of the piston, the cylinder cover was removed, and a number of pipe connections were made to close the cooling system. Using a standard braking device, switched on in a reverse circuit, the torque expended to overcome mechanical losses and conditionally equal to the engine torque T_e was measured. The experimental setup was driven by an electric motor. The loading device was a lever mechanism with the ability to vary the mass of the loads and the distance of the point of application of the weight of the loads from the axis of rotation of the drive. The magnitude of the torque was determined by the product of the mass of the loads and the length of the lever of the loading device. The diagram of the cooling system of the experimental installation is shown in Figure 1. Here the following are indicated accordingly: 1 – expansion tank, 2 – thermometer, 3 – pump, 4 – motor, 5 – electric heater.

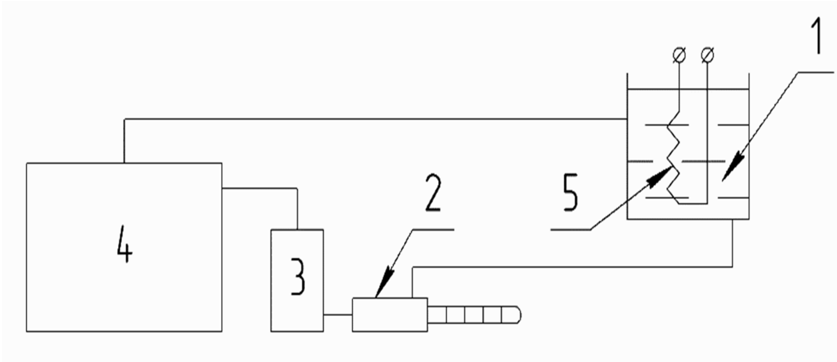

Fig. 1. Diagram of the cooling system of the experimental installation.

In the process of carrying out experimental studies, it was found that when cranking a diesel engine, the water temperature due to friction and mechanical losses increases without turning on the heater to 70 0C. The experiment was carried out as follows. Initially, the temperature of the water in the cooling system was equal to room temperature in the room. Next, the engine was brought to a nominal speed of 1500 min^{-1} and the phase of the main experiment began, during which the torque of mechanical losses was determined and recorded at various temperatures. This continued until the maximum value that can be achieved under the influence of frictional forces. After turning on the heater, the experiment continued until the coolant temperature reached 100 0C.

The experiment used $M14B_2$ oil, two pairs of pistons and three-cylinder liners with varying degrees of wear. The first- and second-cylinder liners had natural wear of 0.04 and 0.10 mm, and the third was artificially bored to simulate wear of 0.2 mm. The results of the experiment are presented in Figure 2.

From the obtained graphs it can be seen that as the temperature of the coolant cools, mechanical losses increase significantly. I would like to note the fact that the larger the gap between the piston and the cylinder liner, all other things being equal, the lower the level of internal mechanical losses in friction pairs. This parameter is a characteristic of changes in the technical condition of the engine during operation. The experimentally obtained dependencies showed that mechanical losses are approximately at the same level for small gaps between the piston rings and the cylinder liner at a temperature of 90 °C and for a variant with increased wear at a temperature of 65 °C. From this we can conclude that when the technical condition of internal combustion engines changes, characterized by increased wear of parts of the cylinder-piston group, a decrease in the coolant temperature can have a positive effect on oil consumption for waste while maintaining other output parameters of the power plant (power and crankshaft speed), which confirms the existence of a relationship between the parameters of the technical condition of power plants and the characteristics of thermodynamic processes.

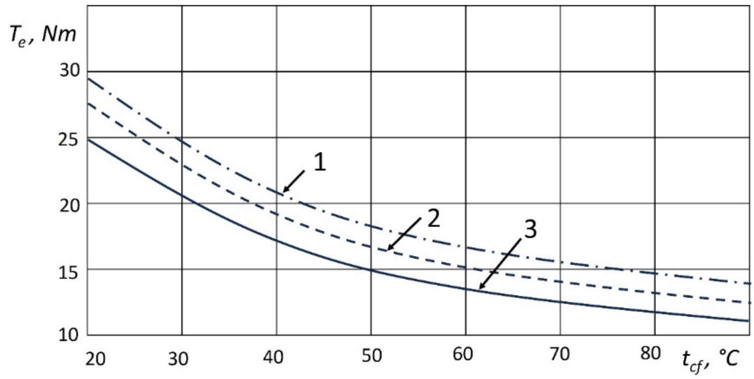

Fig. 2. Experimental dependences of torque on coolant temperature for various variants of the technical condition of the cylinder liner: 1 – wear 0.04 mm, 2 wear 0.10 mm, 3 – wear 0.20 mm.

4 Conclusion

The article presented to the attention of the scientific community contains the results of theoretical and experimental studies showing the existence of a relationship between the parameters of the technical condition of power plants and the characteristics of thermodynamic processes. The research results make it possible to assert that a diesel power plant should be considered a system consisting of components that are equal in their degree of influence on the efficiency of its operation. First of all, such components include the mechanical and thermodynamic parts and the fuel supply system. The temperature of the working surfaces of a power plant is an important characteristic of its technical condition, since the thermodynamic component of torque generation is a function of the fuel combustion temperature in the diesel cylinders. To improve the design and increase the operating efficiency of power plants with diesel internal combustion engines, a more in-depth study of intra-cylinder fuel combustion processes and the development of operational methods for monitoring the thermal state are necessary.

An example of the dynamics of changes in the temperature conditions of the oil film between the piston rings and cylinder liners of marine internal combustion engines is given. Analysis and recording of dynamic temperature operating parameters can ultimately help improve the reliability and durability of power plants.

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