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ANALYSIS OF THE TEMPERATURE AND THERMAL STRESS STATE OF MARINE ENGINE COMPONENTS

Abstract*: Maintaining the temperature and thermal stress of engine components within permissible limits is impossible without some heat loss. It has been established that only 35–45% of the thermal energy is converted into useful (effective) energy. To determine the thermal stress experienced by individual components, the heat released in the cylinder must be apportioned among them. The engine's thermal balance makes it possible to assess the degree of heat utilization, quantify heat losses, and evaluate the potential for reducing them. In turn, the degree of heat utilization can be improved through the recovery of waste heat.*

The thermal stress of engine components is determined not only by the magnitude of the thermal balance components, but also by the heat flux density and intensity. The bottom of the cylinder heads and the piston crown are characterized by the highest heat flux densities. The result of the thermal stress magnitude is the mechanical properties of materials, which determines the reliability and durability of components and assemblies. The thermal stress of engine components can be assessed using various criteria.

Key words: *heat flux density and intensity; thermal stress; useful energy; heat utilization efficiency; heat losses; thermal energy recovery; mechanical properties of materials; reliability and durability of components.*

Language: *English*

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Introduction

The work process in internal combustion engines involves the release of a large amount of heat in the engine cylinder due to fuel combustion, which causes periodic increases in the temperature of the cylinder and piston group components. Under high-pressure, sealed conditions, contact between hot gases and the combustion chamber, cylinder head, cylinder, and piston surfaces causes overheating, which can lead to oil burning, increased friction, component failure, and other issues. Reliable and long-term operation of engine mechanisms is only possible under strictly defined thermal conditions. Overheating causes the thermal expansion of components, leading to deterioration or complete seizure of moving parts. It also reduces cylinder filling, causes oil coking, and can lead to the failure of the valve plate, cylinder head, and other components. In the case of excessive cooling, mixture formation deteriorates, thermal and mechanical losses increase, and wear intensifies.

To avoid these problems and ensure normal engine operation, it is necessary to select a cooling system that maintains the optimum temperature of the engine components within the optimal operating range.

The heat transfer process occurring in the cylinder of an internal combustion engine is a highly complex physical phenomenon, as it involves radiation, conduction, and convection simultaneously [1,2]. At the initial stage, during the ignition and combustion of the fuel-air mixture, radiant energy is transferred to the walls of the combustion chamber and the cylinder head.

At the next stage, convective heat transfer occurs between the coolant and the walls of the cooling jacket. The intensity of this process depends on both structural parameters and the properties of the cooling medium. In other words, the intensity of convective heat transfer is determined by the flow dynamics and the microstructure of the moving medium [3].

As Purtskhvanidze, G., Lejava, M., Shubladze, Z., Gvetadze, V., & Zoidze, V. (2026) [4] noted that „from an energy perspective, heat transfer under nuclear boiling conditions is more favorable because the high heat transfer coefficient allows for efficient heat removal from cooled surfaces at low coolant flow rates“.

The reliability of marine engine operation is affected by the water-chemical parameters in the engine cooling system when various chemical additives are used. This is presented in the paper Purtskhvanidze, G., Lejava, M., Shubladze, Z., Kamladze, A., & Kiknadze, M. (2026) [5], “During the research, it was noted that when additives are used, the enhancement of the anti-corrosion protective effect is associated with an increase in fluid temperature, which is an important factor in maintaining the protective properties of the additives in high-temperature cooling systems.”

Basic part: The thermal energy released during fuel combustion in the engine cylinder cannot be fully converted into useful work because it is impossible to maintain the temperature and thermal stresses of the engine components within permissible limits without dissipating a portion of the generated heat In modern transport internal combustion engines, depending on their design, type, and quality of the work process, 35–50% of the released thermal energy is converted into effective work, while the rest is distributed among various types of losses.

To determine the thermal and temperature stresses of engine components, it is necessary to know how the heat released in the engine cylinder is distributed among its various components. This distribution is referred to as the external heat balance.

The external heat balance allows us to assess the extent of heat utilization, quantify thermal losses, and evaluate the potential for reducing them. It identifies effective ways to utilize the energy of the exhaust gases, design the main elements of the cooling system, and improve engine performance. It should be noted that changes in the engine’s speed and load characteristics significantly affect the components of the heat balance. Therefore, for marine engines, the heat balance equation is derived with external speed for load and propeller characteristics. The heat balance equation is drawn up in absolute units per 1 kg or 1 m³ of fuel consumed during 1 hour of engine operation. The heat balance equation for the external speed characteristic of a combined engine, expressed in absolute units, is written as follows:

$$Q = Q_e + Q_{e.s.} + Q_{e.g.} + Q_{lubr.} + Q_{s.h.}, \quad (1)$$

where Q - is the total amount of heat released as a result of fuel combustion in the engine cylinder.

$$Q = G_{c.h} + H_u \quad (2)$$

where $G_{c.h}$ - is the amount of fuel consumed by the engine in 1 hour, and H_u- is the lowest heat of combustion of the fuel.

Q_e = 632 Ne kcal/hr - is the heat equivalent of the work performed by the engine.

$Q_{e.s.}$ - is the amount of heat transferred to the cooling agent by the engine. If we determine the amount of coolant $G_{c.}$ passing through the cooling jackets per unit time and measure the temperatures at the inlet and outlet of the system, then the amount of heat transferred to the cooling system is as follows:

$$Q_{e.s.} = G_i \cdot c(t_i - t_o), \quad (3)$$

where c - is the specific heat capacity of the cooling agent.

$Q_{e.g.}$ - is the amount of heat carried away by the exhaust gases leaving the cylinder, and it can be written that

$$Q_{e.g.} = Q_{e.g.ent.} + Q_{inc.com.} \quad (4)$$

where $Q_{e.g.ent.}$ - is the enthalpy of the exhaust gases, and $Q_{inc.com.}$- is the thermal energy lost due to the incomplete combustion of heat.

$Q_{lubr.}$- is the amount of heat removed by the oil during the lubrication process;

$Q_{s.h.}$ - heat spent on the operation of various auxiliary mechanisms of the engine.

In most cases, the heat balance equation is written using relative quantities, where each component is expressed as a percentage.

$$q_e + q_{e.s.} + q_{e.g.} + q_{inc.com.} + q_o + q_{s.h.} = 100\% \quad (5)$$

Table 1 presents the average values of the individual components of the external heat balance of a diesel engine during operation at nominal operation of the engine.

Table 1 - Values of the components of the external heat balance of various types of engines

Type of engine	q_e	$q_{e.s.}$	$q_{e.g.}$	$q_{inc.com.}$	q_o	$q_{s.h.}$
Aspirate diesel engine	29-42	20-35	25-40	0-5	2-4	2-7
Supercharged engine	40-48	10-18	20-40	0-7	4-8	2-5

As shown in Table 1, 52–78% of the thermal energy released in the engine is accounted for by heat losses, primarily via the exhaust gases and the cooling system.

The degree of heat utilization can be increased by recovering heat losses. For example, on high-power vessels, the heat from exhaust gases is used in waste-heat recovery boilers. In recent years, on low-power vessels, exhaust gas heat has been utilized in thermochemical generators. In combined marine engines, 10–18% of the heat is removed by the cooling system.

Table 2 - Heat balance components during operation of a river vessel's diesel engine on propeller characteristics

Heat balance components	Loads, %			
	25	50	75	100
Equivalent heat for effective engine operation	25,7	30,5	33,6	35,4
Heat carried away by exhaust gases	24,8	26,2	27,0	25,0
Heat transferred to the coolant	41,3	34,8	31,9	33,5
Uncounted heat losses	8,2	8,5	7,5	6,1

The table shows that, at nominal operating conditions, heat losses on the cooling water are approximately equal to the heat used to perform useful work, whereas at loads below 75%, the heat transferred to the cooling water exceeds the useful heat output.

Figure 1 illustrates a heat distribution graph showing the variation of the balance components during engine operation under different load conditions.

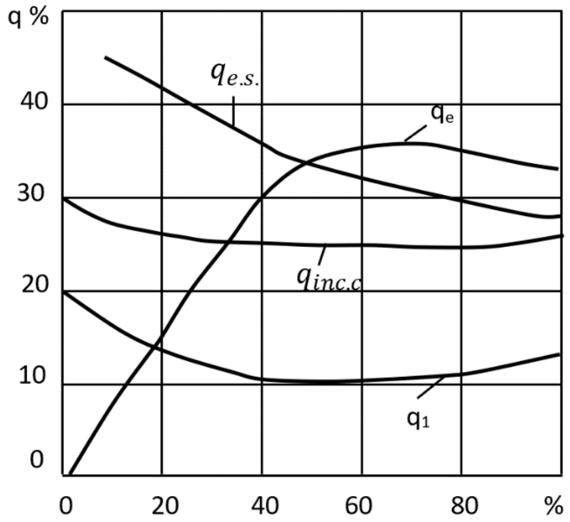

Fig. 1. Variation of external heat balance components depending on engine loads

The temperature and thermal stress state of engine components are determined not only by the magnitude of the thermal balance components, but also by the heat flux density and intensity. As a rule, the main heat-receiving surfaces are the bottom of the cylinder heads, the cylinder liner mirrors, and the piston crown. At the same time, the distribution of heat flux from the working medium in the cylinder to individual elements is significantly non-uniform. Moreover, the underside of the cylinder head and the piston crown exhibit the highest heat flux density.

Thermal stress in components refers to the temperatures of the main components, which are characterized by absolute temperature values and temperature gradients. Their magnitude results in the mechanical properties of materials, temperature stresses, lubrication conditions of friction surfaces, and other factors that directly determine the reliability and durability of components and assemblies.

The concept of thermal stress refers to the amount of heat removed from the unit heat-receiving surface by the cooling system per unit time.

$$\Delta t = t_{max} - t_{min} \qquad (6)$$

In turbocharged engines, the following formula is recommended for assessing the thermal stress of the piston-cylinder group components:

$$q_n = b \cdot C_m^{0,5} \cdot \left(1{,}36\frac{T_{inc}}{T_0}\right)^{0,38} \cdot \left(\frac{d}{\eta_v \cdot P_{inl.}}\right)^{0,38} \qquad (7)$$

where b - is the proportionality coefficient, for four-stroke engines, b =1;

$P_{inl.}$- cylinder filling pressure, MPa;

T_{inc}- temperature of air entering the cylinder, K;

d – Cylinder diameter, dm;

π_v – coefficient of admission;

T_0 - air temperature under normal conditions.

Using the thermal stress factor q_n, the service life can be determined by the following relationship:

$$T = \frac{U_l}{v} = \frac{u_l}{60 q_n p_z \cdot k' \cdot n} \qquad (8)$$

where U_l- limiting wear, determining the service life of components;

k'- coefficient that takes into account the design features of the engine;

n - engine crankshaft rotation frequency, min⁻¹;

ρ_Z - maximum cycle pressure, MPa;

q_n – thermal stress factor.

If we assume that the limiting wear of components is proportional to the diameter of the engine cylinder, then

$$T = k' \cdot \frac{d \cdot 10^3}{q_n \rho_z \cdot n} \qquad (9)$$

The thermal stress of the cylinder and piston group components can be assessed using various criteria. For example, the thermal stress developed on the piston crown can be determined by the amount of heat transferred to the cooling agent and expressed by the formula:

$$Q_p = v N_e g_e \cdot H_u \qquad (10)$$

where N_e - effective power per cylinder;

g_e - effective specific fuel consumption;

H_u - lowest calorific power of fuel;

v - the portion of total heat removed by the piston crown, with oil cooling v = 0,04 - 0,06, with water cooling v = 0,06 – 0,09.

In recent years, the finite element method and the control volume method have been widely used to determine the local temperature of components and their thermal stress state [6]. In this case, the amount of heat transferred during the cycle to a surface with an area ΔF is determined by the formula [7]:

$$Q = \Delta F \cdot \int_0^{t_0} \alpha (T - T_w) dt \qquad (11)$$

while in the equivalent steady-state mode:

$$Q = t_0 \alpha \left(T_{eq}\right) \Delta F \qquad (12)$$

where α – is the average equivalent coefficient of heat transfer.

T_{eq} and T_w – the average equivalent temperatures of the gas and the wall.

From equations (1.11) and (1.12), we obtain the equivalent heat transfer parameters for the steady-state mode

$$\alpha\left(T_{eq} - T_w\right)t_0 = \int_0^{t_0} \alpha(T - T_w)dt \quad (13)$$

If we assume that $T_{eq} = T_w$, we obtain a simplified formula for determining the equivalent heat transfer parameters:

$$\alpha_{eq} = \alpha_{av} = \frac{1}{t_0}\int_0^{t_0} \alpha dt \quad (14)$$

from which

$$T_{eq} = \frac{(\alpha T)_{av}}{\alpha_{av}}. \quad (15)$$

Every component, based on its design properties and operating conditions, has a maximum permissible temperature. For example, for components made of aluminum alloys, the maximum temperature should not exceed 250-300°C; for cast iron components, this value is 400-450°C, and for alloyed steels – 450-500°C. [7].

Table 3 presents the limiting temperatures for the components of the piston-cylinder group made of various materials.

Table 3 - The limiting temperatures for the components of the piston-cylinder group

Piston crown temperature	Light-metal alloy Al-1	2000-250 ^{0}C
	Light-metal alloy Al-4	300-350 ^{0}C
	Steel	400-475 ^{0}C
	Cast iron	400-250 ^{0}C
Temperature in the zone of the No 1 ring of the piston		200-210 ^{0}C
Cylinder face temperature in the head-land ring		200 ^{0}C

Exceeding these temperatures leads to changes in the metal structure and deterioration of its physical properties, resulting in an immediate reduction in component reliability. In this regard, some countries have conducted research into thermal insulation of relatively heated components, which causes changes in the thermal state of engine components [8, 9]. It should also be noted that, in some cases, thermal insulation of the combustion chamber has resulted in reduced engine efficiency due to changes in the working process and increased heat losses. This phenomenon results from changes in mixture formation, ignition, and combustion processes, as well as an increase in the radiative component of heat transfer within the cylinder. Consequently, the use of ceramic materials is not considered acceptable in either modern or future marine diesel engines, which are required to ensure high efficiency and long service life.

Thus, only a liquid cooling system can ensure reliable operation of a marine engine over a long period. Under conditions of maximum working-cycle temperatures, which in modern diesel engines range from 1700–2700°C [10], the cooling system design and its individual components must ensure reliable heat transfer and minimal energy consumption for circulating the coolant.

Conclusions

Based on the research and analysis conducted, the following conclusions can be drawn:

- The thermal balance of the engine allows assessment of the degree of heat utilization, heat losses, and potential ways to reduce them;
- The degree of heat utilization can be increased by recovering heat losses;
- At engine loads below 75%, the heat transferred to the cooling water exceeds the useful heat output, whereas at nominal load conditions, they are approximately equal.

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