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CONTENTS

Keywords: diesel engine; at high altitudes; power loss; cooling system; heat output; thermal factor

Beibit MYRZAKHMETOV[1]*, Aleksander SŁADKOWSKI[2], Gulzada MASHATAYEVA[3]

OPERATING PECULIARITIES OF STANDARD COOLING SYSTEMS OF ENGINES AT HIGH ALTITUDES

Summary. The item under test was the engine without its standard facility-based cooling systems, the lack of which makes it impossible to operate as a power unit of a vehicle in a great majority of experimental research of internal combustion engines at high altitudes. The findings may create a wrong impression of the range of power ratings and economic parameters of the engine when operating at high altitudes because changes in atmospheric conditions exert an effect on the running efficiency of its standard systems as well. It is established that the efficiency loss of the cooling system may cause a forced power limitation of the engine as a result of the experimental research of the diesel engine equipped with all standard facility-based systems at very high altitudes. Thus, the shortage of power may significantly exceed the power loss of the engine due to air density reduction at high altitudes.

1. INTRODUCTION

Internal combustion engines during a widespread development of other types of drives of vehicles continue to be one of the most typical in many sectors of economy. Their share is especially high in hard-to-reach, high-mountain areas, where a significant part of the global population lives.

The internal combustion engine continues to be the main drive of both motor vehicles and agricultural as well as road-building machines, which are normally in constant operation at high altitudes (2000–3000 m above sea level) [1-3] due to the poor infrastructure of these regions. Therefore, the objectives to improve operational and performance characteristics of engines at high-altitudes continue to be relevant.

Much research has established that when operating an internal combustion engine at high altitudes, mainly due to air density reduction, a combustion process abnormality of the fuel-air mixture is observed, which results in a significant degradation of performance and economic parameters (power and efficiency), an increase in the thermal factor of parts, and a loss in their reliability and life [2-4].

In the vast majority of research on internal combustion engines at high altitudes, the item tested has been the engine itself without standard facility-based systems (cooling, lubrication, gas exchange, and others), the lack of which makes it impossible to be operated as a power unit of a vehicle.

At high altitudes, it is considered preferable to operate vehicles with internal combustion engines equipped with boosting systems which partially compensate for a detrimental effect of air density reduction. However, even in such internal combustion engines, disturbances of work process related parameters due to the running conditions of the boosting systems are observed [5-7].

[1] Satbayev University; Satpayeva, 22, 050013 Almaty, Kazakhstan; e-mail: myrzahmetov.ba@gmail.com, orcid.org/0000-0001-5175-3844
[2] Silesian University of Technology; Krasiński 8, 40-019 Katowice, Poland; e-mail: Aleksander.Sladkowski@polsl.pl; orcid.org/0000-0002-1041-4309
[3] Satbayev University; Satpayeva, 22, 050013 Almaty, Kazakhstan; e-mail: gulzadamashatayeva@gmail.com; orcid.org/0000-0002-9363-631X
* Corresponding author. E-mail: myrzahmetov.ba@gmail.com

The change in atmospheric conditions results in a change in running conditions and the performance of these standard systems of the engine, which may also have an effect on the parameters of the engine itself and the vehicle and power unit as a whole.

The modes limitations of the engines at high altitudes against external parameters (exhaust gas temperature or excess air factor) without considering their interconnected operation with standard facility-based systems and processes inside the cylinders may result in a shortage of power or unreasonably high values during operation. The latter can cause a degradation of the parts work capability and the engine's life.

2. EFFECT OF HIGH ALTITUDES ON THE RUNNING EFFICIENCY OF THE STANDARD COOLING SYSTEMS OF AN ENGINE

Cooling and lubrication systems are key standard facility-based systems of engines of vehicles that maintain their normal operation across the entire range of performance.

The effect of changes in atmospheric conditions on the operation of feed and lubrication systems of a diesel engine is insignificant.

The most significant effect may be observed on the thermal efficiency of the standard cooling systems (CSs) that mainly determine the thermal rate of an engine, its power ratings, and economic parameters.

Standard cooling systems are usually designed for interconnected operation with an engine at standard atmospheric pressure and maximum ambient temperature of 40°C, whereas when the altitude is increased, they definitely decrease.

The most commonly used cooling system schematic is a forced air cooling of a radiator by a drive fan. Among other things, the thermal efficiency of the cooling system depends on a fan capacity, which, in turn, depends on frequency of its rotation, density, ram air, the speed of the vehicle, and the condition of the external and internal surfaces of a radiator. Low speed limits are typical for the operation of vehicles and specialized vehicles at high altitudes [3, 9, 10]. This causes a thermal efficiency loss of the cooling system at high altitudes, firstly by an insignificant effect of backward air flow and secondly by a loss of the fan capacity due to air density reduction and its speed drop due to the operation of the internal combustion engine at frequencies correspondent to its maximum torque.

The seal failure of sealed cooling systems can also cause an efficiency loss, as the boiling point of the coolant lowers as the ambient pressure drops.

In the majority of previous experimental research on engines at high altitudes, a significant abnormality of the combustion process in engines has been noted [2, 4, 8].

A significant quantity of pre-mixed combustion is accumulated by the time of self-ignition in the combustion chamber due to excess air factor reduction α and is associated with an extension of ignition time delay of fuel τ_i, which leads to improvements in the performance indicators of the combustion cycle, followed by a thermal factor increase in the components' fire sides of the combustion chamber and a heat transmission increase in the cooling system.

The heat transmission from the radiator of the engine to the ambient air (or thermal efficiency of the cooling system), generally speaking, is determined by the Newton-Richman equation:

$$Q = K \cdot F_a \cdot \Delta t_m, \text{ [W/m}^2\text{]} \tag{1}$$

where K – Total heat transfer factor [W/m· K];

F_a – Radiator surface cooling area [m²];

Δt_m – Temperature driving force between the coolant and the ambient air [°C].

The overall thermal resistance of heat transfer can be expressed as:

$$R_0 = \frac{1}{K} = R_1 + R_{st} + R_2 = \frac{1}{\alpha_B} + \frac{\delta}{\lambda} + \frac{1}{\alpha_a}, \text{ [K/W]} \tag{2}$$

where

R_1 and R_2 – Thermal resistance of internal and outer surfaces of the radiator walls;

α_b and α_a – Heat transfer factors of water and air, respectively [W/m^2 ·K];

δ – Radiator wall thickness [m];

λ – Heat conductivity factor of the radiator wall material [W/m·K].

The heat conductivity factor of the radiator wall material (brass or aluminum) is quite large, and the wall thickness is insignificant. Therefore, its thermal resistance δ/λ is insignificant and can be omitted in calculations. In this case, Formula (2) takes the form of:

$$R_0 = \frac{1}{K} = \frac{1}{\alpha_B} + \frac{1}{\alpha_a}[K/W].$$

However, considering that the thermal resistance of air is much greater than the thermal resistance of water (i.e., $\alpha_a \gg \alpha_B$), this expression takes its final form as follows:

$$K = \alpha_a.$$

Thus, the heat transfer factor from the outer surfaces of the radiator to ambient air is critical to the rate of heat production.

When cooling the radiator, the air is forcedly in motion, which can be depicted by a standard equation of Nusselt:

$$Nu = C \cdot (\mathrm{Re})^n \text{ or } Nu = \frac{\alpha_a - d_e}{\lambda}, \tag{3}$$

where:

Nu and Re – Nusselt and Reynolds numbers, respectively;

C and n – Fixed factors;

d_e – Equivalent diameter.

Reynolds number is defined as

$$\mathrm{Re} = \frac{\rho \cdot \omega \cdot \ell}{\mu}, \tag{4}$$

where:

ρ and ω – Air density [kg/m^3] and speed [m/s], respectively;

ℓ – Length of section, m;

μ – Dynamic viscosity of air, [Pa·s].

From (4) and (3), we obtain an expression for α_a in the form of:

$$\alpha_a = Nu \cdot \lambda + d_e \tag{5}$$

Due to dimensional stability (d_e and ℓ), we find that α_a is primarily defined by dimensions ρ and μ. The calculations show that the reduction in ρ has a greater impact than μ.

Thus, the air density range of ρ for every 1000 m of altitude is about 10%, whereas its viscosity μ in the temperature difference corresponding to this altitude changes by about 1% (i.e., the air density value in Formula (4) is a value of the high order rather than viscosity μ and determines the value of Re).

As follows from (1), the thermal efficiency of the cooling system is also determined by the temperature driving force. The maximum permissible temperature of the coolant in the cooling system of the internal combustion engine is specified by technical specifications for operation and is often limited to 110–120°C, while the ambient air temperature definitely decreases when the altitude increases. Although this increase in temperature driving force Δt_m somewhat improves the heat dissipation condition, as was experimentally established, it does not completely compensate for the thermal efficiency decrease of the cooling system at high altitudes [2]. This creates a need in a forced limitation of power of the internal combustion engine to reduce a thermal load on the cooling system.

Ejection cooling systems have found use in some utility vehicles (military tracked vehicles). The exhaust energy of an engine is used as a high-pressure agent.

The operating mode of the gas jet ejector depends on the parameters of ejecting and ejected gases and is generally descried by the law of conservation of mass:

$$G_3 = G_1 + G_2 \text{ or } G_3/G_1 = n+1, \tag{6}$$

where:

G_1 and G_2 – Mass flow rates of ejecting and ejected gases, respectively;

G_3 – Total gas flow through the ejector mixing chamber;

n – Coefficient of ejection;

This formula shall be presented in the form of an equation of continuity of flow:

$$\rho_3 \cdot \omega_3 \cdot (F_1 + F_2) = \rho_1 \cdot \omega_1 \cdot F_1 + \rho_2 \cdot \omega_2 \cdot F_2, \tag{7}$$

where:

ρ – Gas density, [kg/m^3];

ω – Flow velocities, [m/s];

F – Area of the ejector nozzles, [m^2].

It is obvious that the geometrical dimensions of the ejector F_1 and F_2 are constant and do not depend on changes of environmental parameters. The density of the ejected gas (i.e., air) decreases as the altitude increases above sea level.

The air-mass flow reduction by the engine and the subsequent combustion process delay at high altitudes and temperature increase of exhaust gases result in the reduction of density and mass-flow rate of the ejecting gas. The mass flow rate reduction of ejecting and ejected gases causes thermal performance degradation of the cooling system and can lead to the need to limit power due to poor efficiency.

3. RESEARCH METHOD

The unit of research is a six-cylinder four-stroke diesel engine with a piston with a 15-cm diameter and a 15-cm stroke (6FS15/15 (УТД-20)) from the "Transmash" plant, equipped with all standard facility-based systems and positioned in accordance with the assembly requirements in the engine and transmission compartment of the transport machine. This engine is used in military tracked vehicles and is equipped with an ejection system.

The objective of the research is to assess the impact of high altitudes on the operating process of the engine, the thermal state, and the efficiency of the standard cooling system.

The research conditions are $H = 0$ m above sea level and $H = 3340$ m above sea level, which makes it possible to make a comparative assessment of high altitudes' effects on changes in the parameters of the engine and its systems. In both cases, the same equipment set was used to reduce the instrument error. The unit with an electromechanical dynamometer manufactured by "Numeric" Company (serial#: LPA-250-3000) was used as a test loading device to test power.

The indication was carried out for all cylinders using piezo quartz sensors DT-6 with a natural frequency of 40 kHz and was recorded from the screen of an S-8-14 electron-beam memory storage oscilloscope on a fast film while duplicating the readings on a DL 200|/ RS high-speed recording device of transient processes manufactured by "Datalab" (England) with a quantization step of 5 ms and printing out diagrams on PDP4-002 flatbed two-dimensional potentiometer.

The tests were duplicated using F.AVL 120 P 505 CLK piezo quartz sensors with a thermo-shock protection completed with an AVL 3059 charge amplifier (AVL engineering company, Austria) to increase validity of the obtained indicator-diagrams.

No less than 40–50 pressure traces were recorded, and they were averaged subsequently in each mode under study.

The heat loss tests were carried out by measuring temperatures at characteristic points of the cooling and lubrication systems by thermal resistance with low thermal inertia and by recording the results on a KSP-2 self-recorder. The cooling water flow through the radiator was measured by a Venture nozzle calibrated with hot water and completed with a differential pressure gauge in the range of 0 to 100 kPa. Air flow was measured by RG-1000 gas flow meters. Oil consumption was measured by a TDR8-1 turbine flow sensor calibrated with oil at 90°C. The exhaust gas temperature was measured by chromel-alumel thermocouples at the outlet of each exhaust manifold. The temperature on the fire side in the cylinder head was measured by chromel-copel thermocouples caulked at a depth of 0.3 mm from its fire side [3].

4. RESULTS

The results of the specified diesel engine equipped with all standard facility-based systems, at very high altitudes (3340 meters above sea level (m.a.s.l.)) confirmed that, in addition to a degradation of the main technical and economic performance of the engine itself, the efficiency of the standard cooling system fades, making it necessary to limit effective power.

Fig. 1 shows the comparative external speed characteristics of the engine from which it follows that the power loss was due only to air density reduction at $H = 3340$ m.a.s.l and $n = 2600\,\text{min}^{-1}$. It was equal18.0 kW (or 10%).

Among other things, an additional test-bench cooling system was used due to the poor efficiency of the standard cooling system.

The standard cooling system of the engine was able to maintain the maximum permissible coolant temperature specified by the operating instructions ($t_{cool} \leq 120^{0}C$), only up to 143.3 kW.

Thus, the shortage of power in this mode due only to the poor efficiency of the standard cooling system was 21.7 kW, which exceeds the power losses due to climatic conditions. The total power losses considering the maintenance of the coolant temperature in the cooling system within acceptable limits with an additional test-bench cooling system was approx. 40.0 kW or 22%.

The greatest power loss was observed in the mode of maximum torque at 1600 min^{-1}.

Regardless of barrier parameters, the power loss was 21%. Such a significant power loss with a decrease in speed rate is explained by a more visible decrease of filling factor η_V at high altitudes (0.78 to 0.71). The drop in η_V is reduced ($n = 2600\,\text{min}^{-1}$ η_V 0.75 to 0.72), whereas the speed is increased.

Table 1 shows the results of comparative heat loss tests of the engine when operating in real ground conditions ($H = 0$ m above sea level) and at high altitudes ($H = 3340$ m above sea level) equipped with all standard facility-based systems from which it follows that, despite the power loss of the engine at high altitudes, the thermal load on the cooling system not only decreases but also increases visibly.

This is associated with the discrepancy between the optimal values of the fuel injection advancing angle and an increase in the ignition time delay when the operating conditions of the engine are changed at high altitudes, which causes the performance indicators of the cycle and the combustion process delay to increase and the main combustion phase to shift to the side of the expansion stroke with an increasing area of heat transfer through the cylinder walls [2].

This is also indicated by the temperature increase of exhaust gases during the operation of the internal combustion engine at high altitudes.

Table 2 shows the comparative parameters of the operating process and the performance indicators of the engine cycle when operating in ground conditions (H = 0 m above sea level) and at very high altitudes (H = 3340 m).

An additional bench test cooling system (parameters are denoted as -*) was used to determine the operating process parameters of the engine against external characteristics due to the poor efficiency of the standard cooling system.

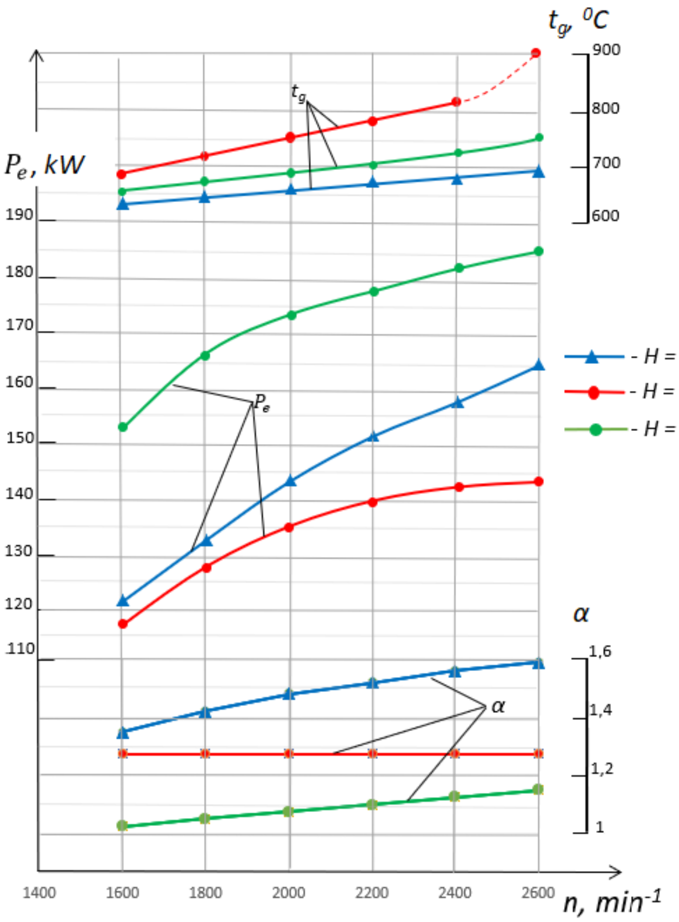

Fig. 1. Comparative external speed characteristics of 6FS15/15 engine when operating under facility-based conditions at heights of $H = 0$ m.a.s.l. and $H = 3340$ m.a.s.l.

Table 1

Heat loss test results

Parameter	Mode $n = 2600\,\text{min}^{-1}$, $H = 0[m.a.s.l]$, $B_0 = 99.8[kPa]$ $T = 294[K]$	Mode $n = 2600\,\text{min}^{-1}$, $H = 3340[m.a.s.l]$, $B_H = 68.3[kPa]$, $T = 278[K]$	Mode $n = 2600\,\text{min}^{-1}$ $H = 3340[m.a.s.l]$, $B_H = 68.3[kPa]$, $T = 278[K]$
	Standard cooling system	Standard cooling system	With additional bench-test cooling system
$P_e\,[kW]$	183	143.3	165
$G_f\,[kg/h]$	50.6	42.9	50.0
$t_{cool}\,[^0C]$	120	120	120
$t_{oil}\,[^0C]$	119	99	105
$Q_{cool}\,[kJ/h(\%)]$	389,000 (18%)	456,000 (22.5%)	515,000 (23.5%)
$Q_{oil}\,[kJ/h(\%)]$	64,250 (3.0%)	67,649 (3.32%)	67,790 (3.41%)

Note: P_e – effective power; G_f – fuel consumption; t_{cool} - coolant temperature in the cooling system; t_{oil} - oil temperature in the lubrication system; Q_{cool} - heat transfer in the cooling system; Q_{oil} - heat transfer in the lubrication system.

Table 2

Comparative parameters of the operating process and performance indicators of the engine cycle

External conditions	n ,	G_f	P_e	η_V	α	φ_{is}	τ_i	λ	$dP/d\varphi$
	[min^{-1}]	[% $G_{nom.}$]	[kW]	P_z/P_s		[degree]	[crankshaft rotation degree]	P_z/P_c	[mPa/ grad]
$H = 0[m.a.s.l]$ $B_0 = 101.05[kPa]$ $T = 293.0[K]$	1600	100	152	0.78	1.27	+5.2	22	2.4	17
	2600	100	182	0.75	1.49	+6, 5	24	2.2	16
$H = 3340[m.a.s.l]$ $B_H = 68.3[kPa]$ $T = 287.0[K]$	1600*	100*	120.7*	0.71*	0.94*	- 2.0*	28*	3.2*	22*
	1600	89	117.7	0.72	1.18	-2.0	30	3.9	27
	2600*	100*	165.6*	0.72*	1.03*	-2.5*	29*	3.1*	24*
	2600	80	143.3	0.73	1.2	-3.0	28	3.1	24

Note: n – crankshaft revolution; G_f – fuel flow; Pe- effective power; η_V – filling factor of cylinders with air; α– excess air factor; φ_{is} – ignition angle (represented with "+" sign - to TDC, represented with "-" down TDC); τ_i– fuel induction time; λ – pressure ratio; dP/dφ– rate of pressure build-up (cycle rigidity).
* with an additional bench-test cooling system.

The analysis of experimental data shows that the weight filling of the cylinders with air is decreased at high altitudes, and the conditions of carburation are degraded when the fuel equipment is constantly adjusted, leading to a performance problem of the end of compression stoke P_c and T_c. Moreover, the fuel carry of sprays is increased, and the time delay of self-ignition τ_i is increased.

The ignition is shifted beyond the top dead center (TDC) when the fuel supply is practically completed by the injector whereas in ground conditions of the operation in the same mode. The ignition is 5–7 degrees to TDC (i.e., φ_i increases by 21%).

Such a significant increase in the induction time of the fuel results in an increase in almost all characteristics of the performance indicators and the rigidity of the operational cycle. This is also noted in the results of other authors [8-10].

The high-frequency fluctuations of pressure on the combustion line are typical for the tested engine even when operating under normal physical conditions typical in the case of detonation in a petrol internal combustion engine [3,4].

The amplitude of these pressure fluctuations significantly increases when operating at high altitudes.

If we assume that these high-frequency pressure fluctuations are generated by pressure waves from nucleation sites for self-ignition, their amplitude increase in the indicator diagrams at high altitudes is explained by the time delay increase of self-ignition, during which a large portion of the injected fuel has to evaporate, mix with air, and form powerful nucleation sites for ignition. This leads to high rates of combustion reaction with an intense heat release—in other words, to the first phase of the intensification of a heat release and, as a consequence, an increase in the pressure and temperature of the cycle.

As a result, the gas thermal loads increase on the fire sides of the combustion chamber parts, increasing the temperature and intensity of heat transmission in the cooling system. The cooling system was prepared for the installment of six chromel-copel thermocouples (t_1 ... t_6) with a filament diameter of 0.5 mm and a hot junction depth setting of 3 mm [2]. The thermometering results are given in Fig. 2.

The reading spread of the thermocouples did not exceed 10°C, indicating a good organization of coolant movement in the combustion head. Fig. 2 shows the averaged temperature values. The highest temperatures were observed in the central part of the fire side of the head in the area of the injector nozzle.

The maximum permissible temperature of the coolant in the standard cooling system of 120°C was already been reached when the engine power was 143.5 kW and $G_f = 0.85B_f^{norm}$. Meanwhile, the maximum temperature in the cylinder head was 228°C.

Further increasing the load on the engine and the fuel supply to the maximum resulted in an excessive increase in the temperature of exhaust gases above the permissible limits.

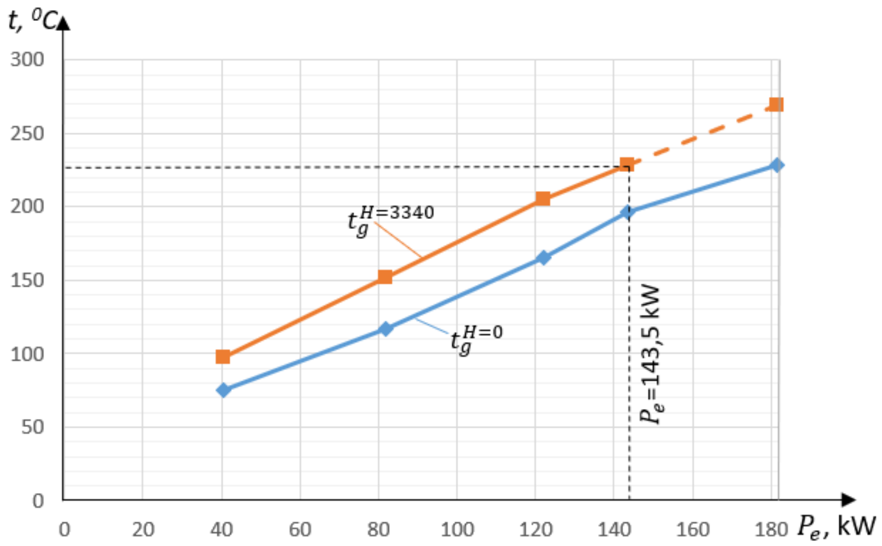

Fig. 2. Thermal state of the fire side of the cylinder head against the load characteristic (n = 2600 min^{-1})

The maximum permissible temperature of exhaust gases is $t_{eg} \leq 750^0 C$, preset by the manufacturer, which corresponds to the maximum effective power (P_e = 143.3 kW), which was provided by the standard cooling system at this height.

In the mode of the maximum power of the engine (P_e = 165 kW) with full fuel delivery and an additional bench-test cooling system, the exhaust gas temperature in the exhaust manifolds of the engine exceeded $t_{eg} \leq 750^0 C$, which is the maximum permissible temperature, and its long-term operation was prohibited to avoid its failure.

Another factor contributing to the thermal load growth on the cooling system is the delay in the fuel combustion process to the side of the power stroke and gas expansion with the intensively growing heat-dispersing surface of the cylinder.

This is indicated by the delayed burning of some of the unburned fuel in the cylinder in the exhaust manifolds and the temperature increase of exhaust gases T_{eg} (Fig. 3).

All the factors mentioned above expedite the deterioration of the standard cooling system and may cause additional limitations to the power of the engine when operating at high altitudes.

Moreover, the magnitude of power shortages due to the efficiency loss of the standard cooling systems of vehicle diesel engines at high altitudes may exceed their power loss due to air density reduction.

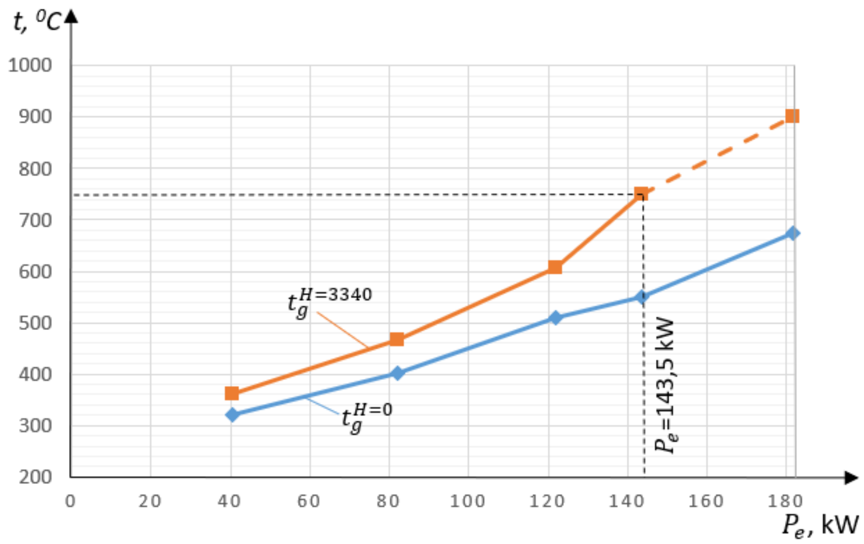

Fig. 3. Engine exhaust gas temperature against load characteristic at n = 2600 min^{-1}

5. CONCLUSIONS

1. Changes in the atmospheric conditions and characteristics of the standard systems of the engine have an effect not only on the technical and economic performance of the engine itself but also on the transport and power plant as a whole. Therefore, a more unbiased evaluation of the range of operating modes of the engine at high altitudes can be outfitted with the standard facility-based systems of the transport and power plant.
2. A reduction in air density at high altitudes leads to the thermal performance degradation of the cooling system due to the heat transfer factor reduction from external heat exchange surface (radiator) and the thermal load increase because of the increase in the performance indicators of the cycle and the heat transmission increase from the working fluid to the coolant.
3. The efficiency loss of the standard cooling system of the transport plant at high altitudes can limit the range of operating modes of the engine and result in a forced additional limitation of load and power of the engine due to the exceedance probability of the maximum permissible temperatures of the cooling system preset by the manufacturer. Moreover, a power shortage due to the thermal performance degradation of the standard cooling system at high altitudes can significantly exceed the magnitude of the forced power loss of the internal combustion engine due to the air density reduction.

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