To the substantiation of charge air parameters on different operating modes of diesel engines of diesel locomotives

O. Ablyalimov [1*]

[1] Tashkent state transport university, 100000 Tashkent, Uzbekistan

Abstract. A numerical method is proposed for quantitative assessment of the specific effective air consumption and the influence of atmospheric air temperature on the working process of a diesel engine, taking into account various modes of its operation. The dynamics of changes in the values of the coefficients of excess air and filling the cylinder with a fresh air charge over the period of the diesel operating process is substantiated depending on the temperature of the outside and charge air, as well as the position of the locomotive driver's controller, obtained in the form of tabular data and graphical dependencies. The possibilities of increasing the fuel efficiency of operating diesel engines up to 5 - 10 percent through quantitative and qualitative regulation of coolant temperatures or through throttling, heating and cooling of charge air are formulated. It is recommended to continue research to improve the quality of the operating process of supercharged transport diesel engines by substantiating the air characteristics of such diesel engines and their subsequent combination with diesel locomotive and fuel characteristics under partial load conditions and, especially, at low ambient temperatures.

1 Introduction

One of the basic systems of diesel locomotives auxiliary equipment, including main ones, is the cooling system of a locomotive diesel engine, the operation of which directly determines its technical life, reliability and efficiency under operating conditions.

As the design of diesel locomotives improves, taking into account the growth of their sectional power, the requirements for the technical condition and performance of the cooling system of diesel locomotives naturally increase.

The fundamental measures for the effective operation of the cooling system of diesel locomotives are to increase the efficiency of the heat dissipation capacity of sections of water-air radiators, taking into account the reduction of their aerodynamic drag and the use of coolant bypass between different circuits of the diesel cooling system.

However, the parameters of charge air and atmospheric air also have a significant impact on the quality of the working process of a diesel engine and, consequently, the diesel locomotive as a whole.

[*] Corresponding author: o.ablyalimov@gmail.com

Numerous works by scientists from far [1-10] and near [11-20] foreign countries are devoted to the issues of increasing the operational reliability and technical life of diesel locomotive diesel engines.

Research by scientists [1-4] concerns the development of technological and technical measures aimed at increasing the efficiency of diesel generator sets, and other research by the authors [5-10] is related to improving the control modes of trains with diesel locomotives along the route and in these works completely questions regarding the justification of the parameters of the cooling system of diesel locomotives are not reflected.

A large number of works, some of which are presented here [11-20], are devoted to research into the efficiency of cooling systems of diesel locomotives in operation, taking into account the influence of the parameters of charge air and atmospheric air at the nominal operating mode of the diesel engine.

Modern cooling systems for diesel locomotives must ensure that, at the nominal operating mode of diesel engines, the water and oil temperatures in front of it are about 90-100 °C at the minimum possible charge air temperature [11]. The best results for these conditions can be provided by low-flow cooling systems [12, 13], the efficiency of which in cooling the charge air can reach approximately 96 percent [11]. At partial loads and when the ambient temperature decreases, the cooling systems must maintain the temperature of water and oil in the diesel engine at a level as close as possible to that indicated above [14].

In accordance with studies [15 – 20], the intensity of charge air cooling should decrease with decreasing load, and at low loads and low ambient temperatures, cooling should be replaced by heating.

However, in these studies [11-20], the issues of choosing the optimal charge air of locomotive diesel engines amount are not sufficiently under frequently changing load operating conditions and outside air temperatures, as well as the operating efficiency of diesel locomotive diesel engines at various degrees of cooling or heating of charge air, depending on the outside air temperature and the operating mode of these diesel engines.

Therefore, theoretical and experimental research in this direction will make it possible to obtain the necessary and useful recommendations for organizing the most efficient working process for diesel locomotive engines, which will ultimately contribute to the implementation of railway transportation of goods and passengers at a level more of higher quality.

2 Objects and methods of research

When creating modern cooling systems, first of all, the problem of ensuring the above-mentioned coolant temperatures for the nominal mode at maximum ambient temperature is solved [18, 20]. The possibility of regulating the temperature of coolants with departure from the nominal operating mode of a diesel engine is laid down when creating cooling systems, but requires a quantitative assessment [11] for special developments and research in terms of constructive support for such capabilities.

On the other hand, the data [23] obtained during rheostat and bench tests of a single-row two-stroke diesel engine 10D100 with counter-moving pistons (factory brand 10DN20.7/2x25.4) made it possible to identify changes in some basic parameters of the diesel operating process depending on the quality and quantitative parameters of atmospheric and charge air, that is, air entering the cylinders with increased density, which is an effective method of increasing diesel power with constant overall dimensions of the cylinders and crankshaft speed.

In addition, the optimal charge air temperature at the inlet to the diesel cylinders, the optimal total excess air ratio were established, and their influence on the efficiency of the diesel operating process was determined.

As shown by the analysis of research results [11-20] and calculations [23], when assessing the quality of the diesel operating process, it is necessary to introduce a new parameter, that is, an efficiency criterion characterizing the level of the specified quality - specific effective air flow, which allows you to most fully assess the quality performance indicators diesel engine at nominal and partial modes of its operation.

This work is devoted to the substantiation of the adopted efficiency criterion and quantitative assessment of the influence of external air temperature on the working process of a diesel engine at nominal and partial modes of its operation, as well as the impact of non-standard conditions arising during the operation of diesel locomotive diesel engines on some parameters of the working process (air) in the cylinder.

The object of the study is a single-row two-stroke diesel locomotive diesel engine 10D100 with counter-moving pistons (factory mark 10DN20.7/2x25.4) and the working process of this diesel engine under various operating conditions.

The subject of the study was the amount of air consumption and the values of the coefficients $\propto_{\text{cycle}}$ of excess air and η_v of filling the cylinder with a fresh charge of air during the diesel operating cycle, depending on the outside air temperature and of the position of the locomotive driver's controller.

To achieve this research goal, the author of this article uses a numerical calculation method taking into account known formulas [22] in the accepted range of changes in outside air temperature T_0 from $T_0 = 233$ °K to $T_0 = 313$ °K with a interval of temperature in $\Delta T_0 = 20$ °K.

The air flow rate G_c at the beginning of compression depends on the reduced air flow rate G_{sp} by the diesel engine, which, according to our calculations and data obtained during testing, fluctuates over a wide range with changes in the temperature T_0 of the outside air. The temperatures and air flow rates after the air cooler significantly affect the excess air coefficient $\propto$, and, consequently, the actual value of the excess air coefficient per cycle $\propto_{\text{cycle}}$ and through it many indicators of diesel performance, including on the indicator η_i and the effective efficiency η_e diesel, indicator p_i and effective p_e diesel pressure and many others.

Let us outline the essence of the numerical method for finding the optimal values of the parameters of the excess air coefficient per cycle $\propto_{\text{cycle}}$ and the indicator η_i coefficient of diesel efficiency during the diesel operating process.

For each of the above temperatures T_0, several temperatures values were taken - T_s of air after the air cooler and T_c of air at the beginning of compression in the diesel cylinder. Based on the calculation data, for each of the determined (calculated) values of G_{sp} and $\propto_{\text{cycle}}$, graphical dependences of them on the diesel engine speed were plotted.

The excess air coefficient, which is directly related to the air flow rate in the diesel cylinder at the beginning of compression, namely:

$$\propto_{\text{cycle}} = \frac{G_c}{q_f \cdot L_0} \tag{1}$$

where G_c - air charge in the cylinder at the beginning of compression, kg/cycle;
q_f - fuel supply per cycle, kg/cycle;
L_0 - theoretically required amount of air for combustion of 1 kg of fuel, kg

$$G_c = \frac{10^4 \cdot p_c \cdot V_c}{R \cdot T_c \cdot (1+\gamma_{fg})} \tag{2}$$

where V_c - volume of the cylinder at the beginning of compression, liter;
$= 1{,}1 \cdot p_s$ - pressure in the cylinder at the beginning of compression, Pa (kg/sm^2);
γ_{rg} - residual gases coefficient;
R - gas constant, J/(mol °K);

p_s - air pressure after air cooler, Pa (kg/sm^2).

The deviation of the actual value of the coefficient $\propto_{cycle}^{val}$ of excess air from the calculated one $\propto_{cal}$, for which the fuel consumption according to the locomotive characteristic and the calculated air consumption G_{cal} are set, can be represented by the following expression [22]:

$$\overline{\alpha} = \frac{\propto_{\text{cycle}}}{\propto_{cal}} = \frac{(1-\frac{\Delta p_{val}}{p_{cal}})\cdot(\frac{T_k}{T_0}-\frac{\Delta T_{val}}{T_s})}{(1-\frac{\Delta p_{cal}}{p_k})\cdot(\frac{T_k}{T_0}-\frac{\Delta T_{cal}}{T_s})} \tag{3}$$

where Δp_{val}, Δp_{cal} - reduction in charge air pressure (actual and calculated) in the air cooler, kg/sm^2;

p_0, T_0 - pressure (Pa, kg/sm^2) and temperature (°K) outside air;

T_s - charge air temperature after the air cooler, °K;

p_k, T_k - pressure (Pa, kg/sm^2) and temperature (°K) air in front of the air cooler;

ΔT_{cal}, ΔT_{val} - calculated and actual reduction in charge air temperature in the air cooler, °K. |

Let us now consider the influence of the parameters of atmospheric (external) and charge air on the coefficient η_v of filling the cylinder with a fresh air charge.

The indicated filling coefficient η_v under boost conditions is determined by the following expression

$$\eta_{vk} = \frac{G_c}{G_k} \tag{4}$$

and according to external (atmospheric) conditions

$$\eta_{v0} = \frac{G_c}{G_0} \tag{5}$$

where G_k - weight of air in the working volume of the cylinder according to boost parameters, kg/cycle;

G_0 - weight of air in the cylinder according to external atmospheric conditions, kg/cycle.

The weight of air in the working volume of the cylinder according to the boost parameters is calculated using the following formula

$$G_k = \frac{10^4 \cdot p_s \cdot V_h}{R \cdot T_s} \tag{6}$$

The weight of air in the cylinder according to external atmospheric conditions is determined using the following formula

$$G_0 = \frac{10^4 \cdot p_0 \cdot V_h}{R \cdot T_0} \tag{7}$$

where V_h - working diesel cylinder displacement, liter;

p_s - pressure after centrifugal supercharger, Pa (kg/sm^2);

T_s - air temperature in the purge receiver after the air cooler, °K.

Each of the values of the cylinder charge with air at the beginning of compression G_c refers to the values G_k and G_0, calculated at different values of T_k and T_0.

3 Results and their discussion

The final data on the actual value of the excess air coefficient $\propto_{\text{cycle}}$ for the diesel operating cycle are given in table 1, where the value T_s is the temperature of the charge air after the air cooler. Moreover, taking into account the large values of the coefficient γ_{rg}, in partial operating modes their influence on the above can be neglected. A sharp increase in the actual

value of the coefficient $\propto_{\text{cycle}}$ of excess air per cycle at low temperatures T_0 of external air in partial operating modes of diesel can be explained by the incompatibility of the characteristics of air charging units with the characteristics of the diesel engine under these conditions.

As can be seen from the above data, the temperature T_s of the charge air after the air cooler significantly affects many indicators of diesel performance, both inside the cylinder - these are the indicator pressure p_i and the efficiency coefficient η_i, the actual coefficient $\propto_{\text{cycle}}$ of excess air during the diesel operating cycle, and after it - these are effective pressure p_e and efficiency η_e and many others. Note that the maximum value of η_i corresponds to well-defined values of the actual coefficient ∝_cycle of excess air per diesel engine operating cycle.

As a result of our research, we have established that at the 7-15th positions of the driver's controller for the 10D100 diesel engine, the optimal values of the excess air coefficient are in the range $\propto_{\text{cycle}}$ = 3.0 – 3.5 units, which agrees quite well with the data of the works [16, 18, 19]. With a further increase in the coefficient $\propto_{\text{cycle}}$, a decrease (reduce) in the value of η_i occurs, and at low engine speeds, the indicated value of η_i decreases more intensively. This is explained by the fact that with significant (large) values of the actual coefficient $\propto_{\text{cycle}}$ of excess air during the diesel operating cycle, the relative heat losses into the cooling system increase and therefore the mixture formation due to injection significantly deteriorates a small portion of diesel fuel into the cylinder.

Table 1. Dynamics of change in the coefficient $\propto_{\text{cycle}}$ of excess air per cycle depending on the diesel operating mode and outside air temperature T_0

Driver controller position n_c	Outdoor temperature T_0, °K Charge air temperature after air cooler T_s, °K					
	233/248	253/268	273/288	293/308	313/328	333/348
1	2	3	4	5	6	7
Actual (real) coefficient $\propto_{\text{cycle}}$ of excess air for the cycle of diesel engine operation						
1	11.20	10.40	9.70	9.10	8.50	7.90
3	3.36	3.10	2.88	2.71	2.52	2.35
5	2.51	2.32	2.16	2.02	1.91	1.76
7	2.52	2.33	2.17	2.03	1.92	1.77
9	2.45	2.26	2.11	1.97	1.83	1.72
11	2.66	2.46	2.29	2.14	2.01	1.87
13	2.84	2.64	2.45	2.29	2.15	2.01
15	3.30	3.06	2.85	2.67	2.51	2.38

Source: «Compiled by the author».

The "fresh" air charge in the cylinder depends on the reduced air flow rate of the diesel engine, which, according to our calculations [21, 22] and data obtained during tests with various combinations of outside air temperature T_0, varies over a wide of range.

Particularly unfavorable are idle modes and operation of a diesel engine under load with a low number of crankshaft revolutions. The optimal values of the excess air coefficient $\propto_{\text{cycle}}$ per the diesel operating cycle for each position of the locomotive driver's controller,

which correspond to the maximum values of the indicator η_i and relative indicator $\eta_{rel\,i}$ efficiency coefficient, are given in table 2.

Thus, based on the analysis carried out, it was established:

- at small positions of the diesel locomotive driver's controller, the actual value of the excess air cycle coefficient $\propto$ for the diesel operating cycle is much higher than its optimal indicators, approximately 2.16 – 5.83 times. To get the diesel engine to economical operating mode at a temperature of $t_0 = +20$ °C, approximately up to the 12th position of the locomotive driver's controller, reduce the air supply to the diesel cylinders or implement its heating, especially when working at small positions of the diesel locomotive driver's controller under load and on mode of idle speed. This can be done by bypassing water, air and exhaust gases;
- at driver of diesel locomotives controller positions above $n_c = 12$ at $t_0 > +20$ °C, it is necessary to increase the amount of air supplied to the cylinders, since the actual values of the coefficient $\propto_{cycle}^{val}$ are lower than the optimal values of the coefficient α_{cycle}^{opt}. This can be achieved by increasing the boost pressure air. At the same time, the greater the value of the excess air coefficient $\propto_{\text{cycle}}$ for the diesel operating cycle at $t_0 = idem$, the faster the combustion process will proceed, because there will be more oxygen per unit (one portion) of diesel fuel.

Table 2. Dynamics of changes in optimal and actual (real) values coefficients $\propto_{\text{cycle}}$ of excess air per cycle depending on the operating mode of the diesel engine

Coefficient $\propto_{\text{cycle}}$ of excess air per diesel operating cycle	Driver controller position n_c						
	1	3	5	9	11	13	15
1	2	3	4	5	6	7	8
Optimal α_{cycle}^{opt}	1.92	2.28	2.64	3.28	3.30	3.42	3.50
Valid $\propto_{cycle}^{val}$	11.20	7.00	5.70	4.70	4.10	3.80	3.50

Source: «Compiled by the author».

The highest value of the indicator efficiency coefficient η_i of a diesel engine will only be when the combustion process occurs instantly. To obtain the maximum efficiency of a diesel engine, it is necessary (and is follow) to achieve an increase in the intensity of the combustion rate. Therefore, the best (most profitable) operating mode of most diesel engines in terms of efficiency is not the nominal one, but the mode with a slightly lower load, about 0.85 - 0.90 units from the nominal one, that is, at large values of the coefficient $\propto_{\text{cycle}}$ of excess air per working cycle of a diesel. The difference in the values of the coefficient $\propto_{\text{cycle}}$ (see table 1) compared to other diesel operating modes is explained only by the discrepancy between the supply of fuel and air to the diesel cylinders.

The dynamics of changes in the ratio of the values η_v/η_{vb} and η_{vo}/η_{vob} depending on the temperature T_s of the air in the purge receiver after the air cooler for some operating modes of the 10DN20.7/2x25.4 diesel engine is shown in fig. 1 and fig. 2, on which the ordinate axis indicates $Z_1 = \frac{\eta_{vk}}{\eta_{vkb}}$ and $Z_2 = \frac{\eta_{vo}}{\eta_{vob}}$, and the abscissa axis shows the values of $\frac{\eta_{vk}}{\eta_{vkb}}$ with a solid line and the dash-dotted line indicates the values $\frac{\eta_{vo}}{\eta_{vob}}$.

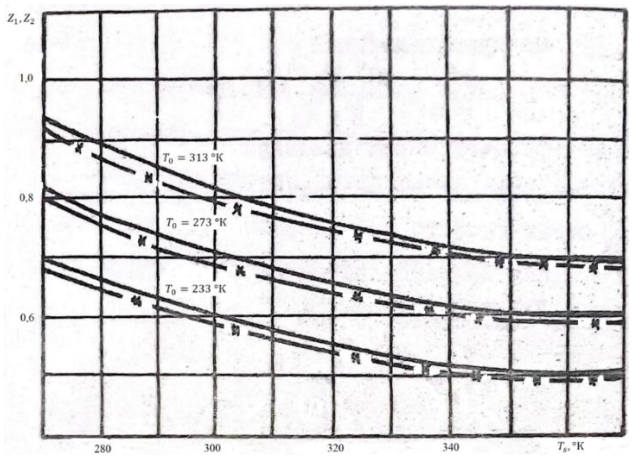

Fig. 1. Change in the relative coefficients of filling the 10D100 diesel engine with air at the crankshaft speed n_{en} = 400 rev/min. Source: «Compiled by the author».

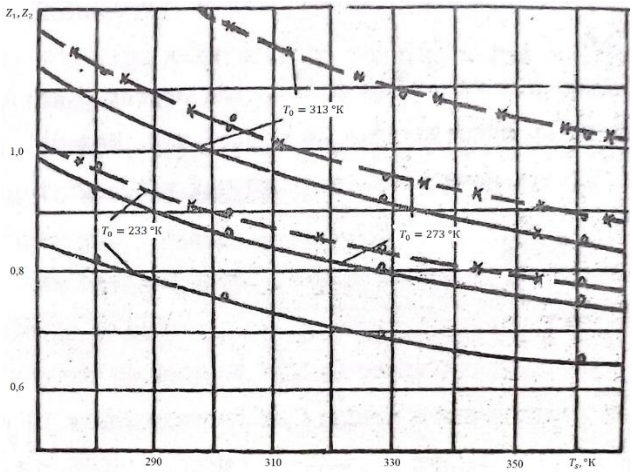

Fig. 2. Change in relative filling factors of diesel 10D100 air at crankshaft speed n_{en} = 590 rev/min. Source: «Compiled by the author».

The nature of the change in the values of η_{vk} and η_{v0} for other diesel operating modes is similar to that shown in fig. 1 and fig. 2. The index "b" indicates parameters under normal atmospheric conditions - these are the pressure and temperature of the outside air, respectively, at p_0 = 760 mm. rt. pillar and at T_0 = 293°K.

4 Conclusion

Based on the above, the following general conclusions and suggestions can be made:

- for existing transport diesel engines at partial load operating modes, the amount of charge air does not correspond to the amount of fuel supplied, which causes incomplete combustion of the working mixture and the release of fuel that has not had time to burn into the atmosphere;
- it is necessary to achieve compatibility of the fuel and air characteristics of a diesel engine in all operating modes under various external atmospheric conditions;

– when all these measures are applied together with a reduction in fuel consumption in partial modes, it is possible to increase (improve) the fuel efficiency of operating diesel engines by 5 - 10 percent.

Further work in this direction is related to the substantiation of the air characteristics of a supercharged diesel engine and their subsequent combination with diesel locomotive and fuel characteristics under conditions of partial loads and, especially, low ambient temperatures. In addition, possibilities for regulating the amount and temperature of charge air through throttling, bypass or heating and cooling should be further explored.

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