Experimental research of the diesel engine with modernized system of air supply

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Abstract. This article deals with experimental research of the diesel engine with modernized system of air supply (MSAS). This system considers steam injection in turbo-compressor which provides increase of its power and also increase air supply in engine cylinders. The results of the experiment show that specific fuel consumption will be decreased on 2.6%, gas temperature before turbocompressor will be decreased on 87 °C. Indeed, diesel power increase of 4% (from 617 kW) was achieved without increase of the cylinder heat temperature.

1. Introduction
Creation of efficient engines is an actual task in conditions of modern economics. That’s why solution of this task is complicated by the fact of limited amount of experimental data about modernized system of air supply (MSAS). Only the results of an experiment conducted by Krivov and Sinatov [1] are known. They conducted they experiment on 6ChN 12/14 diesel. In their experiment, flow rate of the steam which was rejected from steam generator of heat utilizing system to the turbine flow part was equal to 20% of total gas flow rate, air/to/fuel ratio was increased up to18%, and specific fuel consumption was decreased up to 5.3% on nominal load. It was shown that it is possible to increase diesel power output up to 16-17% by means of modernization of air supply system.

It is necessary to note that specified research about MSAS was performed at small-scale low-pressure ($P_{me}<0.1$ MPa) diesel engine with vortex mixture formation during long operation at constant load equal to 85% of nominal. That’s why it is impossible to utilize this data for experimental research of the high-pressure ($P_{me}=1.62$ MPa) large-scale engine 6ChN21/21 operating at variable load characteristics.

Theoretical researches and developed earlier calculation algorithm [2] for MSAS require experimental justification of its efficiency that’s why purposes of presented work are:

- justification of MSAS design solutions and diesel engine with MSAS operating ability;
- diesel engine with MSAS operation efficiency on the regime of partial load;
- Checking of the correctness of main statements of the diesel engine with MSAS parameters calculation algorithm.

2. Modernized system of air supply
This system considers steam injection in turbo-compressor which provides increase of its power and also increase air supply in engine cylinders. Turbo-compressor power is increased by working fluid flow rate increase in the form of steam-gas mixture. Temperature of the steam-gas mixture is decreased because steam has lower temperature than exhaust gas. Further, increase of the air flow rate through engine causes decrease of the specific fuel consumption and temperature of the exhaust gases, which in turn increases durability of entire power plant. System itself consists of simple equipment such as water storage tank, which can be located in any suitable place and have almost any configuration and its volume is estimated from necessary water margin considering real operation regimes of exact energy plants. Water pumps, which provide water pumping from water margin tank into steam generator. Generated steam is pumped through the valve by duct on selected area of the turbocompressor nozzle vanes. Heat source for steam generation is a heat of the exhaust gases. Dimensions of the steam generators are determined from necessary steam flow rate for its charge in engine. Having such system gives an opportunity to inject small portion of steam on transient regime (i.e. during power increase) which provide transient process duration decrease and also pollution exhaust decrease from incompleteness of combustion. This fact causes increase of the energy plant ecological characteristics. Further, analysis [3] shows that additional effect can be expected from MSAS system application. Scheme of the described plant is presented on figure 1.

Figure 1. Principal scheme of the diesel engine with MSAS.

3. Experimental research of the engine with MSAS
Experimental research of the high-pressure diesel engine 6ChN21/21 operation with MSAS was carried out according to a program which consists of three stages.
First stage includes determination of diesel engine with MSAS parameters during its operation/
Steam was charged to a selected area of gas turbine nozzle of the turbocompressor. Sketch of the steam supply is presented on figure 2. External view of the steam supply system is presented of figure 3. Diesel engine with MSAS mounted on experimental unit is presented on figure 4.
Measurement of diesel engine operation parameters was performed on fixed values of power on the two regimes of power values with and without MSAS application.
Steam which was used during experiments has values of temperature \( T_s = 402\ldots406 \) K and pressure 0.26...0.29 MPa. Due to lack of steam generator, steam was ejected to steam ducts from factory steam system. Diesel engine parameters at its operation with MSAS was compared with parameters, obtained by calculation at fuel rates of experiment.
Comparison of the experimental and calculation data is presented in table 1 and its graphic interpretation is presented on figure 5.
Results of the research shows turbocompressor rotor rotation frequency is increased on 800...1200 r/min or 2.5...4.4%, air flow rate was increased on 4...5.5%, fuel rate was decreased on 2.4...3.0 g/kWh or 1.0...1.3%.

This positive effect from MSAS application is explained by the fact that steam adding on the sector of turbine nozzle is equivalent to decrease of the turbine flow section which causes increase of the average pressure before the turbine and consequently, expansion ratio and turbocompressor rotation frequency. Increase of the turbocompressor power causes increase of the diesel air supply and its indicator and efficiency values.

**Figure 2.** Steam supply to a nozzle area: 1 – tube of external steam duct; 2 – Connection flange; 3 – inner steam duct; 4 – steam ducts connection coupling; 5 - coupling bolt; 6 – clamp of steam duct mounting to nozzle shell; 7 – exhaust tubes shell; 8 – turbocompressor shell; 9 - special area of steam adding; 10 – steam nipple; 11 – sector of steam adding; 12 – protection shell of gas duct of turbocompressor.

**Figure 3.** Appearance of gas duct of turbocompressor with sector of steam adding.
Comparison of experimental and calculation data shows small discrepancy (1.2% at air flow rate, 1.8% at gas temperature after turbine, 1.0% at specific fuel consumption). Thus, experimental researches of the engine with MSAS confirms correctness of main statements of suggested calculation algorithm.

Simultaneously, experimental research shows big opportunity for increase of economic efficiency and decrease of heat intensity, particularly in cylinder top, hypothecated in developed MSAS. Indeed, during the experiment at diesel engine operation at load characteristics on the regime of $P_e = 845\, \text{kW}$ и $n = 25\, \text{Hz}$, steam adding to a gas turbine at flow rate of 0.12 kg/s (432 kg/h) causes increase of the flow rate on 0.05 kg/s (3.3%) and air-to-fuel ration on 0.09 (4.6%), as well as decrease gas temperature before turbine on 15 $^\circ\text{C}$ (1.6%) and specific fuel rate on 3 g/kWh (2.6%).

In the meantime, when the steam is added at amount equal to calculation value for a given regime (0.196 kg/s or 705 kg/h), values of $G_{qir}$ and $\alpha$ should correspondingly be decreased at 6 and 8.7% and values of $T_{g1}$ and $b$ should be decreased correspondingly at 87 $^\circ\text{C}$ (8.3%) and 6 g/kWh (2.6%).
Estimation of MSAS efficiency on its operation on diesel engine with increase resistance on the exhaust was performed on second stage of experimental research. Research algorithm in this case considers determination of the diesel engine operation parameters with and without MSAS at different resistances on the exhaust system. Results of the research are presented at table 2 for the three regimes of diesel operation at load characteristics. These results shows that MSAS utilization allows to compensate hazardous influence of increased resistance because it allows to decrease fuel flow rate and gas temperature before the turbine. Effect of MSAS utilization will be higher in case when diesel operates with higher power output and when temperature of the gas before the turbine is closer to maximum allowed value. Indeed, during diesel engine operation at $P_e=551$ kW and $P_{g2}=2.95$ kPa application of the MSAS allows to decrease $T_{g1}$ from 821 to 817 K (i.e. on 4 K), meanwhile during diesel engine operation at $P_e=845$ kW and $P_{g2}=2.5$ kPa application of the MSAS allows to decrease $T_{g1}$ from 933 to 916 K (i.e. on 15 K).

Table 1. Comparison of experimental and calculation parameters of diesel engine operation with MSAS at load characteristics ($n=25$ Hz).

| Parameter                                      | Index | Dimension | $P_e=672$ kW | $P_e=845$ kW |
|------------------------------------------------|-------|-----------|--------------|--------------|
| Steam flow rate of the experiment             | $G_s$ | kg/s      | 0.0869       | 0.0869       |
| Steam fraction of total mass of the mixture   | $g_s$ | %         | 6            | 6            |
| Exhaust gases fraction of total mass of the mixture | $g_e$ | %         | 94           | 94           |
| Temperature of the exhaust gases before turbocompressor | $T_{g1}$ | K       | 883          | 868          |
| Temperature of the mixture before turbocompressor | $T_{sg1}$ | K      | -            | 933          |
| Pressure of the working fluid before compressor | $P_{g1}$ | MPa     | 0.223        | 0.231        |
| Pressure of the air after turbocompressor     | $P_{int}$ | MPa     | 0.228        | 0.309        |
| Air flow rate                                 | $G_{air}$ | kg/s   | 1.307        | 1.336        |
| Temperature of the working fluid after turbocompressor | $T_{g2}$ | K      | 759          | 730          |
| Indicated efficiency                          | $\eta_i$ | %       | 46           | 45.1         |
| Net efficiency                                | $\eta_e$ | %       | 36.8         | 36.64        |
| Effective specific fuel consumption rate       | $b$    | g/kWh    | 233.9        | 227.5        |
| Air/to/fuel rate                              | $\alpha$ | -     | 2.08         | 2.05         |

Table 2. Change of the diesel engine operation parameters depending on operation conditions.

| Diesel power engine, kW | No MSAS | with MSAS |
|-------------------------|---------|-----------|
| $P_{g1}$, kPa           | 1.85    | 2.95      |
| $b$, g/kWh              | 239.4   | 240.4     |
| $T_{g1}$, K             | 816     | 821       |
| $b$, g/kWh              | 236.2   | 236.4     |
| $T_{g1}$, K             | 809     | 817       |
| $P_{g2}$, kPa           | 2.00    | 3.80      |
| $b$, g/kWh              | 236.6   | 237.2     |
| $T_{g1}$, K             | 843     | 854       |
| $b$, g/kWh              | 234.2   | 234.5     |
| $T_{g1}$, K             | 834     | 844       |
| $P_{g3}$, kPa           | 2.5     |           |
| $b$, g/kWh              | 230.5   |           |
| $T_{g1}$, K             | 933     |           |
| $b$, g/kWh              | 227.5   |           |
| $T_{g1}$, K             | 918     |           |

This feature should be considered during creation of high-pressure engines, because it allows widening limitation of exhaust counter-pressure requirements. As it can be concluded from the table 2,
pressure resistance on the exhaust can be increased on 1.1...1.8 kPa at regimes of 551 kW and 617 kW without increase of the exhaust gas temperature. Thermometering of the cylinder head was performed on the third stage of the research to determination MSAS influence on its thermal stress parameters.

Figure 6. Scheme of the thermocouples mounting at bottom of the cylinder head.

Locations of thermocouples mounting are presented on figure 6. Results of the thermometering of the most distinct location are presented at table 3. As it can be seen from the table, decrease of the cylinder head temperature even at decreased flow rates compared to design values is 5...9 degrees. Approximate estimation of the authors allows to make hypotheses that application of the MSAS with design values of steam flow rates will cause decrease of the cylinder head temperature on 12...20 degrees.

Table 3. Results of thermometering of cylinder head with and without MSAS.

| Point | Temperature value, K |
|-------|----------------------|
|       | P_e = 617 kW | P_e = 845 kW |
|       | without MSAS | with MSAS | without MSAS | with MSAS |
| 1     | 493           | 490       | 559           | 554       |
| 3     | 627           | 619       | 664           | 655       |
| 6     | 491           | 488       | 575           | 569       |
| 7     | 578           | 572       | 634           | 628       |
| 8     | 564           | 558       | 630           | 623       |

Thus, application of the MSAS as well as developed enhanced design of the cylinder head will promote decrease of the thermal stress and increase of the head operating ability.

From the other side, experimental research shows that decrease of the cylinder head temperature during diesel engine operation with MSAS gives an opportunity to increase engine power without increase of cylinder head temperature. Indeed, diesel power increase of 4% (from 617 kW) was achieved without increase of the cylinder heat temperature in most distinct locations.

Thus, all purposes of the experimental research are achieved, such as design solutions of steam adding to a turbocompressor nozzle are checked; efficiency of the developed MSAS is confirmed and deviations between calculation parameters of diesel operation with MSAS with experimental data are satisfactory small.
4. Conclusions
On the base of obtained experimental data a conclusion can be made about MSAS application efficiency within energy plants suited for different purposes. Enhancement of the engine performance is achieved by decrease of the specific fuel consumption and cylinder head temperature.

References
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