Numerical study of the processes in the combustion chamber of an engine of diesel generator facilities with valve-inductor generators

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Abstract. A mathematical model of heat and mass transfer processes in the combustion chamber of diesel generator sets with valve-inductor generators has been developed. The main characteristics of a diesel generator have been analysed within a wide range of operating modes.

1. Introduction
Diesel generator facilities are traditionally used as local sources of electric power generation. At the same time, one of the main requirements for them is to maintain a stable rotation frequency when the electric load changes in a wide range. It means the necessity to maintain stable values of the frequency and voltage of the generated electricity that is ensured by appropriate construction of the shaft speed controllers of the drive motor. Most often, such sources of generation most of the time operate at a load, that is less than the nominal one, which leads to excessive consumption of diesel fuel and reduced lifetime of the diesel engine. In a number of works, it is proposed to save diesel fuel and extend the life of the engine by the regulation of its shaft speed depending on the load function of the electric network [1-3]. However, at the same time, there remains a need to ensure stable values of voltage and frequency in the electric network supplying electricity to consumers. These and other requirements to a greater extent correspond to recently developed diesel generator facilities with variable rotation frequency. This is a new type of generating equipment using valve-inductor generators, which has a number of advantages over today's widely used diesel generator facilities with synchronous generators. The main advantages are: reduced fuel consumption (by 15–30%), larger operating ranges of power with optimal drive mode, and longer life of equipment.

Since their application diesel engines have always been equipped with crankshaft rotation frequency regulators, but since they were originally intended to equip vehicles of various purposes (automobiles, tractors, military vehicles, etc.), the main task of such regulators was and remains to provide stable set rotation frequency under varying load. The changes in the rotation frequency setting are supposed to be done manually by means of a special device in this case. The regulator's task remains essentially the same in diesel engines of diesel generator facilities with synchronous generators, but with the only difference being that the rotation frequency must always remain constant in order to maintain the frequency of the generated voltage unchanged.
The transient processes occur in the combustion chamber during an automatic control of the diesel engine rotation frequency. The engine runs at a speed different from the nominal one; as a result, the emissions as well as the fuel consumption may increase. It is also necessary to take into account the change in heat dissipation of the engine in various operating modes and loads. To optimize the operation of diesel engines as part of variable-speed diesel generator facilities, it is necessary to develop a complex mathematical model. So the purpose of this study is to develop a mathematical model of heat and mass transfer processes in the combustion chamber of diesel generator facilities with valve-inductor generators.

2. Mathematical model

The study is conducted for widely used diesel generator facilities in a wide range of crankshaft speed. A six-cylinder in-line diesel engine is considered. The working volume of all cylinders is 6.6 l. The cylinder diameter is 105 mm, the piston stroke is 128 mm, the connecting rod length is 320 mm. The compression ratio is 17. The rotational speed of the crankshaft at nominal power is 2300 rpm. A closed nozzle with multi-jet spraying with seven jets and a nozzle diameter of 0.182 mm is considered. The maximum injection pressure provided by the fuel system was 180 MPa. The ambient temperature in the calculations is 293 K. The temperature of the fresh charge, taking into account air cooling in the cooler, is assumed to be 399 K. The average wall temperature is 450 K.

To simulate the processes occurring in the combustion chamber, a mathematical model of combustion processes taking into account the characteristics of injection, ignition and combustion of the fuel mixture is developed. The model is developed based on the ANSYS® Forte CFD software package. The spatial geometry of the computational domain, representing the inside of the combustion chamber of a diesel engine is constructed. Since the geometry is axisymmetric a 45° sector is taken in order to reduce the estimated time (figure 1). A multi-block structured curvilinear grid consisting of 230,000 computational cells is used for calculations (figure 1). Methodological studies have shown that such detailing is quite sufficient to obtain a grid-independent solution.

![Figure 1. The geometry of the computational domain and the computational mesh.](image)

The Lagrangian dynamic mesh method (ALE) is used to calculate the piston movement. During the movement of the piston, the computational cells are deformed together with a decrease in the volume of the combustion chamber. To model turbulence, the unsteady RANS $k$-$\varepsilon$ model of turbulence for Re-Normalisation Group (RNG) is used.

The full-cone model, which includes atomization of the fuel, breakup of its droplets, their collision and coalescence, as well as evaporation is used to simulate the atomization of diesel fuel. In this case, the initial characteristics of the spray (droplet diameter and their speed) are determined empirically using the nozzle flow rate coefficient. To simulate the further decay and breakup of fuel droplets, the Rayleigh–Taylor model [4] is used.
To simulate the evaporation of droplets, a multi-component model is used. That evaporation model considers a spherical drop of liquid, which consists of a finite number of components that evaporate without chemical reactions in a gaseous medium [5]. A generalized model of the interaction of turbulence and chemistry (from Kong et al. [6]), which is widely used for simulating the diesel engines, is applied to model the effect of turbulence on the kinetics of fuel combustion. That model assumes that the rate of a chemical reaction is partially limited by the speed of turbulent mixing. For this, an effective time scale is introduced into the model, which is the sum of the characteristic time scale of mixing and the characteristic time scale of the chemical reaction. The characteristic mixing time is determined from the turbulent characteristics of the flow, and the characteristic chemical reaction time is determined from the solution of the equations of chemical kinetics. Diesel fuel is represented as a surrogate fuel model: n-heptane (C\textsubscript{7}H\textsubscript{16}) and a mixture of n-decane (C\textsubscript{10}H\textsubscript{22}) and A\textsubscript{2}CH\textsubscript{3} in a mass ratio of 67% and 33%, respectively. To simulate the kinetics of combustion of diesel fuel in the gas phase, the kinetic mechanism (Diesel_1COMp_35sp_CHem.iNp), containing 74 elementary reactions and 35 gas components is used. Radiative heat transfer is modelled using the discrete ordinate (DO) model; and the absorption coefficient is calculated using the weighted sum of grey gases model (WSGGM). To simulate the formation of soot in the combustion chamber of a diesel engine, a two-stage model, consisting of competing mechanisms of formation [7] and oxidation [8] of soot particles, is used.

The transfer equations are discretized using the control volume method on an unstructured grid. The connection of the velocity and pressure fields for an incompressible fluid is realized using the SIMPLE procedure. The quasi-second-order upwind (QSOU) method is used to approximate the convective terms of the equation for the momentum components. To approximate the convective terms of the equation for turbulent characteristics, a second-order upwind scheme is used. The unsteady terms are approximated using an implicit first-order scheme. The diffusion terms are approximated by a second-order scheme.

3. The simulation results

Analysis of the characteristics of a diesel generator is carried out within a wide range of operating modes. Figure 2 shows the operating integral characteristics of the propulsion system depending on the rotational speed of the crankshaft. As is seen, within the adjustment range from 1000 to 2300 rpm, the power and energy characteristics change very significantly. Under these conditions, the use of generator sets with variable rotational speed will be the most optimal, because this allows using the diesel engine as efficiently as possible, adjusting it to the electrical load of the network.

![Figure 2. Power and torque depending on the rotational speed of the crankshaft.](image)

However, a very important circumstance is a significant influence of the operating mode of the diesel generator on its environmental performance. As an example, figures 3-4 show local distributions of
velocity magnitude and carbon oxide in the combustion chamber for three different engine operating modes. Emissions of harmful substances significantly increase in modes that are far from optimal. Thus, in particular, the local values of soot emissions when increasing the rotational speed of the crankshaft from 1000 to 2300 rpm are reduced by more than two times, the local values of nitrogen oxides decrease 1.7 times, while the underburning of high-molecular hydrocarbons decrease by 30%. At that, as it is seen, the scatter of local temperature in the combustion chamber does not exceed 100 degrees.

![Figure 3](image1.png)

**Figure 3.** Distribution of the velocity magnitude in the combustion chamber of the engine for different speeds of the crankshaft (a – 1000 rpm, b – 1800 rpm, c – 2300 rpm).

![Figure 4](image2.png)

**Figure 4.** Distribution of the mass fraction of carbon oxide in the combustion chamber of the engine for different speeds of the crankshaft (a – 1000 rpm, b – 1800 rpm, c – 2300 rpm).

However, as the rotational speed of the crankshaft increases, the amount of fuel and air mixture supplied to the combustion chamber also increases. Therefore, even though local values of harmful emissions in low-rotational speed modes may be lower, gross emissions usually tend to increase with increasing rotational speed. In this regard, to optimize the operation mode of diesel generator sets in terms of environmental characteristics, it is more rational to analyze the emission values reduced to the power. Figure 5 shows the correlation between specific soot emissions and crankshaft rotational speed.
of rotation. As is obvious, the specific emissions of soot, in this case, are increasing. At the same time, calculations show that the specific emissions of nitrogen oxides decrease with increasing rotation rotational speed. Thus, when improving diesel generators with the variable rotational speed it is necessary to take into account many different factors that are non-linearly related to each other, including environmental performance. In this case, the optimization problem arises. The developed mathematical model allows performing this kind of optimization.

![Figure 5. The emissions of soot particles and NOx depending on the crankshaft rotational speed](image)

**Conclusion**

A mathematical model of heat and mass transfer processes in the combustion chamber of diesel generator sets with valve-inductor generators has been developed. The mathematical model takes into account the actual geometry of the combustion chamber and the operating conditions of the diesel engine.

Numerical simulation of heat exchange and combustion processes in the combustion chamber in the range of crankshaft rotation frequency from 1000 to 2300 rpm has been carried out. The features of the behavior of local and integral characteristics of the engine combustion chamber have been investigated. The dependences of the engine power and torque on the crankshaft rotation speed have been obtained. Also, in the course of calculations, the dependences of emissions of soot, nitrogen oxides and carbon oxides have been obtained at various engine operating conditions.

The developed mathematical model will be combined with the mathematical model of the electrical part of the generator, and a digital twin of the diesel generator set with a valve-inductor generator will be developed on this basis.

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