Досліджувалася проблема підвищення енергоефективності систем полегшення пуску дизельних двигунів за рахунок підігрівання повітряного заряду. В основу підвищення енергоефективності закладено підігрівання лише частини заряду. У результаті в циліндрі двигуна утворюється повітряний заряд, що складається з двох шарів повітря з різною температурою.

Для обґрунтування нового методу полегшення холодного пуску багатолітрового дизельного двигуна проведено чисельне дослідження стиснення різнотемпературного повітряного заряду в двигуні. Чисельно досліджувалася зміна температурного поля заряду під час стиснення з урахуванням вихрових потоків, що виникають при формуванні заряду в циліндрі двигуна на прикладі двигуна типу 6ТД. З аналізу температурного поля заряду виявлено наявність умов для надійного самозаймання палива у заряді під час його стиснення. Для формування двох шарів повітря, що мають різну температуру, за умов моделювання задавалося спочатку нагнітання холодного повітря в циліндр двигуна при температурі 253 К. Далі здійснювалось нагнітання підігрітого повітря при температурі 773 К. Об'ємна доля підігрітого повітря в заряді склала 10 %.

За результатами моделювання виявлено, що при стисненні зберігається наявність шарів заряду з різними температурами. Підтверджено досягнення температури самозаймання палива в попередньо підігрітому шарі повітря при температурі впускного повітря – 20 °C.

Отримані результати можуть бути використані для обґрунтування вимог до енергоефективних систем полегшення холодного пуску дизельних двигунів

Ключові слова: холодний пуск, дизельний двигун, чисельне дослідження, процес стиснення, полегшення пуску

UDC 621.436
DOI: 10.15587/1729-4061.2018.150376

NUMERICAL STUDY OF THE PROCESS OF COMPRESSING A TURBULIZED TWO-TEMPERATURE AIR CHARGE IN THE DIESEL ENGINE

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1. Introduction

In the diesel engines fuel ignition occurs by compressing the air charge in the engine's cylinder. During compression, there is an increase in the pressure and temperature of the charge. The reliable ignition and rapid fuel combustion, which is injected into the engine's cylinder, temperature of the air charge must exceed 450–500 °C [1, 2].

When starting an engine at low ambient temperatures, temperature of the air charge may not reach the specified limit, which leads to a failure in the engine start or to an increase in the emission of harmful substances. A decrease in the charge temperature is due to the following processes. When the air charge is compressed, it is cooled by the cold walls of the engine's cylinder. There occurs an increase in the leakage of part of the air charge due to the lowered seal in the pair piston-barrel due to the insufficient thermal expansion of cold parts of the engine's cylinder-piston group.

In engines with a turbocharger, the starting rotations are accompanied by a decrease in the degree of compressor compression, which also reduces the temperature of the intake air. In these cases, auxiliary means are used to facilitate the start of internal combustion engines.

As regards powerful engines, there are commonly applied auxiliary means for a cold start, which enable the heating of an engine in general or the heating of air that enters the engine's cylinder [3]. Warming up an engine in general is energetically costly and requires a lot of time [4]. Heating the intake air is more energy efficient compared to energy consumption when warming up an engine. However, this method for start facilitation has certain disadvantages. In particular, the application of torch air heaters leads to a significant reduction in the concentration of oxygen in the intake air, which causes a failure to start or a prolonged engine start. Electric air heaters require excessive high power, which leads to the additional load on a rechargeable battery with a corresponding decrease in the probability of starting the engine [5, 6]. In order to increase energy efficiency of the start, it was proposed to heat only a part of the intake air to create a two-temperature air charge in the engine's cylinder [1].

Thus, it is a relevant task to improve energy efficiency of the systems that would facilitate the start of diesel engines based on heating a part of the air charge.

2. Literature review and problem statement

A task on improving energy efficiency of the system that facilitates the start based on the heating elements was addresses in paper [7]. It was proposed to connect an electric heating element to the power source with variable voltage, which changes over time in line with a specialized algorithm. The application of such a technique to facilitate the start made it possible to ensure a reliable start of the engine at an inlet air temperature of −25.5 °C to −16 °C, to reduce the time required to heat the system before the start to 10 seconds, to limit a voltage drop at rechargeable batteries to 15 %. However, this system provides the heating of the entire volume of air that enters an engine, which is a constraint for the further improvement of the start energy efficiency.

The authors of papers [8, 9], based on the results of experimental studies, revealed another issue related to a cold start of the diesel engine when biodiesel fuel or liquefied gas are used. They identified the reduced indicator work in such engines at a low inlet air temperature. This testifies to the need to increase the temperature of the intake air, which requires the employment of energy-efficient systems that facilitate the start.

Paper [10] investigated the development of a flame in the engine's cylinder at an inlet air temperature of −29 °C. The displacement of the flame front was determined based on its optical radiation. The authors found that the spontaneous combustion of fuel occurred in a zone of the elevated temperature near a spark plug. This allowed them to argue on that the presence of a local high-temperature zone in an air charge would be enough to ensure the conditions for the self-ignition of fuel. A variant to solve the problem on cold starting the engines equipped with spark plugs, investigated in [11], implied the injection of a pilot portion of fuel. It was found that combustion of the pilot portion of fuel creates a high-temperature zone in the charge. That is why, during subsequent injection of the main portion of fuel, there are conditions in the charge for its intense combustion. Thus, the formation of a high-temperature layer in the air charge enables a reliable start of the diesel engine.

The research, reported in paper [12], shows a more acute problem related to cold-starting the diesel engines with a turbocharger. This is due to the reduced compression ratio in such engines. That is why there is an increase in the number of diesel power units that are equipped with systems to facilitate their cold start. Study [13] addressed the effect of the cold state of an engine on the toxicity of combustion products. It was established that an increase in the air charge temperature inside an unwarmed engine results in the more complete fuel combustion and reduces the emissions of harmful substances.

Papers [1, 14] proposed a new method for facilitating the start, whose energy efficiency is ensured through heating, beyond the engine's cylinder, only a part of the inlet air. As a result, a two-layer air charge with different temperatures forms in the cylinder. Based on the results of numerical studies into the process of compression of an ideal two-temperature charge, the presence of conditions for the reliable fuel self-ignition was established [14]. Along with this, paper [14] failed to consider the effect of turbulent eddies of air that emerge in the engine's cylinder at the time when it is filled with an air charge.

The above allows us to argue about the expediency of conducting a study into the process of compression of the turbulized two-temperature air charge, in order to elucidate the conditions for reliable fuel self-ignition in the diesel engine.

3. The aim and objectives of the study

The aim of this work is to study numerically a temperature field of the two-temperature turbulized air charge at its compression in order to reveal the existence of conditions for the reliable fuel self-ignition.

To accomplish the aim, the following tasks have been set:

– to consider in the numerical study the effect of vortex flows that emerge during the formation of a two-temperature layer air charge on a change in the temperature field of the charge at its compression in the cylinder of the 6TD-type engine;

– to establish the existence of conditions for the reliable fuel self-ignition in a turbulized two-temperature air charge at its compression.

4. Statement of the problem and a mathematical model of air charge compression in the 6TD-type diesel engine

The problem on modeling was stated in relation to the engine 6TD. This is a valveless, two-stroke, opposed engine with counter-moving pistons. Schematic of the cross-section of the engine's cylinder-piston group is shown in Fig. 1.

Diameter of the cylinder is 120 mm. Maximum distance between the pistons is 245 mm. A full stroke of each piston is 120 mm. Air charge in such an engine forms at the intake stroke by pressurizing air into the cylinder through the inlet windows. The inlet windows are of the following dimensions: height – 25 mm, width – 16 mm, tangential slope is to 20°. Due to the tangential slope, vortex flows form in the air charge. In order to form two air layers with different temperatures we assigned under the conditions for modeling, first, the injection of cold air at a temperature of 253 K, followed by the injection of heated air at a temperature of 773 K. The volumetric fraction of the heated air in the charge was 10 %. Velocity of air flow at the inlet to the cylinder was taken to be 30 m/s. The air was pressurized under atmospheric pressure. The calculation accounted for the heat exchange between the air charge and the walls of the combustion chamber, as well as the process of thermal diffusion in a two-temperature charge. It was accepted that the surface temperature of the cylinder and piston was constant and equaled 253 K. Leaks of the gas charge at compression between the piston and the cylinder were neglected. Initial distance between the pistons prior to the start of compression was 195 mm. This distance corresponds to the closing angles of the intake and exhaust windows in the engine 6TD. It was accepted that the frequency of starting rotations of the engine was 150 min^{-1}. By recalculating the starting frequency, and taking into consideration the structure of the crank mechanism, the speed of each piston was assigned by equation $v(t)=0.943\cdot\sin(5\pi\cdot(t+0.056))$ in m/s. The calculation was performed in the time interval $\Delta t=0.144$ s, which is equal to the time of a compression stroke at the accepted starting rotations. The pistons were assigned in the form of flat boundaries that cannot be penetrated by gas, and which are movable. The resulting distance between the pistons that is observed at the top dead center (TDC) was 13 mm. At a given distance, the resulting volume matches the volume of the combustion chamber in the engine 6TD at TDC. An increase in the resulting distance between the pistons is due to that the actual surfaces of this engine's pistons are not flat.

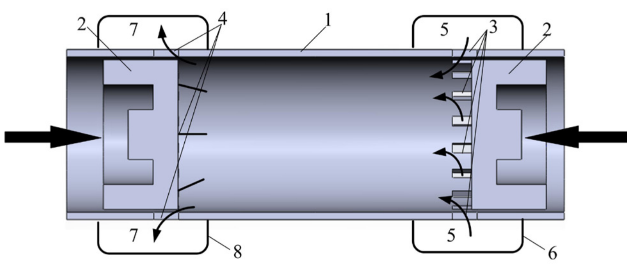

Fig. 1. Schematic of the cross-section of a cylinder-piston group of the 6TD-type engine: 1 – cylinder, 2 – pistons; 3 – intake windows; 4 – exhaust windows; 5 – flow of inlet air; 6 – intake collector; 7 – flow of exhaust air; 8 – exhaust collector. Arrows indicate a direction of the piston motion at compression

3D-simulation of the air charge compression process in the engine's cylinder was performed employing the programming environment ANSYS. In order to study numerically the stated problem, a system of the Navier-Stoke equations [15–18] is applied, which includes the laws of preservation of mass, pulse, and energy of the non-stationary spatial flow within the Euler approach in the Cartesian coordinate system (x_i, i=1, 2, 3) in the general form:

$$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k)=0, \tag{1}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_i u_k-\tau_{ik})+\frac{\partial p}{\partial x_i}=0, \tag{2}$$

$$\frac{\partial(\rho E)}{\partial t}+\frac{\partial}{\partial x_k}\left((\rho E+p)u_k+q_k-\tau_{ik}u_i\right)=0, \tag{3}$$

where ρ is the density, u is the speed, t is the time, p is the pressure, E is the energy, τ is the stress tensor, q is the heat flow; lower indexes denote summing different directions.

A stress tensor is calculated from expression:

$$\tau_{ik}=-2\mu\left(\frac{1}{2}\left(\frac{\partial u_k}{\partial x_i}+\frac{\partial u_i}{\partial x_k}\right)-\frac{1}{3}\partial iv\bar{u}\delta_{ik}\right), \tag{4}$$

where μ is the dynamic viscosity coefficient; δ_{ik} is the Kronecker Delta.

When calculating density, pressure, and enthalpy h of the layered air charge, the mixing rules are applied:

$$\frac{1}{\rho}=\sum_{b=1}^{B}\frac{1}{p_b}, \tag{5}$$

$$p=\sum_{b=1}^{B}p_b, \tag{6}$$

$$h=\sum_{b=1}^{B}c_b h_b, \tag{7}$$

where c is the concentration of a component.

In order to determine the concentration of components in an air charge, the system of equations (1) to (7) is supplemented by an equation for determining the concentration of components:

$$\frac{\partial\rho c_b}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k c_b)=\frac{\partial}{\partial x_k}\left((D_{ij}+D_{ij}^t)\frac{\partial c_b}{\partial x_k}\right), b=1, 2, \dots, B, \tag{8}$$

where c_b is the concentration of a b-component in the air charge $\sum_{b=1}^{B}y_b=1$; D_{ij} and and D_{ij}^t are the coefficients of molecular and turbulent diffusion, which are governed by the Fick's law, that is, $D_{ij}=D\delta_{ij}$, $D_{ij}^t=\delta_{ij}\frac{\mu_t}{\sigma}$.

A diffusion heat flow is modeled using the following equation

$$q_k=-\left(\frac{\mu_l}{\mathrm{Pr}}+\frac{\mu_t}{\sigma}\right)c_p\frac{\partial T}{\partial x_k}, \tag{9}$$

where μ_l is the laminar viscosity; μ_t is the turbulent viscosity; Pr is the Prandtl number; σ is the Schmidt number; c_p is the specific heat at constant pressure; T is temperature.

Thermophysical properties of the liquid medium were determined from equations of state, empirical and semi-empirical dependences. That is, we applied the dependences of density, viscosity, thermal conductivity, specific heat capacity, diffusion coefficients of the liquid medium components, on pressure, temperature, and the concentration of components in the medium.

In order to solve the non-stationary Navier-Stokes equations, we employed the Reynolds averaging method.

5. Results of the numerical study into the process of compression of a turbulized two-temperature air charge in the 6TD-type engine

The distribution of temperature in a turbulized air charge upon completion of air injection prior to the onset of compression is presented in Fig. 2

The result obtained indicates that given the turbulization of an air flow, the cold and heated layers in the air charge partially mix. The result of mixing is an increase in the volumetric share of the charge with an elevated temperature. In this case, the cold air concentrates in the center of the cylinder.

At compression, there is an increase in temperature in two layers of the air charge (Fig. 3, 4).

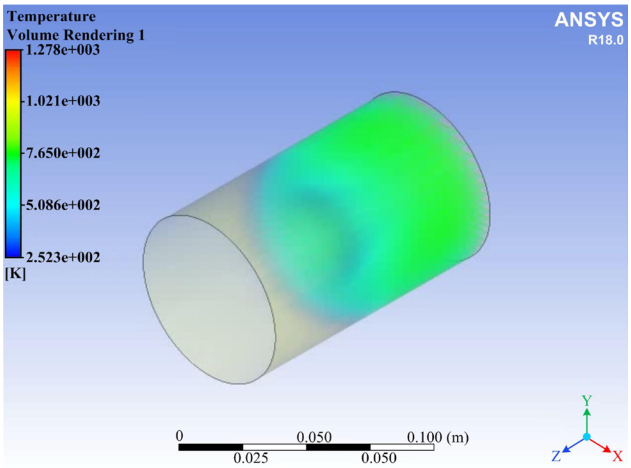

Fig. 2. Distribution of temperature in a turbulized two-temperature air charge prior to the onset of compression

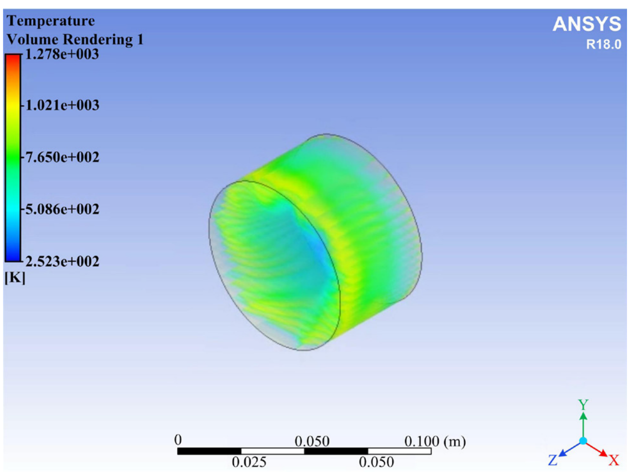

Fig. 3. Distribution of temperature in a turbulized two-temperature air charge at 80 deg. to TDC

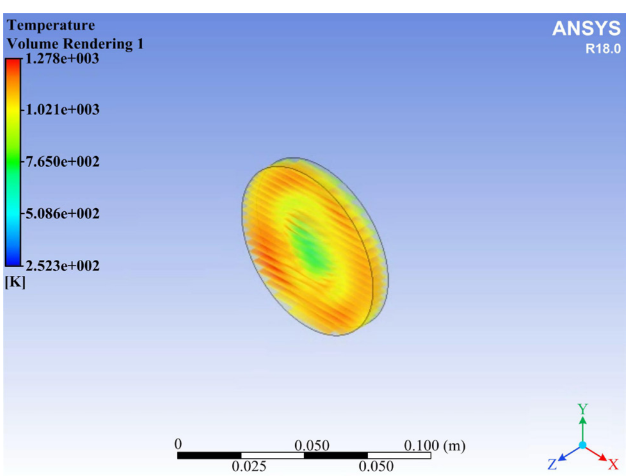

Fig. 4. Distribution of temperature in a turbulized two-temperature air charge in the air charge at TDC

Specifically, at 80 degrees to TDC, in the layer of the charge, which had an initial elevated temperature of 773 K, temperature of the gas rises to 1,000 K (Fig. 3).

In another part of the charge, where the initial temperature was 253 K, the gas temperature increases to 500 K. When approaching TDC, the presence of layers with different temperatures in the charge is maintained, but a layer with the low temperature is observed only in the center of the cylinder. At the periphery, air layers with different temperatures mix. When approaching TDC, temperature of the layer with preheating amounts to 1,200 K, while in the layer without heating it reaches only 650 K (Fig. 4). In this case, there are local different-temperature zones in the layers.

6. Discussion of results of studying the process of compression of a turbulized two-temperature air charge in the diesel engine

This study is continuation of work aimed to improve energy efficiency of the cold start system by heating part of the air charge [1, 14]. The advantage of the present study is accounting for the effect of vortex flows on the temperature field of the air charge, which made it possible to bring modeling conditions closer to the actual conditions for the charge formation in an engine.

It is known [2] that the reliable start of the diesel engine occurs when the charge temperature reaches 700–850 K. The results obtained indicate that even under conditions of turbulization of an air charge, at compression there is the presence of charge layers with different temperatures. In a colder layer, temperature of the charge does not reach the temperature limit of reliable fuel self-ignition. The preheated layer of the charge exceeds the temperature limit, which creates conditions for the reliable start of an engine. This is explained by that due to compression of the preheated charge layer there is a faster increase in its temperature. Thus, the fuel that penetrates the high-temperature layer of the charge will lead to its reliable self-ignition. Combustion of fuel in this layer will ensure a further increase in pressure in the combustion chamber, which would contribute to forming the conditions for the self-ignition of fuel, which penetrated the low-temperature layer of the charge.

Limitations of this study are related to the idealization of conditions for filling the engine's cylinder with an air charge. Specifically, the presence of residual gases after the previous cycle of combustion was not taken into consideration.

The shortcomings of the present study are due to the application of a condition for an instantaneous interruption in the supply of a portion of heated air. However, the elimination of this drawback will not lead to a qualitative change in the result obtained, and under actual conditions that could be neutralized by changing the time when heated air is supplied.

The obtained results could be applied to substantiate the requirements for an experimental sample of the system that would facilitate engine start, which provides for a partial heating of the air charge. Further experimental studies would make it possible to refine the requirements to energy-efficient systems for facilitating cold start of the diesel engines.

7. Conclusions

1. Based on the results of numerical modeling of compression of a two-layered air charge with different temperatures in a cylinder of the engine of 6TD type, we investigated a change in the temperature field in the charge. We accounted for the vortex flows that emerge at charge formation in the engine's cylinder. In order to create two air layers with different temperatures, we first assigned under the conditions of modeling the injection of cold air into the engine's cylinder at a temperature of 253 K, followed by the injection of heated air at a temperature of 773 K. The volumetric share of heated air in the charge was 10 %.

2. The presence of conditions for reliable fuel self-ignition in a turbulized two-temperature layered air charge at its compression has been established. At TDC, temperature of the preheated layer amounts to 1,200 K, while in the layer without heating it reaches 650 K only. That confirms the expediency to continue work on the construction of an experimental sample of the system for facilitating engine start, which enables partial heating of the air charge.

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