IRSTI 28.17.23 https://doi.org/10.26577/RCPh.2020.v75.i4.07

A. Askarova, S. Bolegenova, V. Messerle,
S. Bolegenova, Sh. Ospanova*, M. Bodykbayeva

Al-Farabi Kazakh national university, Kazakhstan, Almaty
*e-mail: Shynar.Ospanova@kaznu.kz

INVESTIGATION OF THE LIQUID FUEL SINGLE-HOLE INJECTION IN THE COMBUSTION CHAMBER

On modern engines fuel injection has completely replaced the carburetor power system. But at the same time, among automakers there is still no consensus about which injection system is preferable, since each of them has its own advantages and limitations. In this work it was conducted the study of the atomization and combustion processes of single-hole injection of liquid fuel in a model chamber of the internal combustion engine. In this injection system air is mixed with fuel in the intake manifold, a complex and sensitive carburetor has been replaced by an injector, therefore this type of spray is called single-point. In multi-hole injection systems an individual injector is installed in the intake manifold of each cylinder, which supplies fuel directly to the intake valve. Thus, the fuel mixture is prepared immediately before being fed into the combustion chamber. Therefore, it turns out to be homogeneous in its composition and approximately the same in quality for each of the cylinders. As a result, this has a beneficial effect on the power and economy of the engine, as well as on the toxicity of exhaust gases. As a result of the computational experiments, the thermal and aerodynamic characteristics of the flow in the combustion chamber were obtained. The obtained computer simulation data were compared with experiments, which showed that the proposed in our work numerical model of liquid fuels spray adequately describes the real processes of atomization and combustion of various types liquid fuels.

Key words: atomization, single-hole injection, combustion chamber, liquid fuel, numerical simulation.

Ә. Асқарова, С. Бөлегенова, В. Мессерле,
С. Бөлегенова, Ш. Оспанова*, М. Бодықбаева

Әл-Фараби атындағы Қазақ ұлттық университеті, Қазақстан, Алматы
*e-mail: Shynar.Ospanova@kaznu.kz

Жану камерасындағы бір ағыншалы сұйық отын бүркуін зерттеу

Заманауи іштен жану қозғалтқыштарында отынды бүрку әдісі карбюраторлық қоректендіру жүйесін толығымен алмастырды. Алайда, автокөлік өндірушілердің арасында қай жүйенің басымырақ екендігі туралы бірдей көзқарас жоқ, өйткені, әрбірінің өзінің артықшылықтары мен кемшіліктері бар. Берілген жұмыста іштен жану қозғалтқышының модельдік камерасындағы сұйық отынның бір ағыншалы бүрку және жану процестеріне зерттеу жүргізілді. Аталған бүрку жүйесінде ауа отынмен кіріс коллекторында араласады, күрделі, әрі сезімтал карбюратор инжектормен алмастырылады, сондықтан, аталған бүрку түрі бірнүктелік деп те аталады. Көпағыншалы бүрку жүйелерінде әрбір цилиндрдің кіріс түтігінде жеке форсунка орналастырылады, соңғысы отынды кіріс клапанына береді. Осылайша, отын қоспасы жану камерасына берер алдын әзірленеді. Сондықтан құрамы бойынша ол біртекті, әрі әрбір цилиндр үшін сапасы тұрғысынан бірдей болады. Нәтижесінде аталған қасиет мотордың қуаты мен үнемділігіне, шығыс газдардың улылығына жағымды әсер етеді. Жүргізілген есептеуіш тәжірибелердің негізінде жану камерасындағы ағыстың жылулық және аэродинамикалық сипаттамаларына қол жеткізілді. Алынған компьютерлік модельдеу нәтижелерін тәжірибелік мәліметтермен салыстырылу көрсеткендей, жұмыста ұсынылған тамшыларды бүркудің сандық моделі әр түрлі сұйық отындарды бүрку және жану процестерін дұрыс сипаттайтындығы белгілі болды.

Ключевые слова: бүрку, бір ағыншалы бүрку, жану, сұйық отын, сандық модельдеу.

А. Аскарова, С. Болегенова, В. Мессерле,
С. Болегенова, Ш. Оспанова*, М. Бодыкбаева

Казахский национальный университет им. аль-Фараби, Казахстан, Алматы
*e-mail: Shynar.Ospanova@kaznu.kz

Исследование одноструйного впрыска жидкого топлива в камере сгорания

На современных двигателях впрыск топлива полностью вытеснил карбюраторную систему питания. Но при этом, среди автопроизводителей до сих пор нет единого мнения, какая система впрыска предпочтительней, поскольку каждая из них обладает своими достоинствами и недостатками. В данной работе было проведено исследование процессов распыла и горения одноструйного впрыска жидкого топлива в модельной камере двигателя внутреннего сгорания. В этой системе впрыска воздух смешивается с топливом во впускном коллекторе, сложный и чувствительный карбюратор заменен на инжектор, поэтому этот тип распыла получил название одноточечного. В системах многоструйного впрыска во впускном патрубке каждого цилиндра устанавливается индивидуальная форсунка, которая подает топливо непосредственно на впускной клапан. Таким образом, топливная смесь готовится непосредственно перед подачей в камеру сгорания. Поэтому она получается однородной по своему составу и примерно одинакова по качеству для каждого из цилиндров. В результате данное свойство благотворно сказывается на мощности и экономичности мотора, а также на токсичности выхлопных газов. В результате проведенных вычислительных экспериментов получены тепловые и аэродинамические характеристики течения в камере сгорания. Полученные результаты компьютерного моделирования были сравнены с экспериментальными данными, которые показали, что предложенная в нашей работе численная модель впрыска капель адекватно описывает реальные процессы распыла и горения различного вида жидких топлив.

Ключевые слова: распыл, одноструйный впрыск, горение, жидкое топливо, численное моделирование.

Introduction

Air pollution today is one of the pressing problems of large and industrial cities of the republic. Among them, the leading place in the concentration of harmful substances is the city of Almaty. This is due to natural, climatic, technogenic conditions: the location at the foot of the mountains, in an extremely unfavorable place for providing clean air, since the weak circulation of air masses, characteristic of mountainous terrain, contributes to the accumulation of harmful impurities in the air. Their main sources in Almaty are motor vehicles, industrial enterprises, the private residential sector using solid fuel heating, thermal power plants located near the city. The atmospheric air of the city is saturated with carbon monoxide, nitrogen dioxide and formaldehyde; the average concentration of these chemical elements is several times higher than the maximum permissible concentration established by sanitary standards. In recent years, the state of the air environment in Almaty has worsened due to an increase in the number of sources of pollution, especially the fleet of cars, unplanned construction of high-rise buildings that hinder the air flow, an increasing population and a reduction in green areas [1-4].

According to statistics, the annual volume of emissions of harmful substances into the atmosphere of Almaty is about 232 thousand tons. At the same time, 3 thousand tons are thrown away by industrial enterprises, 16 thousand tons – in the residential private sector and 23 thousand tons are produced by thermal power plants (Figure 1).

The largest share in the volume of air emissions falls on motor vehicles. This is 190 thousand tons or 80 percent of the total volume, incl. by pollutants included in the indicator of the air pollution index: suspended solids (soot) – 308.8 tons per year; carbon oxides – 145829.9 tons per year; nitrogen oxides – 17990.2 tons per year; sulfur oxides – 1860.2 tons per year; formaldehyde – 133.9 tons per year; others (hydrocarbon, benzene, etc.) – 23977 tons per year. The impact of these pollutants on health is manifested in a wide range of biological effects: from an increase in the frequency of cough and other symptoms from the upper and lower respiratory tract, exacerbation of bronchial asthma, an increase in the incidence of bronchitis to an increase in cardiovascular diseases [5, 6].

As calculations and dynamics of growth of the main indicators show, the relationship between environmental pollution, the incidence of respiratory diseases in the population, the cost of the

disease (government and private spending, non-produced gross regional product) has a directly proportional relationship. There is a positive trend in all indicators. Accordingly, in order to reduce losses both from the state and the population, it is necessary to take measures to reduce environmental pollution, which will lead to a decrease in the incidence of diseases of the population, and, accordingly, to reduce the costs of the state and the population.

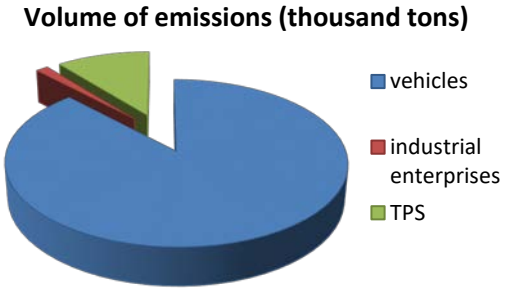


Figure 1 – The annual volume of emissions of harmful substances into the atmosphere of Almaty

In connection with the above, intensification of production, reduction of material consumption of equipment, economical consumption of fuel, and environmental protection are acquiring special significance and relevance. It is very important to create a scientific basis for intensive technological processes that ensure the integrated use of fuel and its waste, excluding the harmful effects of production on the biosphere. The new strategy for nature conservation and energy conservation involves the selection of the most effective achievements of scientific and technological progress. Among them, three main groups of measures stand out: utilization, energy modernization, intensive energy saving.

Physical statement of the problem

The heart of any car is an internal combustion engine, designed to convert chemical energy into mechanical energy. Gasoline and diesel engines are distinguished by fuel type. Mechanical energy moves the pistons up and down the inner cylinders. The pistons are connected to the crankshaft and the movement of the pistons, known as linear motion, creates a rotation of the shaft that drives the wheels.

Modern internal combustion engines use high-tech fuel injectors to deliver fuel to the engine in the most efficient way. There are different types of fuel injection systems depending on the type of engine. The most commonly used engines are spark ignition (SI), port injection (PFI or GDI) and direct injection (DI) engines. In spark ignition engines, the injection pressure ranges from 2 to 3 bar, and in direct injection engines from 100 to 200 bar. Diesel engines with direct injection operate at much higher pressures, these values are about 10 times or more than spark ignition engines. Injection systems are usually electronically controlled, since the opening and closing of the injector must be quick, which reduces fuel waste [7-11].

In GDI engines, fuel is injected directly from several injector holes at a pressure of 200 bar. The multi-hole injection structure of the GDI engine is composed of combinations of fluid bundles and droplets of different sizes, and these are dependent on injection pressure. When liquid is injected, ring-shaped injections are created in the engine. Typically, liquid bundles form at the inlet in the vicinity of the injector nozzle and the bundles break into droplets downstream due to interaction with air, which contributes to the growth of instability on the liquid surface. Droplet decay continues further downstream, which facilitates evaporation (Fig.2) [12, 13].

The combustion mechanism of liquid fuels in internal combustion engines includes several stages: a spark (or other external ignition source); ignition of the air-vapor mixture; combustion of the vapor-air mixture at the surface of the liquid; increased evaporation rate due to the transfer of heat from the flame.

Figure 2 – Cross-sectional view of a gasoline direct injection (GDI) engine [12]:
1 – needle, 2 – valve, 3 – injector body, 4 – fuel drive, 5 – electrical connector, 6 – power drive, 7 – nozzle

One of the most fundamental differences between combustion phenomena is based on flame pre-mixing and diffusion processes. In the first case, all reagents are thoroughly mixed before the combustion process, and in the second, the fuel and oxidant are mixed until the stage of consumption.

Apart from spark ignition engines, in almost all other internal combustion engine designs, the injected liquid fuel is not premixed.

Liquid fuels such as gasoline, diesel, light oil, fuel oil or kerosene are injected before combustion and must mix well with air. For these purposes, various types of nozzles are used. The injectors are divided into two groups: mechanical injectors and dual injection injectors. The perfection of the combustion of liquid fuel depends on the quality of its atomization, which is characterized by the distribution of droplets in size, the average diameter of the droplets, the opening angle and range of the jet, the amount of liquid passing per unit time through the unit of area of the free cross-section of the jet.

Mathematical model of the liquid fuel atomization

The continuity equation for the reaction component m has the form [14]:

$$\frac{\partial \rho_m}{\partial t} + \vec{\nabla}(\rho_m \vec{u}) = \vec{\nabla}\left[\rho D \vec{\nabla}\left(\frac{\rho_m}{\rho}\right)\right] + \dot{\rho}_m^c + \dot{\rho}^s \delta_{m1}, \quad (1)$$

where D is the diffusion coefficient, ρ_m is the mass density of the liquid phase, ρ is the total mass density, $\dot{\rho}_m^c$ is the chemical source term; $\dot{\rho}^s$ source term due to injection; u is the fluid velocity.

Equation of motion for a mixture of liquids is [15]:

$$\frac{\partial(\rho\vec{u})}{\partial t} + \vec{\nabla}(\rho\vec{u}\vec{u}) = -\frac{1}{a^2}\vec{\nabla}\text{p-A}_0\vec{\nabla}(\tfrac{2}{3}\rho k) + \vec{\nabla}\vec{\sigma} + \vec{F}^s + \rho\vec{g}, \quad (2)$$

where p is the fluid pressure. In the equation, A_0 is 0 for laminar flow and 1 when one of the turbulence models is used.

The internal energy equation is presented below [15]:

$$\frac{\partial(\rho\vec{I})}{\partial t} + \vec{\nabla}(\rho\vec{u}\vec{I}) = -\rho\vec{\nabla}\vec{u} + (1-A_0)\vec{\sigma}\vec{\nabla}\vec{u} - \vec{\nabla}\vec{J} + A_0\rho\varepsilon + \dot{Q}^c + \dot{Q}^s, \quad (3)$$

where I is the specific internal energy, $\dot{Q}^c$ is the source term due to the heat release as a result of a chemical reaction, and $\dot{Q}^s$ is the heat brought by the injected fuel. The vector of heat change J is the sum of electrical conductivity and enthalpy transfer.

For technical applications, a more acceptable method is based on the solution of the averaged Navier-Stokes equations or Reynolds equations. In the approach of modeling the Reynolds-averaged Navier-Stokes equations (RANS), the ensemble averaging operation is applied to the basic equations, that is, all temporal and spatial scales of turbulence contribute to the dynamics of the averaged flow [16].

When calculating various characteristics of the flow, a system of equations of turbulent transfer was used, for the closure of which the standard turbulence $k-\varepsilon$ model was used, since in studies related to the study of heat and mass transfer processes in turbulent flows of liquid fuels, this model exhibits stability, efficiency, and reasonable accuracy, which makes it most applicable for solving industrial problems [17-20]:

$$\rho\frac{\partial k}{\partial t} + \rho\frac{\partial \overline{u}_j k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]\frac{\partial \overline{u}_i}{\partial x_j} + G - \frac{2}{3}\rho k\delta_{ij}\frac{\partial \overline{u}_i}{\partial x_j} - \rho\varepsilon, \quad (4)$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho\frac{\partial \overline{u}_j \varepsilon}{\partial x_j} - \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] = c_{\varepsilon_1}\frac{\varepsilon}{k} - G - \left[\left(\frac{2}{3}c_{\varepsilon_2} - c_{\varepsilon_3}\right)\rho\varepsilon\delta_{ij}\frac{\partial \overline{u}_i}{\partial x_j}\right] - c_{\varepsilon_2}\rho\frac{\varepsilon^2}{k} \quad (5)$$

The quantities c_{ε_1}, c_{ε_2}, c_{ε_3}, σ_k, σ_ε are model constants that are determined from the experiment.

This paper presents the results of the atomization of single-hole liquid fuel injection modeling depending on various external parameters. In this work to simulate the processes of single-hole injection of liquid fuel droplets the following parameters were used:

- the injection pressure P_i=100 and 150 bar;
- the initial fuel temperature T_f =363,15 K;

- the pressure in the combustion chamber P_c =1,54 bar;

- the temperature in the combustion chamber T_c =306,15 K;

- the duration of the injection time t=3,32 ms;

- total injection mass m=24.9 mg.

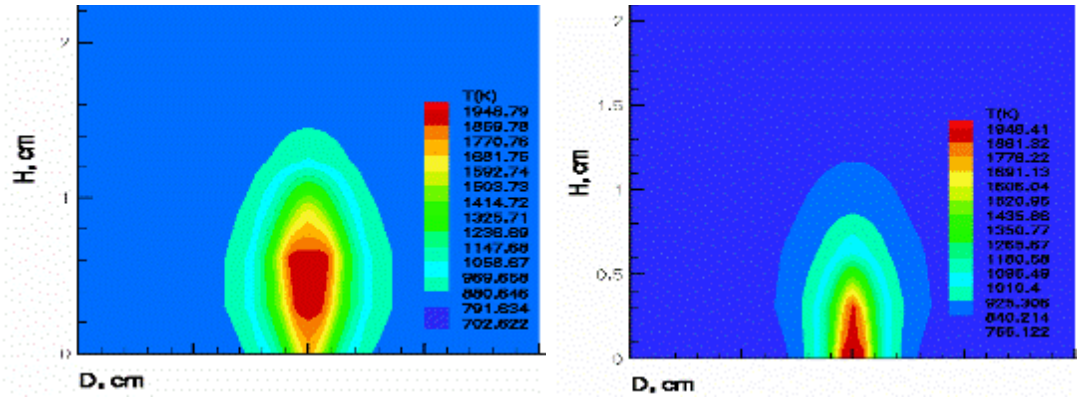
The operating fuel was isooctane.

Similar studies of the processes of spraying, dispersion and combustion of liquid fuel droplets in the combustion chamber were carried out in various works by the authors [21-25]. In these works, the optimal combustion modes of heptane, gasoline and tetradecane were determined depending on the initial temperature of the oxidizer, the injection mass and the droplet velocity in the combustion chamber. Therefore, all the initial conditions for modeling thermal processes were taken on the basis of data from previous works.

Numerical simulation results

By using a mathematical model the results of numerical modeling of the processes of spray, ignition and combustion of liquid fuel are presented depending on two initial pressures in the combustion chamber under high turbulence. The following figures show the simulation results of liquid fuel atomization in a model engine combustion chamber.

When liquid fuel is atomized into a stationary or moving gas, a two-phase reaction jet is formed, which burns to form a liquid fuel torch. As shown in Figure 3 an increase in pressure in the combustion chamber leads to an increase in the high temperature region. This behavior can be observed up to a pressure of 100 bar for isooctane. A further increase in the pressure in the combustion chamber leads to the fact that the region of high temperatures narrows and already at a pressure of 150 bar this region decreases (Figure 3, b).

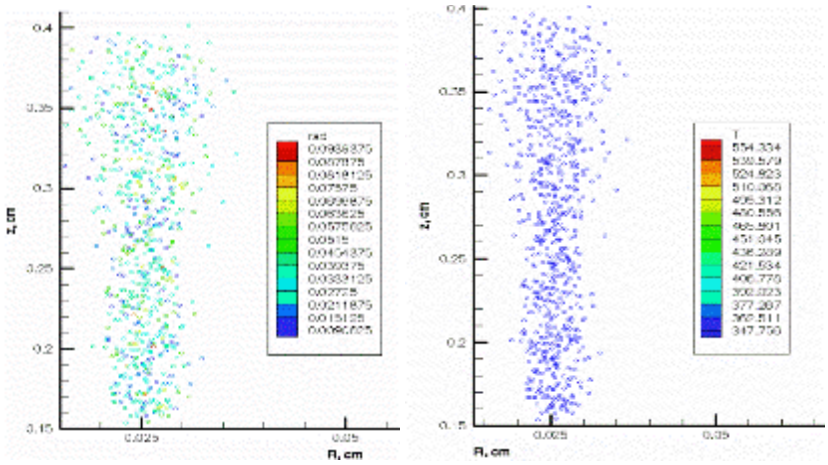


a) P=100 bar *b*) P=150 bar

Figure 3 – Distribution of the maximum temperature in the space of the combustion chamber during the combustion of isooctane

Thus, analyzing this Figure 3, we can conclude that the optimal pressure for octane is 100 bar.

The following Figure 4 shows the dispersion of isooctane droplets along the radius and specific temperature of particles. Figure 4 shows the distribution of isooctane droplets in the combustion chamber depending on the radius and specific temperature of the particles. As can be seen, the droplet dispersion is dense, the droplets rise to 0.42 cm along the height of the combustion chamber (Figure 4, a). Consequently, the radius of the droplets at the height of the chamber was 7 μm. Also, the specific temperature of each particle heated to high values was 363 K. The droplets rise to 0.42 cm along the height of the chamber (Figure 4, b).

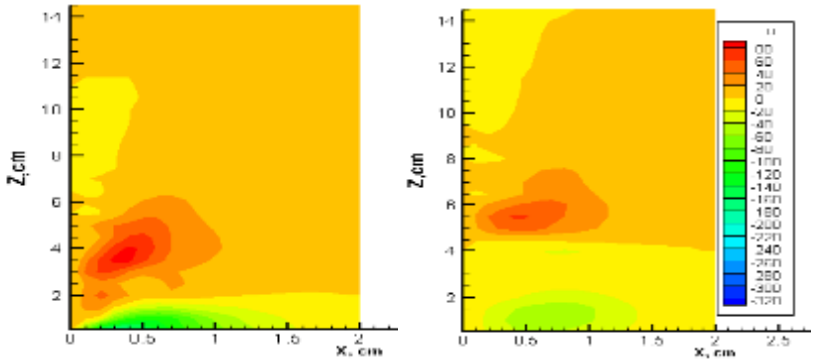


a) radial distribution *b*) specific temperature distribution

Figure 4 – Dispersion of isooctane droplets in terms of radius and specific temperature over the height of the combustion chamber at P=100 bar

Also during the computational experiments the aerodynamic and thermal characteristics of the spray and combustion of isooctane in the combustion chamber were obtained. Figure 5 shows the distribution of the transverse component of the droplet velocity in the combustion chamber. At the initial moment of time 1.2 ms in most of the volume of the chamber, the combustion rate of isooctane was 20 m/s, and on the axis of the chamber at the moment t=2.5 ms, the velocity of isooctane droplets reached a maximum of 80 m/s.

The following Figure 6 shows the distribution of the longitudinal velocity component of isooctane droplets in the combustion chamber. As can be seen from the figure, the droplet velocity reaches its maximum 550 m/s on the camera axis. At the same time, in the rest of the combustion chamber, the fuel velocity remains constant at 50 m/s.



a) t=1.2 ms b) t=2.5 ms

Figure 5 – Distribution of the transverse component of the velocity of isooctane droplets at different times

Figure 7 shows the distribution of fuel concentration along the height of the combustion chamber. At the initial moment of time, when the fuel is ignited, droplets with a higher density are concentrated in the lower part of the chamber; over time, due to the processes of evaporation and collision, as well as due to high temperatures, they begin to rise upward towards the exit of the combustion chamber.

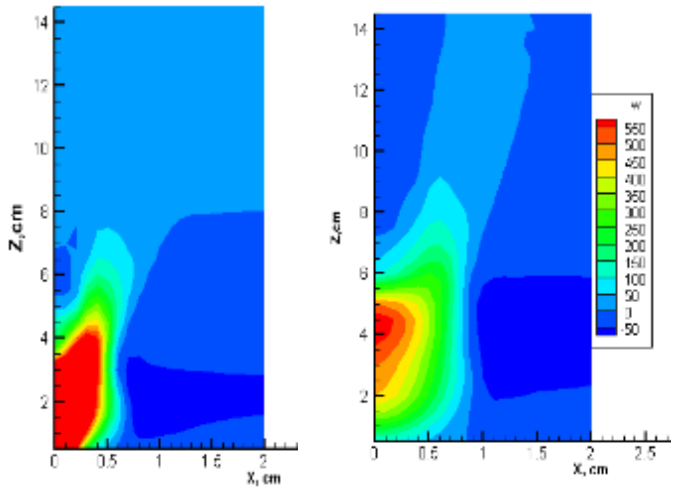


Figure 6 – Distribution of the longitudinal component of the velocity of isooctane droplets at different times

The region encompassing the maximum temperature is large, due to the evaporation and adhesion of isooctane droplets in the lower part of the chamber, although the liquid phase remains, the combustion of hydrocarbon liquid fuels occurs in the gas phase.

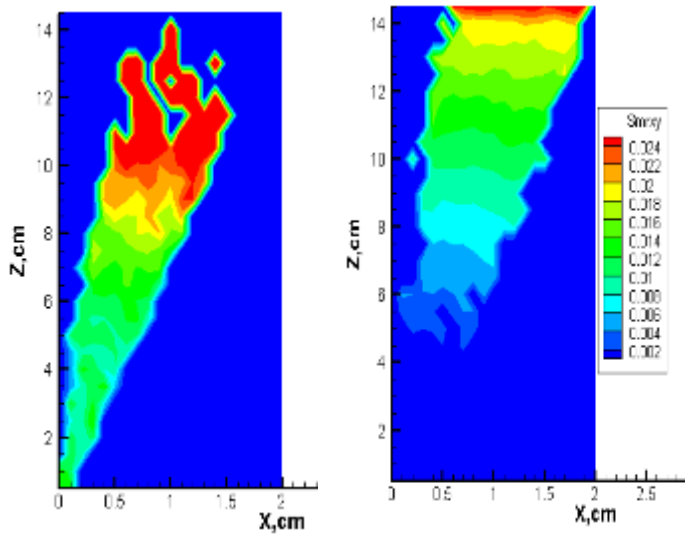
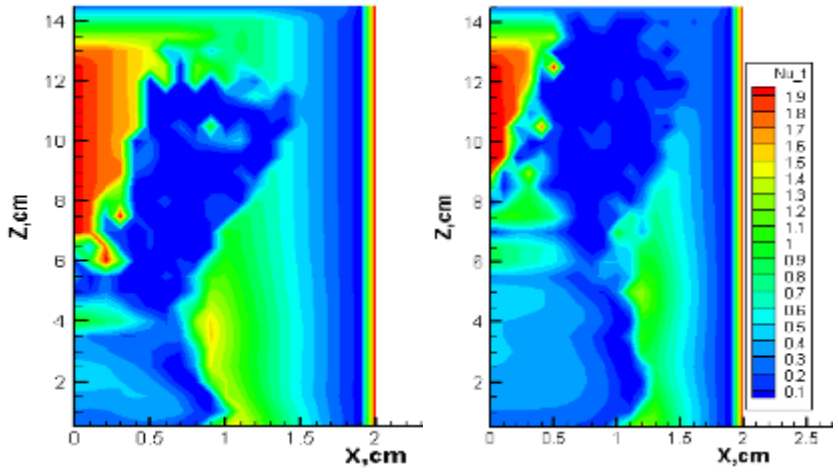


Figure 7 – Distribution of fuel concentration at different points in time

Figure 8 shows the intensity of heat transfer due to convection and heat conduction, which is described by the Nusselt criterion. As we know from the laws of heat transfer in a stationary medium, the Nusselt number is always greater than or equal to 1, since the heat flux due to convection always exceeds in magnitude the heat flux due to heat conduction. Since in our case the process is described at high turbulence, as we can see from the figure, a strong convective heat flux is observed on the chamber axis, which is a characteristic of a turbulent flow.

At the initial moment of time, when the fuel and the oxidizer mix intensively, the Nusselt criterion is of high value. Then, after a while, along the movement of heat to the outlet of the combustion chamber, the intensity of heat exchange fades away and the flow becomes stable.



t = 1.2 ms t = 2.5 ms

Figure 8 – The intensity of convective heat transfer
in the combustion chamber at different points in time

Also in the work, the results of numerical simulation of the processes of isooctane drops atomization were compared with the experimental data of some foreign authors [26]. The results of computational experiments on the change in the temporal distributions of the Sauter mean droplet diameter (SMD) of isooctane with distance from the injector are shown in the figures below.

Sauter mean diameter is the mean surface-volumetric diameter of the droplets. The results obtained are compared with the experimental data presented in [26]. Here at various distances from the injector 10 mm, 20 mm, 30 mm, 40 mm, 50 mm and 60 mm for isooctane the experimental studies were conducted. We also did similar studies at the distance from the injector x=50 mm and 60 mm for isooctane. As can be seen from Figures 9-10, the experimental and simulation data are in good agreement. Analyzing the obtained data, which are presented in Figures 9-10, it can be assumed that the simulated and experimental data are in good agreement for liquid fuel.

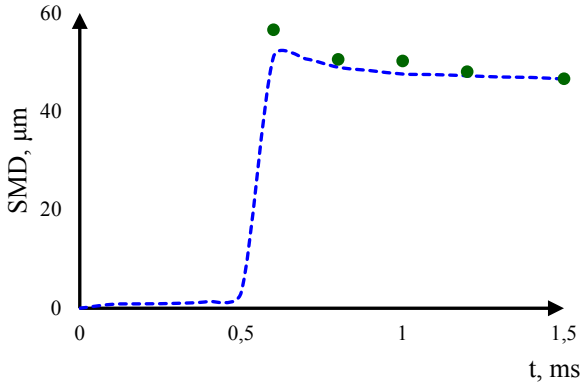


Figure 9 – Comparison with the experiment of the temporal distributions
of the Sauter mean droplet diameter (SMD) of isooctane at a distance of 50 mm from the injector:
blue line – numerical simulation; **dot** – experiment

The analysis of the obtained results presented in this work indicates a good coincidence of the numerical results with the experimental data and allows us to conclude that the numerical model of liquid fuels spraying proposed in this work adequately describes real spraying processes and, consequently, the combustion process of liquid fuels of various types.

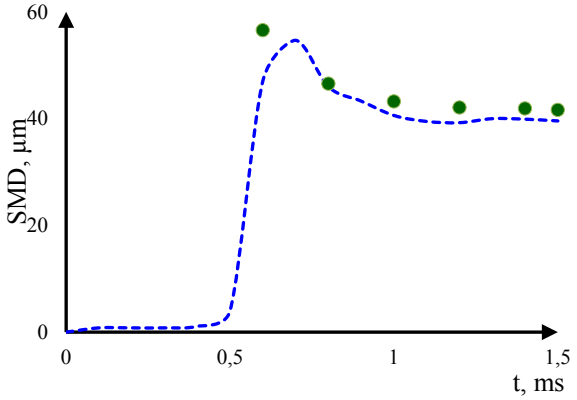


Figure 10 – Comparison with the experiment of the temporal distributions of the Sauter mean droplet diameter (SMD) of isooctane at a distance of 60 mm from the injector: **blue line** – numerical simulation; **dot** – experiment

Conclusion

This paper presents the results of modeling of single-hole fuel injection in internal combustion engines. Here, the liquid is injected in the form of droplets, which are assumed to have an average size comparable to the diameter of the nozzle outlet.

The paper presents the results of computational experiments to determine the optimal conditions for the combustion of liquid fuel (isooctane). The results obtained were compared with experimental data. There were conducted the processes of atomization and combustion of liquid fuel depending on various initial conditions. The influence of pressure in the combustion chamber on the processes of spray and dispersion of droplets at high turbulence were obtained. The optimal combustion parameters for isooctane are determined.

Acknowledgements

This work was supported by the Ministry of Education and Science of the Republic of Kazakhstan (No. AP08857288).

References

1 Beketayeva M., Gabitova Z., Bekmukhamet A., Bolegenova S. Control of harmful emissions concentration into the atmosphere of megacities of Kazakhstan Republic //Proc. of International conf. on Future Information Engineering. – Beijing, 2014. – Vol.10. – P. 252-258.

2 Bolegenova S., Beketayeva M., Leithner R., Ergalieva A., Nugymanova A. Computational modeling of heat and mass transfer processes in combustion chamber at power plant of Kazakhstan //Proc. of MATEC Web of Conferences. – 2016. – Vol. 76. – P. 5.

3 Askarova A., Bolegenova S., Georgiev A., Nugymanova A., Baizhuma Zh. The use of a new “clean” technology for burning low-grade coal in on boilers of Kazakhstan TPPs //Bulgarian Chemical Communications. – 2018. – Vol. 50. – P. 53-60.

4 Messerle V., Askarova A., Ustimenko A. Reduction of noxious substance emissions at the pulverized fuel combustion in the combustor of the BKZ-160 boiler of the Almaty heat electro power station using the "Overfire Air" technology //Thermophysics and Aeromechanics. – 2016. – Vol. 231. – P. 125-134.

5 Renard L. The automobile manufacturers' global competitiveness and dimension effects: Differentiation and cost advantages reconciled //International Journal of Automotive Technology and Management. – 2002. – Vol. 2, №3 (4). – P. 280-288.

6 Национальный доклад о состоянии окружающей среды и использовании природных ресурсов Республики Казахстан за 2019 год //Республиканская специализированная газета «Экология Казахстана». – 2020. – №9(056). – С. 8.

7 Befrui B., Corbinelli G., D'Onofrio M., Varble D. GDI multi-hole injector internal flow and spray analysis // SAE Technical Paper. – 2011. – Vol. 8, iss.1. – P. 1-11.

8 Prosperi B., Helie J., Bazile R. PIV measurements of injection pressure effect on gas entrainment in GDI engines / 21st Annual Conf. on Liquid Atomization and Spray Systems. – Mugla, 2007. – P. 1115-1121.

9 Wood A., Wigley G., Helie J. Analysis of Multi-hole GDI Injectors under Flash Boiling Conditions //17th Intern. Symposium on Applications of Laser Techniques to Fluid Mechanics. – Lisbon, 2014. – P. 1-10.

10 Mojtabi M., Chadwick N., Wigley G., Helie J. The effect of flash boiling on breakup and atomisation in GDI sprays //Proc. of the 22nd European Conf. on Liquid Atomization and Spray Systems. – Como Lake, 2008. – P. 1-9.

11 Wigley G., Mojtabi M., Williams M., Pitcher G, Nuglisch H. The Effect of Fuel Properties on Liquid Breakup and Atomization in GDI Sprays //10th Intern. Congress on Liquid Atomization and Spray Systems (ICLASS, 2006). – Kyoto, 2006. – Vol. 6. – P. 53-62.

12 Zeng W., Xu M., Zhang G., Zhang Y., Cleary D.J. Atomization and vaporization for flash-boiling multi-hole sprays with alcohol fuels //Fuel. – 2012. – Vol.95. – P. 287-297.

13 Askarova A., Ospanova Sh., et.al. 3D modelling of heat and mass transfer processes during the combustion of liquid fuel //Bulgarian Chemical Communications. – 2016. – Vol. 48. – P. 229-235.

14 Gorokhovski M. The stochastic Lagrangian model of drop breakup in the computation of liquid sprays //Atomization and Sprays. – 2001. – Vol. 1. – P. 169-176.

15 Amsden D.C., Amsden A.A. The KIVA Story: A Paradigm of Technology Transfer //IEEE Transactions on Professional Communication Journal. – 1993. – Vol. 36, №4. – P. 190-195.

16 Bolegenova S., Ospanova Sh., et.al. Investigation of various types of liquid fuel atomization and combustion processes at high turbulence //Journal of engineering and applied sciences. – 2018. – Vol. 13. – P. 4054-4064.

17 P. Safarik, V. Maximov Investigation of heat and mass transfer processes in the combustion chamber of industrial power plant boiler. Part 2. Distribution of concentrations of O_2, CO, CO_2, NO //Journal of Applied and Computational Mechanics. – 2018. – Vol. 12. – P. 127-138.

18 Askarova A., Bolegenova S., Beketayeva M. Modeling of heat mass transfer in high-temperature reacting flows with combustion //High Temperature. – 2018. – Vol. 56. – P. 738-743.

19 Askarova A., Safarik P., Nugymanova A., Bolegenova S. Minimization of toxic emissions during burning low-grade fuel at Kazakhstan thermal power plant //Acta Polytechnica. – 2020. – Vol. 60(3). – P. 206-213.

20 Ospanova Sh., Maximov V., Bolegenova S., Beketayeva M. The computational study of heat and mass transfer processes at combustion of pulverized kazakh coal in real conditions of energy objects //J. Bulgarian Chemical Communications. – 2018. – Vol. 50. – P. 61-67.

21 Askarova A., et al. Investigation of the different Reynolds numbers influence on the atomization and combustion processes of liquid fuel //Bulgarian Chemical Communications. – 2018. – Vol. 50. – P. 68-77.

22 Ospanova Sh., Berezovskaya I., et.al. Numerical simulation of the oxidant's temperature and influence on the liquid fuel combustion processes at high pressures //Journal of Engineering and Applied Sciences. – 2015. – Vol.10. – P. 90-95.

23 Beketayeva M.T., Bolegenova S.A., et al. Influence of boundary conditions to heat and mass transfer processes // International Journal of Mechanics. – 2016. – Vol. 10. – P. 320-325.

24 Mazhrenova N., Ospanova Sh., et.al. 3D modelling of heat and mass transfer processes during the combustion of liquid fuel //Bulgarian Chemical Communications. – 2016. – Vol. 48. – P. 229-235.

25 Ospanova Sh., Bolegenova S., et.al. 3D modeling of heat and mass transfer during combustion of solid fuel in BKZ-420-140-7c combustion chamber of Kazakhstan //Journal of Applied Fluid Mechanics. – 2016. – Vol. 9. – P. 699-709.

26 Arcoumanis C., Gavaises M. Linking nozzle flow with spray characteristics in a diesel fuel injection systems //Atomization and Sprays. – 1998. – Vol. 8. – P. 307–347.

References

1 M. Beketayeva et.al. Proc. Int. Conf. Future Inform. Engin. (Beijing, China, 2014), p.252-258.

2 S. Bolegenova et.al. Proc. of MATEC Web of Conf. (2016), p.5.

3 A. Askarova, S. Bolegenova, A. Georgiev, A. Nugymanova and Zh. Baizhuma, J. Bulg. Chem. Commun., 50, 53-60 (2018).

4 V. Messerle, A. Askarova and A. Ustimenko Thermoph.&Aeromech., 231, 125-134 (2016).

5 L. Renard Int. J. Aut. Techn.&Managm., 2 (3), 280-288 (2002).

6 Republican specialized newspaper "Ecology of Kazakhstan", 9(056), 8 (2020). (in Russ)

7 B. Befrui, G. Corbinelli, D'Onofrio M. and Varble D. SAE Tech. Paper, 8 (1), 1-11 (2011).

8 B. Prosperi, et.al. Proc. 21st An. Conf. Liq. Atom.&Spray Syst. (Mugla, Turkey, 2007), p.1115-1121.

9 A. Wood, et.al. Pros. 17th Int. Symp. Appl. Laser Tech. Fluid Mech. (Lisbon, Portugal, 2014), p.1-10.

10 M. Mojtabi, et.al. Proc. 22nd Europ. Conf. Liquid Atom.&Spray Syst. (Como Lake, 2008), p.1-9.

11 G. Wigley, et.al. Proc. 10th Int. Cong. Liquid Atom.&Spray Syst. (ICLASS, 2006) (Kyoto, Japan, 2006), p.53-62.

12 W. Zeng, M. Xu, G. Zhang and Y. Zhang Fuel, 95, 287-297 (2012).

13 A. Askarova, et.al., J. Bulg. Chem. Commun., 48, 229-235 (2016).

14 M. Gorokhovski. Atom.&Sprays, 1, 169-176, (2001).

15 Amsden D.C., Amsden A.A. IEEE Trans. Prof. Commun. J., 36(4), 490-195 (1993).

16 Bolegenova S, et.al. J. Eng. Appl. Sc., 13, 4054-4064 (2018).

17 P. Safarik, V. Maximov J. Appl. Comp. Mech., 12, 127-138 (2018).

18 A. Askarova, et.al. High Temp., 56, 738-743 (2018).

19 A. Askarova , et.al. Acta Polytech., 60(3), 206-213 (2020).

20 Sh. Ospanova, et.al. J. Bulg. Chem. Commun., 50, 61-67 (2018).

21 A. Askarova, et al. J. Bulg. Chem. Commun., 50, 68-77 (2018).

22 Sh. Ospanova, et.al. J. Eng. Appl. Sc., 10, 90-95 (2015).

23 M.T. Beketayeva, et al. Int. J. Mech., 10, 320-325 (2016).

24 N. Mazhrenova, et.al. J. Bulg. Chem. Commun., 48, 229-235 (2016).

25 Sh. Ospanova, et.al. J. Appl. Fluid Mech., 9, 699-709 (2016).

26 C. Arcoumanis, M. Gavaises. Atom.&Sprays, 8, 307-347 (1998).