Experimental investigation of spray propagation under crossflow conditions with Shadowgraph and Schlieren techniques

T S Zueva[1,3], L Weiss [2], M Wensing [2] and A B Garyaev [1]

[1] Department of Heat and Mass Transfer Processes and Installations, National Research University "Moscow Power Engineering Institute",
14 Krasnokazarmennaya Street, Moscow 111250, Russia
[2] Institute of Engineering Thermodynamics, Friedrich-Alexander University,
Am Weichselgarten 8, Erlangen D-91058, Germany

[3] ZuevaTS-1993@yandex.ru

Abstract. This paper is devoted to the description and analysis of the experimental results which were carried out to investigate sprays of liquid hydrocarbons under crossflow conditions. The experimental conditions corresponded to the injection conditions of gasoline sprays in a cylinder of an internal combustion engine. Two types of liquid hydrocarbons, isooctane and ethanol, were used as injected fuels. The injection pressure varied between 100 and 170 bar, the air crossflow velocity ranged from 0 till 50 ms^{-1} and the fuel temperature from 25 till 98 °C. Two optical methods, Shadowgraph and Schlieren, were used to visualize the spray movement over time. The boundaries of liquid and vapour spray phases as well as basic principles of spray propagation and evaporation under crossflow conditions were obtained after processing and analysing these images.

1. Introduction

According to the data of the International Energy Agency the consumption of oil products by all type of transport has been growing every year. In 2016 the total amount of consumed oil products was 2.531 billion tons of oil equivalent, in 2017 this amount has raised up to 2.588 billion tons of oil equivalent, showing a growth of 2.25%. Although alternative fuels become more popular with time, traditional hydrocarbon fuels still hold the position of the main automotive fuel. Thus, the current problem of reducing harmful emissions from all types of transport including cars stays significant.

The key point of solving this problem is to optimize the mixture formation process in the combustion chamber of an internal combustion engine. The theoretical fuel economy in modern direct injection engines in comparison with the port fuel injection engines is up to 60% in the idle regime, up to 35% in low and middle loaded regimes and up to 6% in full load regimes [1]. This economy is achieved due to three aspects of the direct injection engines that distinguish them from the engines with port fuel injection. The first is running the engine in a stratified mode in low load, middle load and idle regimes. The global air ratio λ in the cylinder at stratified mixture formation is more than 1. An ignitable fuel concentration is only provided in the small area close to the spark plug. The mixture in the other parts of the combustion chamber is lean. This fact also significantly reduces heat losses from the cylinder walls. The second is the reduction of throttling losses, since the necessary concentration of the fuel-air mixture is mainly achieved by controlling the amount of injected fuel instead of the air mass. The third component is an increase in the compression ratio. The heat expended on the evaporation of the direct injected spray is extracted from the ambient air in the combustion chamber. As a result, the probability of knocking is reduced, and thus the compression ratio can be increased. Due to the significant fuel savings in direct injection engines, the amount of CO2 emissions is lower accordingly.

The interaction of a crossflow with the fuel spray is an important mechanism for spray targeting and mixture formation. The incoming air during the intake phase induces such a crossflow in relation to the fuel spray [2-6, 10]. Thus, there is a research interest in spray investigations under crossflow conditions. This also includes the investigation of the phase interaction between liquid (spray) and gas (crossflow). In the fundamental researches about spray and jet flows [8-9] only the models of interaction "liquid jet – liquid medium" or "gas jet – gas medium" are described, i.e. the issues of interphase interaction are not considered, which makes them not applicable for modelling the movement of liquid sprays under crossflow conditions. Abramovich in his fundamental research [7] described separately the movement of spray with admixtures, the movement of gas sprays in liquid medium and gas spray influenced by gas crossflow. For this reason, it does not allow completely to describe double-phase sprays under crossflow conditions theoretically. At the same time, there is a large number of empirical equations and experimental data describing the spray trajectory and propagation, the movement of its centre of mass, spray velocity profiles, heat and mass transfer in the spray, etc. [2-6, 10]. However, any empirical equations that do not rely on basic theory have only a narrow range of application.

Due to cavitation the fuel exits the nozzle already as a two-phase flow. The fuel evaporates further until the saturation limit of the ambient gas is reached, just like water in dry air. The crossflow constantly supplies unsaturated dry air to the jet, which supports the evaporation process, preventing the establishment of a "vapor-liquid" equilibrium. However, the amount of the research about the mechanisms and driving forces of evaporation in sprays under crossflow conditions is currently limited [11-13].

Thus, there is a necessity to create a theoretically based and experimentally confirmed model that describes the hydrodynamics and heat and mass transfer in sprays of liquid hydrocarbons under cross flow conditions. The authors have previously published versions of a model describing the spray hydrodynamics under crossflow conditions [14]. Actual paper adds experimental approach and data acquisition to research the behaviour of such flows and to support the theoretical model.

2. Description of the experiment

The experiments were carried out at the laboratories of the Institute of Engineering Thermodynamics of the Friedrich-Alexander University (FAU) in Erlangen, Germany. The fuel injection set up is shown in figure 1.

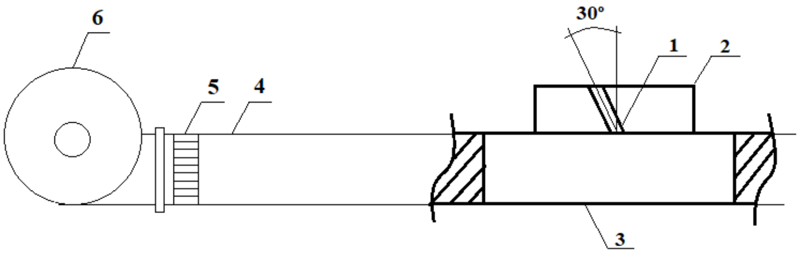

Figure 1. The fuel injection set up.

The numbers in the figure 1 indicate the following elements:

1 - a hole for the injector. This hole was made in the injector sleeve, it is designed to fix the injector at an angle of 30° to the vertical. As the nozzle in the injector is made at this angle to the vertical it is necessary to have the injector also at 30° to the vertical for keeping the spray injected exactly vertically down.

2 - an injector sleeve. It is a water container with inlet and outlet holes for heating liquid and an injector hole. The sleeve is needed for heat up the injector inserted into it. By heating up the injector, the injected fuel is also heated.

3 - an injection channel from acrylic glass. The inner section of the channel is a square with the size 70x70 mm. The channel walls are 4 mm thick.
4 - an air flow channel. This channel is needed to achieve a steady turbulent flow of air in it. The length of the channel is equal to 40 characteristic dimensions.
5 - a grid for flow stabilization. The size of the grid cells is 5 mm. The grid is also needed to stabilize the flow in the channel.
6 - a fan. It creates an air flow of the required speed.

The experimental parameters and values are shown in the table 1. The injection pressure is selected based on the injection pressure in real gasoline direct injection engines, which roughly varies from 100 to 300 bar. The crossflow velocity is also selected based on the velocity of the charge in the combustion chamber of the engine, which can reach 50 ms^{-1}.

Table 1. Experimental settings.

Parameter	Value
Injection pressure, bar	100, 170
Ambient pressure, bar	1
Crossflow velocity, ms^{-1}	0, 5, 15, 30, 50
Fuel type	Isooctane, ethanol
Temperature of isooctane, °C	25, 50, 85, 98
Temperature of ethanol, °C	25, 38, 50, 78, 98
Injector type	One-hole
Nozzle diameter, mm	0,17

Isooctane and ethanol were chosen as the injected fuels. It is known that, gasoline is a mixture of hydrocarbons, while isooctane is the closest substance to it in terms of physical, thermodynamic, and chemical properties. Ethanol is an important additive to petrol fuel, and its percentage in this fuel can be as high as 10%.

The fuel temperature was controlled with a water temperature control unit. Thus, the upper temperature limit was 100 °C. A typical fuel temperature in gasoline engines is 90 °C. However, for a wider research of heat and mass transfer and hydrodynamics, we investigated different fuel temperatures from ambient to 98 °C. First, we picked the boiling points of the fuel, which are 78 °C (ethanol) and 98 °C (isooctane) at a pressure of 1 bar. The idea was to investigate the behaviour of fuel sprays in a state close to boiling point. We also heated ethanol to 98 °C (the boiling point of isooctane), which is 20 °C higher than its own boiling point. This was done to research the injection of already boiling fuel into the crossflow. The intermediate temperatures were chosen based on the following considerations: the ratio of heat of vaporization and enthalpy at a pressure of 1 bar for each fuel was found. These ratios coincided at a temperature value of 85 °C for isooctane and 38 °C for ethanol. It was assumed that the evaporation pattern at these temperatures should be the same for two fuels, so these temperatures were included in the research. Also, the experiments were conducted at the same temperature of 50 °C for both fuels.

The one-hole injector was chosen for the experiments since the main goal of the research is a fundamental investigation of the principles of propagation and heat-mass transfer in spray under crossflow conditions. This injector allows to have only one single spray and as a result avoid the interaction between sprays. In real engines injectors with 5-6 holes are usually used.

Visualization of the injected process was performed by means of two optical techniques Shadowgraph and Schlieren, described in detail in [15-16]. The Shadowgraph technique visualizes only the liquid phase of the spray, while the Schlieren method allows to see both: the liquid and vapor phase of the spray. In Schlieren, parallel light rays are refracted by gradients in the optical density of a spray.

When light bundle is refocused, the parallel portion of the light has a slightly different focal point than the refracted light. This allows to block the refracted light with a so-called Schlieren knife-edge and a resulting image of a relief of the optical gradients in the spray is obtained. The optical density gradients are caused by differences in chemical composition, density, temperature or pressure.

The schemas of the two optical setups used are respectively shown in the figure 2 and figure 3. The numbering of the elements is continued.

7 – converging lens. The focal length is equal to the distance from the lens to the object 8.
8 – the slit with rectangular cross-section approximately 3x7 mm.
9,12 – parabolic mirrors. The focal length of the mirror 9 is equal to the distance to the object 8, the focal length of the mirror 12 is equal to the distance to the object 13.
10,11 – flat mirrors.
13 – knife edge.
14 – the pulse generator was set to constant mode.
15 – water heater with tubes for circulation of heating liquid. The liquid heats up the injected fuel.
16 – fuel system.
17 – fuel system control panel.
18 – injector control unit.
19 – highspeed camera recording at a rate of 20 000 images per second.
20 – trigger was used to synchronise the moment of the injection and the moment of the photo acquisition. It was also used to regulate the number of injections, the duration of injection and the delay time for the camera or the injector.
21 – PC.
22 – illuminated diffusion screen for creating a homogeneous light field.

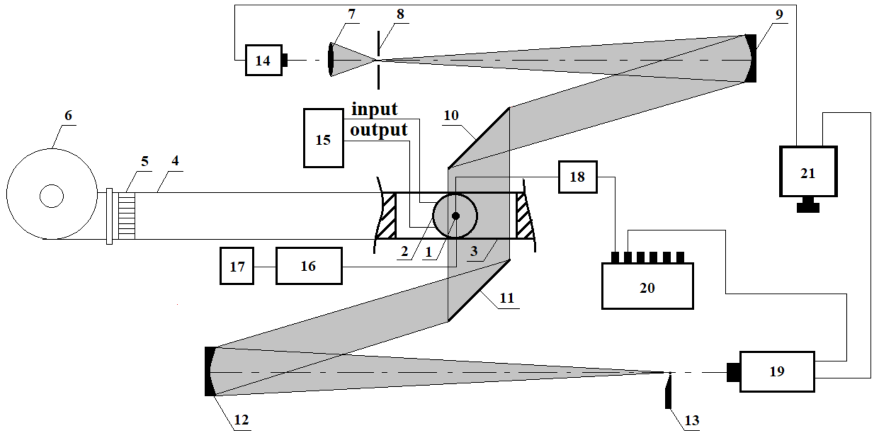

Figure 2. Schlieren set up.

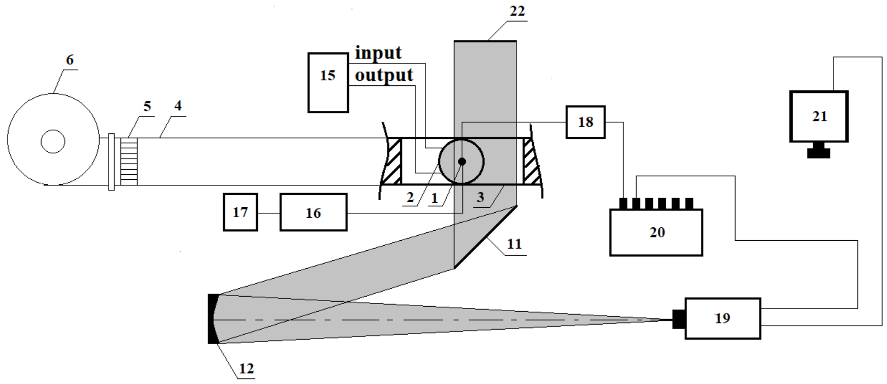

Figure 3. Shadowgraph set up.

The optical elements 7-13 must be perfectly symmetric about the axis of the injection channel to avoid distortion of the resulting image. Gray colour on the figure 2 and figure 3 shows the path of light rays. A diffusion screen 22 was installed instead of elements 7-10, 14 when assembling the set up shown in figure 3. On this screen during the experiment the shadow of the liquid phase of the spray was displayed and photographed.

3. Experimental results

The number of the injections were made during the experiment is 1400 (10 for each variation of the experiment). 200 photos of the spray were taken for each injection at different time points from 0 to 10 ms with the time step of 50 µs. The duration of fuel injection was 1.65 ms.

The photos of an ethanol spray made at different times at a pressure of 170 bar without crossflow are shown in the figure 4 and figure 5. The photos in figure 4 are made using the Shadowgraph method and in figure 5 using the Schlieren method.

The formation of the vapour is most typical for the spray boundaries regions. In addition, there are some "discontinuity" of the liquid phase in the spray, i.e., such areas where the concentration of the liquid phase changes in an abrupt manner, which is associated with turbulence in the spray.

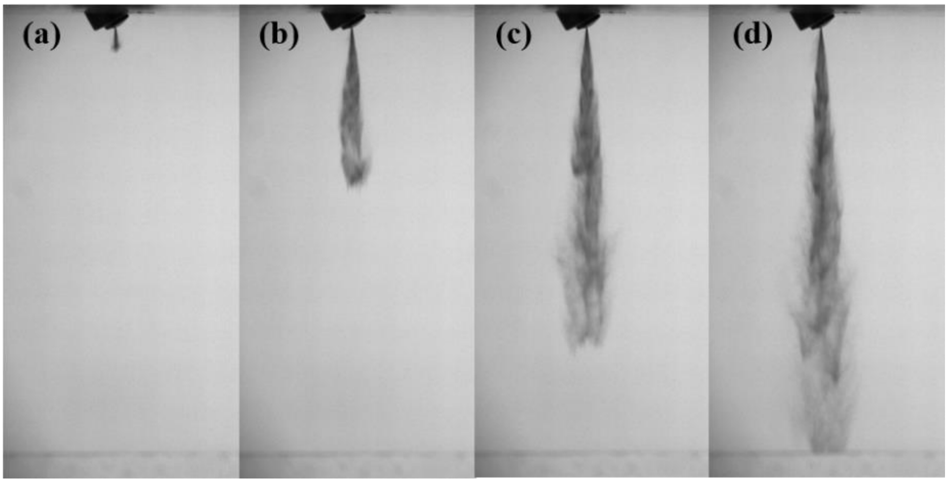

Figure 4. Ethanol sprays in different timepoints with Shadowgraph technique: a – 0.35 ms; b – 0.5 ms; c – 0.75 ms; d – 1 ms

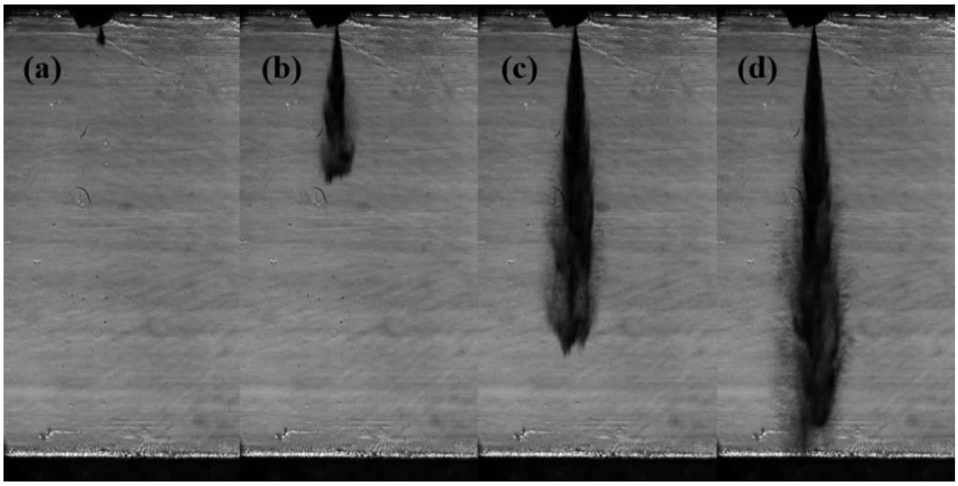

Figure 5. Ethanol sprays in different timepoints with Schlieren technique: a – 0.35 ms; b – 0.5 ms; c – 0.75 ms; d – 1 ms

The photos of ethanol and isooctane sprays influenced by the crossflow with the velocity of 50 ms^{-1} and temperature of the fuels 25°C are presented in figure 6. It is observed that the drift of ethanol spray is higher than for isooctane spray. Accordingly, the penetration is lower for ethanol.

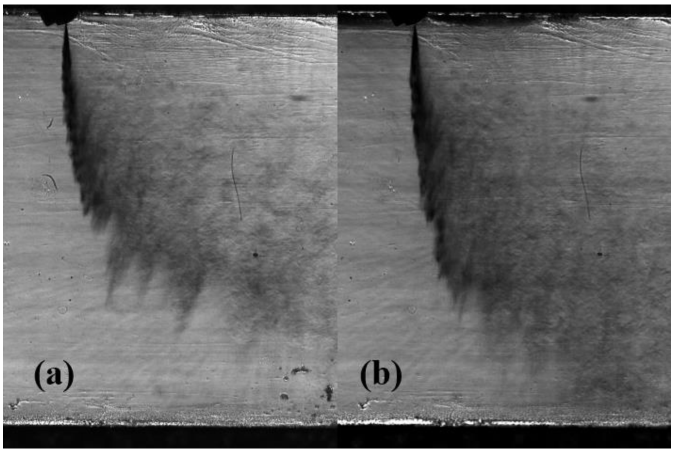

Figure 6. Drift for ethanol spray (a) and for isooctane spray (b) at the temperature 25 °C and crossflow velocity 50 ms^{-1}

Each photo has a certain number of pixels, and each pixel in its turn is characterized by a certain intensity. Pixels with background intensity were subtracted (background subtraction), then the boundaries of the liquid phase were determined from the pictures made by means of Shadowgraph technique, and the boundaries of the vapor phase were determined from the pictures made by means of Schlieren technique. Then the obtained borders were averaged, which is possible since 10 photos were taken for each moment of time. Figure 7 shows isooctane spays without crossflow with the temperature increased from 25 to 98 °C. The white dashed line shows the boundary of the liquid phase of the spray, and the solid black line shows the boundary of the vapor phase. These boundaries were defined by means of Matlab software.

While the photos in figure 7 are showing the same point in time, it can be seen that as the temperature increases, the spray propagation decreases, and the spray itself expands, which is associated with an increase in the vapor phase in the spray.

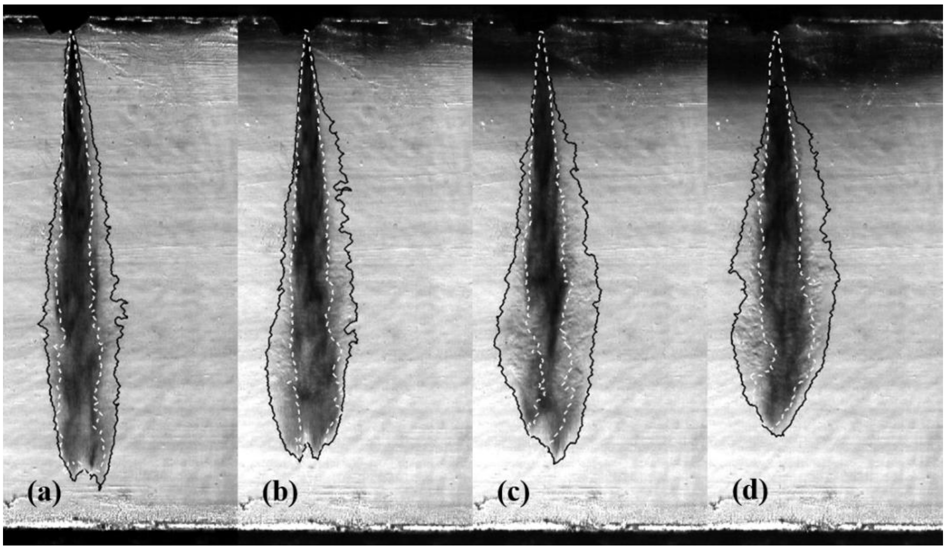

Figure 7. Isooctane sprays at the temperature of 25°C (a), 50 °C (b), 85 °C (c) and 98 °C (d) without crossflow

In addition, a difference in the behaviour of isooctane and ethanol sprays at the boiling point is observed. Figure 8 shows ethanol and isooctane sprays at the temperatures of 78 °C and 98 °C and the crossflow velocities of 5 and 30 m/s. The boundaries of the vapor and liquid phases for ethanol practically coincide (see figure 8 (b), (d)), while for isooctane it does not happen (see figure 8 (a), (c)). This behaviour persists for other velocities of the crossflow.

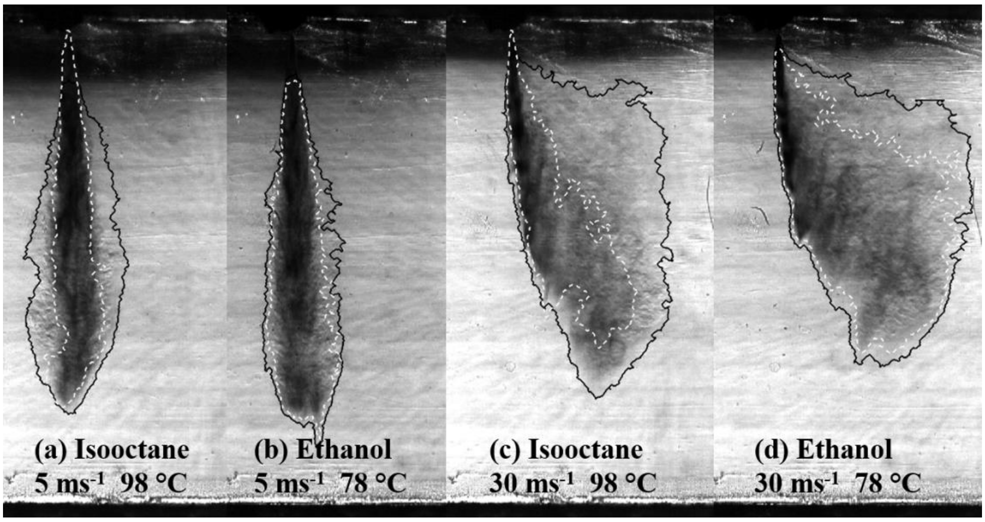

Figure 8. Isooctane sprays at the temperature 98 °C and crossflow velocity 5 ms^{-1} (a) and 30 ms^{-1} (c), and ethanol sprays at the temperature 78 °C and crossflow velocity 5 ms^{-1} (b) and 30 ms^{-1} (d)

4. Conclusions

A method for the determination of the boundaries of the vapor and liquid phases during the injection of hydrocarbon fuel sprays into a gas medium has been developed. The method is based on the processing of digital images obtained for the same flow by Schlieren and Shadowgraph techniques. By means of this method it is possible to estimate the proportion of liquid and vapor phase in the injected spray for different gas and liquid velocities, temperatures, and fuel type.

In addition, the results of the experiments revealed a few features of the propagation of liquid hydrocarbon sprays of different temperatures influenced by the crossflow of different velocities, which can include:

- the distribution of vapor and liquid in the spray is inhomogeneous. There are discontinuities – an abrupt change in the concentration – of the liquid phase in the spray.
- ethanol sprays are more strongly influenced by the crossflow than isooctane sprays. The concentration of the liquid phase in the isooctane sprays is higher than in the ethanol sprays.
- in the conditions without crossflow the spray propagation decreases with an increase of the fuel temperature, and the spray itself expands. It takes place because of the increase of the vapor phase in the spray.
- under the same injection conditions and temperatures close to boiling points, the boundaries of the liquid and vapor phases for ethanol sprays almost coincide, which is not valid for isooctane sprays.

The obtained results allow us to better and more precise describe the processes of hydrodynamics and heat and mass transfer in the combustion chamber of the engine to improve its overall efficiency and reduce the emissions.

Acknowledgments

Tatiana Zueva is grateful to German Academic Exchange Service and Ministry of Science and Higher Education of Russian Federation for financial support of her internship (project № 1207190) at Engineering Thermodynamics Institute of Friedrich-Alexander University and Prof. Dr.-Ing. Michael Wensing, as well as all scientific staff of the department, for scientific supervision of the research.

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