The atomization and burning of biofuels in the combustion chambers of gas turbine engines

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Abstract. The present work analyzes the effect of physical properties of liquid fuels with high viscosity (including biofuels) on the spray and burning characteristics. The study showed that the spray characteristics behind devices well atomized fuel oil, may significantly deteriorate when using biofuels, until the collapse of the fuel bubble. To avoid this phenomenon it is necessary to carry out the calculation of the fuel film form when designing the nozzles. As a result of this calculation boundary curves in the coordinates of the Reynolds number on fuel - the Laplace number are built, characterizing the transition from sheet breakup to spraying. It is shown that these curves are described by a power function with the same exponent for nozzles of various designs. The swirl of air surrounding the nozzle in the same direction, as the swirl of fuel film, can significantly improve the performance of atomization of highly viscous fuel. Moreover the value of the tangential air velocity has the determining influence on the film shape. For carrying out of hot tests in aviation combustor some embodiments of liquid fuels were proved and the most preferred one was chosen. Fire tests of combustion chamber compartment at conventional fuel have shown comprehensible characteristics, in particular wide side-altars of the stable combustion. The blended biofuel application makes worse combustion stability in comparison with kerosene. A number of measures was recommended to modernize the conventional combustors when using biofuels in gas turbine engines.

1. Introduction
The continuous improvement of the environmental requirements of ICAO (International Civil Aviation Organization) [1] makes to carry out new researches to develop low-emission gas turbine engines for aircraft and plants. Great promise in this trend is the use of renewable biofuels [2]. When using biofuel exhaust smoking decreases and also the emission of solid carbon, carbon monoxide and sulfur and the total carbon dioxide emission. Biofuels have, however, some features compared with conventional fuels, such as high viscosity and a low calorific value, which obstruct them atomization and burning.

The present work is work is researches [3-5] continuation. It analyzes the effect of physical properties of liquid fuels with high viscosity (including biofuels) on the spray and combustion characteristics concerning gas turbine engines (GTE) and plants.

2. Research technique
Experimental studies of the features of fuel–air sprays were performed at the Central Institute of Aviation Motors using laser diagnostics setup. The description of test bench is given in reference [3].
As the main object of study, a double-channel fuel burner with combined centrifugal-airblast design was chosen [5]. A pressure-swirl pilot channel with cylindrical outlet nozzle is mounted on the burner axis. The main fuel feed channel is airblast with a ring nozzle. It is placed between the two air swirlers. The outer radius $r_c$ of the fuel nozzle in a pneumatic atomizer is 11 mm and 0.55 mm in a pressure-swirl atomizer.

When designing injectors, a significant danger is the collapse of the fuel bubble, especially at low modes and for viscous fuels. To prevent this phenomenon, it is necessary to calculate the shape of the fuel film. Theoretical bases of the applied calculation method are set forth in [6]. The simplified system of mass and momentum conservation equations in the coordinate system connected with a film surface taking into account gravity forces was solved by numerical method. Initial data about a film thickness, spray angle, longitudinal and tangential liquid velocities were set from hydraulic design of an injector. For hydraulic calculations the program nozzle, based on a technique [7] with some refinements of authors was used. To model biofuels, mixtures of an ideal diesel with rapeseed oil of various concentrations were considered. Density $\rho_f$ and surface tension $\sigma_f$ changed weakly with the concentration of the mixture. However, the kinematic viscosity $\nu_f$ varied widely (from $4.17 \times 10^{-6}$ m$^2$/s for 100% of diesel to $88.62 \times 10^{-6}$ m$^2$/s for 100% of rapeseed oil).

3. The results of the investigation of the film shape for fossil and blended fuels

As is known [7], the shape of the film changes with Weber criterion for the fluid $W_e = \frac{\rho_w \nu_f \delta}{\sigma_f}$ ($\delta$ - film thickness, $\nu_f$ - fluid tangential velocity) which describes the ratio of inertia and surface tension. For small Weber numbers, the film takes the form of bubbles, breaking up at the beginning of the second wave. With Weber number increasing the gap moves toward the nozzle, another configuration is shaped in the form of tulip and the film breaks up during the first wave. With a further increase in the Weber number, the film break up into droplets near the nozzle, the spray takes the form of a cone. This mode is called spraying.

The calculated forms of the film behind the central nozzle when spraying the ideal diesel-rapeseed oil mixtures at fuel mass flow rate $G_f = 1.8$ g/s into the stationary air are shown in figure 1. As we can see from this figure, pure oil fuel (diesel) is sprayed by the atomizer. As the calculation shows, the Weber number decreases with liquid viscosity increasing. Viscosity is not included in this criterion, it in this case affects indirectly - through the change in the tangential velocity and the thickness of the fuel film at the nozzle outlet. With an oil percentage of 30 to 60%, the film takes the form of a tulip, and the spray mode is replaced by a break up mode. With an oil percentage of 70 to 100%, the fuel film collapses to form bubbles. The physical properties of the mixture with a 30-50
percent oil share roughly correspond to the widely used biodiesel (Fame). Consequently, a device that is well spraying petroleum fuels, may require additional air supply when using biofuels.

\[ u_a = 15, \quad w_a = 0 \]

\[ u_a = 0, \quad w_a = -10 \]

\[ u_a = 0, \quad w_a = 10 \]

Figure 2. Calculated forms of the diesel 20 % - rapeseed oil 80% mixture film behind the central nozzle with air supply; \( G_l = 1.8 \text{ g/s} \).

The calculated forms of fuel film with air supply are shown in figure 2. Here \( u_a \) and \( w_a \) are the axial and tangential air velocities. As one can see, the swirl of air surrounding the nozzle in the same direction, as the swirl of fuel film, allows the fuel spray to be opened at relatively low swirl speeds, in this case air increases the swirl of the film. When the air rotates in the opposite direction, the spray opening is worse, since the fuel swirl in this case decreases. The addition of the longitudinal velocity component weakly improves the spray openability.

Figure 3. Photos of the spray behind the peripheral nozzle; \( G_l=20 \text{ g/s} \); a - diesel 50 % - rapeseed oil 50% mixture without air supply; b, c – pneumatic spraying, \( \Delta P = 3 \text{ kPa} \); b) - diesel, kerosene; c) - diesel 50 % - rapeseed oil 50% mixture.

The opening of the fuel bubble behind the main nozzle for viscous fuels is significantly worse than for the pilot one, as the thickness of the film behind it is much greater. However, with pneumatic spraying, the spray angle is practically independent of the type of fuel. It makes more than 80º even for such viscous fuel as a mixture of 50% diesel with 50% rapeseed oil, since the spraying is determined by the swirling air flows (figure 3). In experiments, the average fuel mass flow rate was 3-4 m/s, air - about 20 m/s with a swirl of 45-60º.

It should be noted that the critical Weber numbers at which the spraying mode occurs depend on the fuel viscosity and the geometric parameters of the injector. The criteria that include these parameters are the Reynolds number of fuel at the nozzle exit \( \text{Re}_f = \frac{w_f \delta}{\mu_f} \), which expresses the ratio of inertia and viscosity, and the Laplace number \( \text{Lp} = \frac{\rho_f \delta \gamma / \mu_f}{\text{Re}_f^2 / \text{We}_f} \), which describes the relationship between surface tension and viscosity. Since the density and surface tension coefficient for the fuels considered varies slightly, the Laplace number characterizes the influence of the viscosity of the liquid fuel. For a particular fuel, that is, for a fixed Laplace number, the change in the Reynolds number characterizes the change in the fluid flow rate. These criteria can be used to determine the boundary curves for the break up of a jet or film. Figure 4 presents the calculated boundary curves in
the coordinates \( \lg \text{Re}_f - \lg \text{Lp} \) characterizing the transition from the break up of the "tulip" film to spraying for the central and peripheral nozzles of the device under investigation. Calculation results for some other pressure-swirl nozzles are shown too. In calculations for each type of fuel (i.e., fixed \( \text{Lp} \)), the mass flow rate of liquid, i.e. \( \text{Re}_f \), was increased until the spray took the conic form. Critical mass flow rates or transitional \( \text{Re}_f \) were determined for kerosene TS1, diesel, diesel-rapeaspeed oil mixtures of different concentrations, and so for kerosene 40% - FAME 60% mixture. Experimental points are also presented, which show that the calculated critical \( \text{Re}_f \) are very close to those measured. As can be seen from figure 4, in logarithmic coordinates, the boundary curves have the form of straight lines with the same inclination angle for injectors of different design.

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![Figure 4. Areas of film breakup of a centrifugal-pneumatic nozzle when spraying fuels of different viscosities into a fixed air environment; ■ - peripheral nozzle, calculation; ● - central nozzle, calculation; ○ - experiment; ▲ - pressure-swirl nozzle with \( r_c = 1.9 \text{ mm} \); ◀ - pressure-swirl nozzle with \( r_c = 0.2 \text{ mm} \); Lines - approximations by power functions.](image)

So in the coordinates \( \text{Re}-\text{Lp} \), the curves separating the regions of break up and spraying are described by a power function with the same exponent. The equations of these curves have the form

\[
\lg \text{Lp} = A \lg \text{Re}_f
\]

or

\[
\text{Lp} = \text{L}_{0\text{f}} \text{Re}_f^A
\]

where \( A = -\lg \text{L}_{0\text{f}}/\lg \text{Re}_0 = 1.92 \) for all injectors, \( \text{Re}_0 \) – Reynolds number appropriate break up– spraying transition at \( \text{Lp} = 1 \), \( \text{L}_{0\text{f}} \) - Laplace number appropriate the transition at \( \text{Re}_f = 1 \).

Formulas (1-2) make it possible to determine the boundaries of the spraying region for any injector the critical mass flow rate is known for a single fuel, for example, kerosene. In this case, it is possible to calculate the constant \( \text{L}_{0\text{f}} \) from (1) or (2), and then determine the transient Reynolds numbers for unconventional viscous fuels.

4. Hot tests in aviation combustor

For carrying out of hot tests in aviation combustor mixed biofuel on the basis of aviation kerosene (as most close relating to a turbine engine) has been chosen as alternative fuel. The combustion value of biofuels is significantly lower than that of fossil fuels. Furthermore, the viscosity of vegetable oils is ten times greater than the viscosity of the organic fuel. Therefore, for aircraft engines blend of biofuels with conventional aviation fuels is more preferable then pure biofuels. Various versions of a percentage ratio of components of combustible mixtures on the basis of plant oil and ethanol have been investigated. In the capacity of the main component aviation kerosene TS 1 and gasoline have been chosen. The mix in a ratio of 40% of kerosene TS 1, 20% of castor oil, 40% of ethanol has been chosen as the most homogeneous and well mixed without any precipitations and stratifications. It’s physical features are: \( \rho_f = 850 \text{ kg/m}^3 \), \( \nu_f = 4.7 \times 10^{-6} \text{ m}^2/\text{s} \), \( \sigma_f = 27 \times 10^{-3} \text{ N/m} \).

Hot tests were performed at the Central Institute of Aviation Motors using combusting chamber test rig. Fire tests of a burner with the low-emission aviation combustion chamber compartment has been conducted. Starts were conducted only on one pilot channel of a burner. Fuel mass flow rate ranged from 1 to 5.7 g/s. The part of the air arriving in the flame tube front, passed through air swirlers of the burner. Thus the centrifugal–pneumatic spraying was provided. The operation mode corresponded to the altitude of an order of 2 km.
Test results are given in figures 5-7. The curves of combustor’s blowout characteristics at different air excess coefficients $\alpha_C$ and total air volume flow rates $Q_C$ were obtained. Here $\alpha_C$ - the general excess-air coefficient in the combustion chamber - the relation of total air mass flow rate passing through the chamber to the air flow rate required theoretically for complete combustion of the fuel arriving at the same time in this chamber. So $\alpha_C < 1$ means rich fuel-air mixture and $\alpha_C > 1$ means lean mixture.

![Diagram](Q_c m^3/s vs \alpha_C)

**Figure 5.** Boundary lines of ignition and blowout in the combustion chamber compartment:
- ● – lean blowout; ■ – rich blowout.

![Flame photos](Flame photos)

**Figure 6.** Flame photos at various $\alpha_C$ from wake-up to lean blowout (kerosene).

![Flame photos](Flame photos)

**Figure 7.** Flame photos at various $\alpha_C$ mixed fuel from wake-up to lean blowout; mixed fuel.

The received blowout boundary line shows, that for conventional fuel (figure 5a, 6) the combustor steadily works (the area within the curve) in the coefficient of air excess $\alpha_C$ range from 1 to 10 and till $Q_C = 0.4 \text{ m}^3/\text{c}$. The area boundary reaches satisfactory values on $\alpha_C$, and comprehensible values on $Q_C$. The ignition domain (within the curve in figure 5a) is sufficient on the square for assured firing of the combustion chamber. When passing to blended fuel the lean blowout boundary is reduced from 10 to 6.5 at maximum volume flow rate. The flame colour (figure 7) changes while maintaining its overall structure due the reducing of combusting efficiency and flame temperature and the increasing of soot production.

Thus biofuel application makes worse combustion stability characteristics for aircraft engines in comparison with kerosene. At biofuel use it is necessary to provide a number of actions for modernization of conventional aviation combustion chambers. The main activities are the optimization of the fuel injection system to reduce the dispersion of droplets of fuel-air aerosol and the creation of a
sufficiently intensive and extended back-flow zone due to the swirler system. The optimized nozzle device [8] was designed and manufactured in CIAM. Comparative tests of a full-size combustion chamber on a high-altitude stand are carried out. Test results for a height of 7 km are shown in figure 8. As one can see from this figure, the boundary of the ignition region is $\alpha_C = 5$, which is almost twice much as for the base version. In this case it is also increased by 20% in volume flow rate in comparison with the base variant, reaching a value of 1.43 m$^3$/s. The boundary of the lean blowout is also significantly better for the variant with the new injectors. At an altitude of 7 km, $\alpha_C = 6$ for the original version, $\alpha_C = 10$ for the variant with the new nozzle and $\alpha_C = 12$ for the variant with the new nozzle and swirler. Thus, the combustion chamber equipped with a new injector module produced by CIAM showed better results on the ignition and lean blowout limits in comparison with the base version. These results make it possible to assume that the measures to improve the spraying in the combustion chambers will provide acceptable characteristics for the wake up and sustainability of combustion in the transition to alternative fuels in both aviation and stationary GTE.

**Summary**

Boundary curves in the coordinates of the Reynolds number on fuel - the Laplace number are built, characterizing the transition from sheet breakup to spraying. It was shown that the spray characteristics behind devices well atomized fuel oil, may significantly deteriorate when using biofuels, until the collapse of the fuel bubble. At biofuel use it is necessary to provide a number of actions for modernization of conventional aviation combustors. The swirl of air surrounding the nozzle in the same direction, as the swirl of fuel film, can significantly improve the atomization of highly viscous fuel. Moreover the value of the tangential air velocity has the determining influence on the film shape. The optimized nozzle device was designed in CIAM. The combustor with that device showed the better results on the ignition and lean blowout limits in comparison with the base version.

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![Figure 8. Ignition (dotted line) and lean flameout (thick line) boundary at 7 km altitude: blue line base injector, red line – new injector; green line – new injector with swirler; kerosene.](image-url)