Numerical and experimental investigation of gas dynamic and mixture formation in swirling flow behind the gas-stabilizer with azimuthal fuel supply

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Abstract. Numerical and experimental research of gas dynamic and mixture formation in multiphase swirling flow behind the gas-stabilizer with azimuthal fuel supply. Methodology of steady and unsteady calculation of liquid-droplet fuel distribution behind the gas-dynamic stabilizer is described and compared. Different approach for fuel supply are considered and analyzed. Space distribution of droplet mass concentrations for different swirl angles at the inlet are measured and compared with numerical simulation results.

1. Introduction
The questions of flame stabilization, despite their long history with more than half of century researchers work, is still very important for design of aviation engine combustion chambers. Existing trends in combustion chamber design - using of premixed combustion and multizones schemes, only increase the actuality of flame stabilization questions. Typically some types of bluff bodies, caverns or stabilizers are used for flame stabilizations. Another concept based on gas-dynamic stabilization, when combinations of jets and mixing layers used for build system with required pressure gradients and flow structure. For these scheme operational process can be managed through flow structure control by injected fuel and air velocity variation. In earlier works [1-3] scheme of combustion chamber with gas-dynamic stabilization were proposed and investigated, both numerically and experimentally. Current work continues investigations of this scheme for newly proposed way of liquid fuel supply, in opposite to previous works, liquid fuel is supplied in azimuthal direction. The scheme of device is shown at fig. 1.

Presented gas-dynamic stabilizer operating process control is carrying out by transversal air jets supply in swirling flow. In this case flame stabilization is taking place in recirculation zone behind the stabilizer front wall. This zone is forming by interaction between swirling airflow from swirler and air jets, which are injected in combustion chamber perpendicular to axis through the system of six holes. Fuel supply is also carrying out the system of six holes on cylindrical surface of stabilizer. Fuel jets supply with azimuthal angle Θ = 45° is considered in this paper. As it shown in previous works, main parameters, which control the cold flow structure in combustion chamber are impulses of injected masses of air and fuel. For characterize impulses three dimensionless parameters are proposed: swirl intensity $S_w$, intensity of transversal jets blowing $V_j$ and fuel injection velocity $V_f$. Here swirl intensity
of flow at swirler outlet is \( S_w = V_\phi/V_z \), blowing parameter is \( V_j = V_r/V_0 \), mean mass flow velocity of airflow through swirler is \( V_0 \); \( V_\phi \), \( V_z \) and \( V_r \) are rotating, longitudinal and radial velocity components correspondingly. In current work influence of liquid fuel supply in radial and azimuthal directions on fuel droplets sizes and distribution behind the stabilizer is analyzing.

![Figure 1. Photo of the combustion chamber fragment with central body](image)

2. Experimental investigation

Radial fuel supply was considered in papers [1-3]. It was shown that in these cases fuel distribution in jet cross section behind the swirler is sufficiently uniform and average droplet size in outlet jet is 30 – 40 \( \mu \)m. It was ascertained that optimal value of swirl intensity of airflow equals \( S_w \approx 0.6 \) (swirl angle \( \phi = 30^\circ \)). At this swirl intensity value and typical values of intensity parameter of transversal air supply through stabilizer in the range of \( V_j = 0.4 \div 1.2 \) parameter \( V_j \) has sufficient influence on flow structure and drop-liquid and vapor fuel concentration distribution behind the stabilizer. Comparison of calculation results for \( S_w = 1.0, V_j = 1.0 \) and \( S_w = 0.6, V_j = 0.6 \) showed that there is an agreement between simulation and experimental data with a tolerable accuracy in velocity profiles, forming droplets size and concentrations distribution.

Experimental study for fuel jets supply with azimuthal angle \( \Theta = 45^\circ \) was carried out in this research. Flow structures and recirculating zones behind the stabilizer were studied in the open space at distance 10 ÷ 50 mm downstream from stabilizer front wall. Unsteady flow was being detected by dust-laden flow registration in laser knife by digital camera filming. Pictures of spray cones in the open space for swirl angle of the airflow \( \phi_1 = + 30^\circ \) and \( \phi_2 = -30^\circ \) at slanting fuel supply are presented on figures 2a and 2b correspondingly, picture corresponding to radial fuel supply at \( \phi = 30^\circ \) is presented on figure 2c. Direction of fuel jets supply is considered as positive direction of swirling, \( G_f \) - fuel mass flow rate (kerosene TS-1), \( G_a \) – air mass flow rate, \( \Delta P \) – pressure drop on swirler.

![Figure 2. Atomization cone photo for kerosene and operating conditions \( G_f = 5.0 \) g/s, \( G_a = 47 \) g/s, \( \Delta P = 5 \) kPa and a) opposite swirl - 30°; b) co-swirling flow + 30°, c) radial fuel injection.](image)
These pictures show that maximum spray cone expansion occurs at radial fuel supply. Spray cone has minimum cross size when airflow swirling has same direction as droplet motion. Opposite direction of airflow swirling corresponds to transversal fuel velocity decrease at start and bell-type expansion of the cone at greater distance. Experimental research of spray cone characteristics is carried out by direct method of particle image processing Shadowgraph (PIS) of La Vision. This method of fuel droplets size and velocity obtaining is based on processing of series of droplets pictures in different spray cone cross sections.

Results of droplet longitudinal velocity components measurements at different distance from stabilizer front wall for swirl angles ± 30° are presented on figure 3 a-c.

**Figure 3.** Distribution of longitudinal droplet velocity for co-swirling flow (red line) and opposite fuel-air swirl (blue line) at different distances X from the front wall: a) X = 10 mm; b) X = 30 mm; c) X = 50 mm.

Fuel droplets velocities distribution shows that maximum droplet velocities in air-fuel mixture change insignificantly in axial direction downstream and equal approximately 30 m/s and 20 m/s for different swirling directions. Droplets size at constant medium properties is defined by difference of liquid and air velocities. Airflow longitudinal velocity component at swirler outlet corresponding to drop of pressure $\Delta P = 5$ kPa equals 63 m/s, rotational velocity component at swirl angle 30° equals approximately 36 m/s. Fuel jets flow velocity at mass flow rate 5 g/s equals approximately 10 m/s, azimuthal velocity component – 6 m/s. Thus, relative droplet velocity in circular direction equals 30 m/s and 42 m/s for two different swirling directions. Difference between these two values is relatively small – 12 m/s, hence droplets sizes in both cases are practically the same (figure 4). Results of droplet size measurements for airflow swirl angles ± 30° are presented on figure 4, SMD is average median droplet diameter, X is distance from stabilizer front wall.

**Figure 4.** Droplets sizes SMD for co-swirling flow (red line) and opposite direction swirl (blue line) at different distances from the front wall: a) X = 10 mm; b) X = 30 mm; c) X = 50 mm.

Thus, measurements showed that swirling direction has no significant influence on fuel spraying fineness in gas-dynamic stabilizer. Radial droplet size distributions appears to be very similar for different types of fuel supply: along, opposite and perpendicular to flow. Figure 4 shows that main part of droplet atomizing process occurs at distance 10 mm from stabilizer front wall. Maximum droplet size in spray cone at this distance equals approximately 80 µm, partial secondary atomization occurs downstream, hence peripheral cone droplet size equals 60 µm. Results for different swirl angles (±
30°) of fuel droplets mass flow rate $G_f$ distributions measurements in different cross sections behind the stabilizer are presented on figure 5. Droplet concentrations distributions in different cross sections are similar to presented ones.

![Figure 5](image)

**Figure 5.** Distribution of fuel mass flux for co-swirling flow (red line) and opposite direction of air-fuel swirl (blue line) at different distances from the front wall: a) X = 10 mm; b) X = 30 mm; c) X = 50 mm.

### 3. Numerical simulation

Problems of airflow simulation, spreading and breaking of fuel jets in airflow, fuel droplets motion and droplet-air mixture formation was solved in calculation research for obtaining of characteristics of the mixture formation behind the stabilizer. Methodology of this research consists of instantaneous airflow velocity fields obtaining, calculation of droplet motion in these fields, calculation of instantaneous fuel concentration fields, averaging and obtaining required characteristics of the mixture formation from fuel droplets and air in the working volume. Fluid dynamics computation is carried out using methodology presented in [1, 4], it is taking into account unsteady flow behavior. Calculation of fuel jet spreading in the airflow is carried out with simplified model [5] in this paper. According to this model configuration of injecting liquid jet is calculating with the assumption that the shape of jet cross section is staying constant along the direction of spreading, surface tension forces are neglecting in this case in comparison with aerodynamic forces. Computational results obtaining with these assumptions for jet atomizer with exit nozzle diameter 0.4 mm show that fuel jet break for ($S_w = 0.6; V_j = 0.6$) regime occurs at the distance $L^*$ approximately equaled 3 mm, jet incline angle towards stabilizer axis equals $\psi_m \approx 30^\circ$. Average median diameter (SMD) of formed droplets equals $D_m \approx 50 \mu m$ according to results obtained with calculation methodology [5]. Methodology of droplet-liquid fuel concentration fields calculation is based on analysis of single droplets motion. It is assumed that initial droplets size distribution is obeyed the Rozin-Rammler law with parameter $n = 3$: $\Omega = 1 - \exp[-(D/D_m)^n]$, and droplets circular (angle $\phi$) and longitudinal (angle $\psi$) directions distribution is obeyed the normal law. Here $\Omega$ – relative droplets part with the diameter smaller than $D, D_m$ – average median droplet diameter. Initial droplets velocities $V_0$ is given by absolute value $V_0$ and longitudinal and circular angles values : $\psi_m$ and $\phi_m$. Initial droplets escape coordinates are defined by solution of fuel jet break up in airflow problem, droplet escape angles are defined by experimental data of spraying in the free space. Average median droplet diameter in spraying cone $D_m$ is calculated using methodology [6], fuel mass flow rate $G_f$ for considered regime is specified as $G_f = 2.5 \text{ g/s}$. Fuel type is kerosene TS-1.

Methodology of concentrations fields calculation is taking into account unsteady airflow behavior. Averaging of this set of instantaneous velocity fields obtained on different iteration process stages is considered as average flow field. Fuel concentration calculations results in averaged flow field appear to be steady concentration field. Droplet motion trajectories and concentration fields (so-called instantaneous concentration filed) are calculating for each instantaneous velocity field. This set of instantaneous fields is averaging and considering as an averaged unsteady concentration field. Described methodology adequacy is proved by comparison of experimental data and computational results of velocity and concentration fields [1]. Concentration fields of liquid-droplet fuel $C_v$ obtained with steady (figure 6a) and unsteady (figure 6b) models calculations are presented on figure 6.
Figure 6. Mean liquid-droplet concentration $C_v$ in axial section, $S_w = 0.6$, $V_j = 0.6$: 
(a) steady model, b) unsteady model.

Comparison of results obtained with steady and unsteady models shows that distribution differs even qualitatively. Steady calculations show significant droplets separation at the outer flow boundary, while in the unsteady approach significant fuel part is concentrated near stabilizer. Thus, experimental research of spraying cone characteristics obtained with shadowgraphy method of air-droplets medium diagnostics with fuel supply at angle 45° from gas-dynamic stabilizer side surface showed that fuel injection in azimuthal direction leads to significant changes in velocity distribution behind the gas-dynamic stabilizer. Opposite swirling direction is expanding spraying cone, which leads to displacement of greater part of fuel mass flow towards the periphery of cone and decrease of longitudinal droplets velocity component. However, radial droplets size distributions in spraying cone for different types of fuel supply (along, opposite and perpendicular to flow) appear to be very similar for considered flow regimes.

It was shown that main process of droplets atomization occurs at distance lesser than 10 mm from stabilizer front wall. Maximum droplets size in spraying cone in this distance equals approximately 80 μm, partial secondary atomization occurs downstream, peripheral cone droplet size equals 60 μm.

4. Conclusions
Case of azimuthal liquid fuel supply for gas dynamic stabilizer scheme of combustion chamber were investigated numerically and for cold flow experimentally. Results for airflow regime $S_w = 0.6$ and $V_j = 0.6$ is discussed. Steady and unsteady calculations are carried out. It is shown that steady and unsteady calculations results differ significantly. Thus, unsteady calculation results show that main part of liquid-droplet fuel is concentrated within 40 mm radial distance from stabilizer axis and 50 mm distance from its front wall in longitudinal direction.

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