A method of air-blast atomization of foamed liquid fuels for advanced combustors of gas-turbine engines

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Abstract. The design of the combined nozzle module with bubbling and pneumatic spraying for the low-emission combustion GTE chamber has been carried out. Based on pervious work and literature analyze a prototype of new combined nozzle module with five places of bubbling air supplying were pre-designed. To pre-select the position of the emulsification holes and to determine the possibility of combining the emulsion and pneumatic spraying principles in one design a series of experiments was carried out. The first results obtained using even not optimized device, showed that in modes close to the ground start and idle, the quality of the fuel spraying was improved by 30 % using the method of low-flow fuel bubbling.

Symbols

\[ \Delta P_a \] pressure differential of the air, kPa;
\[ \Delta P_{ab} \] pressure differential of the air bubbling, kPa;
\[ G_{ab} \] mass flow rate of the air bubbling, g/s;
\[ G_f \] mass fuel rate, g/s;
\[ BAFR \] bubbling air fuel rate attitude;
\[ AAFR \] air fuel rate attitude;
\[ \psi \] spray angle, °;
\[ D_{32} \] Sauter mean diameter, mkm
\[ C_V \] volume fuel concentration

1. Introduction

The process of atomization and evaporation of liquid fuels is crucial for the efficient and reliable combustion chamber (CC) operation in modern gas turbine engines (GTE), and directly affects the level of harmful substances formation in the exhaust gases. International Civil Aviation Organization (ICAO) standards toughening [1] require the search for new highly effective methods of spraying, allowing to obtain a fine-disperse mixture which is homogeneously seeded with liquid fuel particles with air in the front part of the CC.

Classifications and descriptions of device operation, given, for example, in [2] can help in the search and selection of the spraying method.

One of the highly effective ways of liquid fuel breaking into droplets is the bubbling method, which consists of high-pressure air supplied directly into the atomizer fuel ducts. The process of liquid fuel and air bubbles mixture foaming and instantaneous spraying allows breaking the fuel film...
efficiently due to a rapid increase in air volume at the atomizer nozzle outlet. According to preliminary estimations even at low (up to 0.2 MPa) pressures of the mixed components, it is possible to obtain an aerosol with a mean Zauter particle diameter less than 30 µm.

However, the question of dilution and homogeneous mixing of the finely dispersed fuel-air mixture remains. The method of bubbling in pure form is not applicable in the GTE combustion chambers due to the small ratio of resulting mixture air and fuel flow rates. In connection with the above, a combination of this method with the pneumatic breaking and mixing method has been proposed. A fine-disperse mixing of high-density aerosol without significant coagulation and droplet size growth is a complex task in itself. Therefore, at this stage, the task of mixing of large air volumes hasn’t been set, the goal is to bring the fuel and air mass flows ratio to the level of 0.5 -1.

Another problem is that the GTE has a large amount of free air, but to raise its pressure much higher than the existing compressed total mass is problematic. Therefore, it is necessary to look for ways to reduce significantly the air pressure difference for bubbling.

The main measured parameters characterizing the spraying quality are:

- The mean Zauter drop diameter according to the numerous works in the start and the idle modes should be 20-40 µm.
- The angle of the fuel-air pattern at supplied components at various differences of for modern super short combustion chambers should be about 90º.
- The fuel droplets concentration distribution nonuniformity in the cross-section of the pattern should not be less than 25 % of the average value.
- A flow mode should be stable at least visually.

The possibilities to reduce the pressure of the air, which is going to the bubbling, depending on the location of the air supply, in particular, have been experimentally investigated. The features of the air supply to the fuel swirler ducts, and the fuel supply to the swirler have been revealed.

2. The experimental results

When choosing hole in the fuel tube wall for bubbling air, it is necessary to take into account a limited supply pressure and possible low air flow, as well as the specified final characteristics of the air-fuel pattern (its shape in the radial and circumferential direction; the stability of the angle; the absence of pulsation; the fineness of the spray). Five places of bubbling air supplying were pre-selected (Figure 1A). Besides, it was necessary to choose the diameter, number, and direction of the bubbling holes.

![Figure 1](image.png) **Figure 1.** Pre-selected of bubbling ducts position.

The supplying point 1 located in front of the slot jet would obviously require the highest emulsifying air supply pressure. It would not allow regulating fuel flow in a wide range without a rapid increase of emulsifying air flow. It should be expected that air supplied through the hole 1 would have the least impact on the pulsations formation due to better mixing on the jet. Based on this, it was decided to conduct preliminary experiments. The supplying point 2 allows slightly reducing the emulsifying air supply pressure but in general, has the same disadvantages as the air supplying through hole 1. Besides, the probability of pulsations and fuel-air pattern nonuniformity increasing would be
higher than in the supplying point 1. No tests have been carried out with this hole position. The supplying point 3 located at the screw ducts inlet allows slightly reducing the supplying pressure. This allows reducing the emulsifying air flow, and by the hole slope in the direction of the fuel flow it may affect the nonuniformity and stability of the spray pattern. Supplying point 4 is located in the middle of the screw. It allows significantly reducing the air supply pressure and keeping all the advantages of a close location 3. Tests have been carried out for supplying points 4 and 5. The supplying point 5 located almost at the outlet of the screw, has one serious advantage: the supply pressure of the emulsifying air becomes close to the differential on the front plate. This eliminates the need for an external source of emulsifying air.

The modification with the supplying point 4 and its version with an inclined inlet of emulsifying air was the main modification in the tests. The schematic diagram of this atomizer is shown in Figure 1b.

The spraying air flow passing through the swirler 1 and accelerating at the entrance of the nozzle 2 enters the edge 3 of the nozzle 2 and opens at a certain angle limiting the fuel-air pattern, and ensures its stability. The fuel getting into the grooves 4 of the screw 5 is twisted in the same direction as the air in the swirl 1. The auxiliary air passing through the holes 6 enters the grooves 4 of the screw 5 adjusting the fuel flow by "partial locking" and simultaneously drowning its flow to the screw 5 outlet forming a jet, a film, or a veil - depending on the auxiliary air presence and its amount. Tearing from the edge 7 fuel or fuel-air veil rushes to the edge 3 in the same direction as the opening angle of the spraying air swirling flow.

The results of experiments that were carried out to pre-select the position of the emulsification holes and to determine the possibility of combining the emulsion and pneumatic spraying principles in one design are given in Table 1. The cylindrical screw had a grooves inclination angle to the nozzle axis equal to 35°, the components temperature was 288 K. The holes for the fuel with air emulsifying were located in front of the slit jet, the diameter of the holes was 0.4 mm. The pattern was scanned at a distance of 30 mm.

### Table 1. The experiment results

| №  | \(\Delta P_a\), kPa | \(\Delta P_{ab}\), kPa | \(G_{ab}\), g/s | \(G_f\), g/s | BAFR | AAFR | \(\psi\), ° | \(\overline{D}_{32}\), mkm | \(\overline{C}_V\) |
|----|-------------------|-------------------|--------------|--------------|------|------|---------|----------------|--------|
| 1  | 0                 | 430               | 1.8          | 4.8          | 0.375 | 0    | 50      | 12             | 3.94   |
| 2  | 0                 | 430               | 1.55         | 9.5          | 0.163 | 0    | 52      | 23             | 8.66   |
| 3  | 0                 | 430               | 1.40         | 11           | 0.127 | 0    | 54      | 33             | 17.26  |
| 4  | 0                 | 430               | 1.20         | 12.6         | 0.095 | 0    | 56      | 40             | 23.43  |
| 5  | 48                | 0                 | 0            | 3.9          | 0     | 0.923| 65      | 12             | 6.56   |
| 6  | 51                | 0                 | 0            | 9.1          | 0     | 0.407| 63      | 17             | 9.97   |
| 7  | 25                | 0                 | 0            | 3.9          | 0     | 0.564| 69      | 23             | 8.74   |
| 8  | 27                | 0                 | 0            | 9.1          | 0     | 0.253| 71      | 31             | 14.98  |
| 9  | 17                | 430               | 1.2          | 12.6         | 0.095 | 0.214| 68      | 36             | 15.10  |

From table 1 it follows that the size of the droplets during bubbling, as well as during only pneumatic spraying increases with increasing fuel flow (see points 1-4 and 5-8).

To ensure the droplets sizes at emulsion spraying to be comparable to the sizes received at pneumatic spraying, the bubbling air had to be given at a pressure differential exceeding a pressure differential for pneumatic spraying by 8 times (see points 1 and 5). The addition of pneumatic air improves the results of emulsion spraying (points 4 and 9). The angle of the pattern with pure emulsion atomization was 10° less than that with pneumatic because the angle of the fuel screw grooves and the air swirler differed by 10° (35° and 45°, respectively).

Reducing the droplet size by two methods of spraying combination allowed continuing research in the selected direction to improve the results by optimizing the geometric parameters in the following nozzle modifications. To increase the spray pattern angle (up to \(\approx 90^\circ\)) in the following modifications the angle of the grooves to the screw axis was increased to 45°.
When the fuel is bubbling with air in front of the slit jet, a stable fuel-air pattern with a good atomization fineness is obtained but to achieve this result it is required, as noted above, to greatly increase the pressure differential $\Delta P_{ab}$ (up to 430 kPa). This is accompanied by a flow rate of bubbling air increase and fuel supply pressure increase at the same flow rate. Since such inflated values of pressure and flow rate of bubbling air do not agree with the requirement of their minimization, the main experiments have been carried out with the air supply through the holes with the outlet to the screw grooves 4 and 5 (Figure 1a).

![Figure 2](image1.png)

**Figure 2.** Models of screws with fuel bubbling by air for nozzles B1 (a), B2 (b) and B3 (c).

The screws with three options of bubbling holes were used in new models. The holes were located in each groove and had a diameter of 0.58 mm. In the 1st nozzle version (B1) with a screw shown in Figure 2a, the holes were located in the middle of the screw length. The axes of the holes were sloped to the axis of the screw at the angle of 55°. In the 2nd version of the nozzle (B2) these holes were made normal to the conical surface of the screw (85° to its axis), Figure 2b. In the 3rd version of the nozzle (B3) inclined holes were shifted to the output end of the screw, the distance from the center to the end of the screw was 1.4 mm (Figure 2c).

To select the best option of the three screws B1, B2, B3 (Figure 2a, b, c) some results of experiments carried out with one foaming atomization are presented in Table 2.

| №  | $\Delta P_a$, kPa | $\Delta P_{ab}$, kPa | $G_{ab}$, g/s | $G_f$, g/s | AAFR | BAFR | $\psi$, ° | $\bar{D}_{32}$, mkm | $\bar{C}_V$ |
|----|------------------|---------------------|-------------|----------|-------|-------|-----------|----------------|----------|
| 1  | 0                | 60                  | 0.48        | 3.12     | 0     | 0.154 | 83        | 63             | 7.5      |
| 2  | 0                | 113                 | 0.73        | 3.12     | 0     | 0.234 | 74        | 47             | 7.5      |
| 3  | 0                | 46.7                | 0.41        | 3.12     | 0     | 0.131 | 86        | 80             | 7.7      |
| 4  | 0                | 102                 | 0.676       | 2.99     | 0     | 0.226 | 82        | 52             | 8.7      |
| 5  | 0                | 55.3                | 0.47        | 2.99     | 0     | 0.157 | 97        | 62             | 8.7      |
| 6  | 0                | 102                 | 0.7         | 2.99     | 0     | 0.234 | 81        | 48             | 10       |

From Table 2 it follows that the nozzles B1 and B3 allow getting smaller drops than B2, while B3 allows obtaining the same SMD values at lower pressures than B1. At the same time, B1 allows obtaining a more stable shape and a smaller dependence of the spray root angle (only 9°) at the flow rate of bubbling air compared to the nozzle B3. Thus the slope of the emulsion holes to the screw axis and their placement at a distance from the output end of the screw exceeding 1.4 mm (as B1) are useful to obtain small droplets. The experimental data for nozzles B1 with pneumatic spraying is given in Table 3.
Having considered the points of the pneumatic spray 1, 2, and 4 from Table 3, it can be noticed that to improve the atomization fineness by about 2-5.5 times with the constant fuel flow, it is necessary to increase the pressure of the pneumatic air by about the same number of times. It is also seen that at the mode which is close to starting (point 1), only pneumatic spraying doesn’t allow achieving a good fineness of the drops. By increasing fuel flow at constant pneumatic air pressure differential close to the idling conditions (points 3 – 5), we get the weak SMD changing. Line 6 of the Table refers to the experiment with the front device around the nozzle. The blowing air reduces the coagulation of the droplets, therefore, by increasing slightly the pneumatic air pressure, it was possible to significantly reduce the droplet size and increase the stability of the pattern.

With increasing air pressure $\Delta P_{ab}$ from 32.4 kPa to 138 kPa the droplet size decreases at first by about the same number of times as $\Delta P_{ab}$ (points 7, 8), but with the further increase in $\Delta P_{ab}$, the droplet size begins to slowly increase at the modes with bubbling only. With increasing pressure approximately by 1.8 times up to 255 kPa the drop size increases by 14% (points 8, 10).

The additional supplying of pneumatic air with pressure differential $\Delta P_a$ up to 4 kPa had practically no impact on the droplet size (points 9, 10). But comparing points 1 and 9, we find out that the use of emulsifying air at low-pressure differentials $\Delta P_a$, corresponding to the start modes, allows reducing the size of the droplets about two times. With further increasing of $\Delta P_a$ pneumatic air begins to work actively, leading to a marked decrease in droplet size (points 11 - 13). At a pneumatic air pressure differential of 25 kPa, and the bubbling air pressure ranged from 100 to 170 kPa, the size of the droplets is no longer dependent on fuel flow (points 13 – 15) in the investigated modes. The last line of Table 3 shows that with a further increase of the pneumatic air pressure differential ($\Delta P_a \geq 25$ kPa) the use of bubbling air to obtain a satisfactory fineness of the spray at modes above the idle can be abandoned.

Thus the field of application of fuel emulsification by air is limited to start and idle modes. The addition of gas and liquid pulse flows provides better stability of the fuel-air pattern, and longer fuel stability in the high-speed air flow provides better atomization and the absence of droplets separation in size. A wide range of changes in the fuel flow rate is possible as a result of partial locking of the liquid supplying ducts with auxiliary air.

Based on the accumulated experience, the design of a combined nozzle module with bubbling and pneumatic spraying for a low-emission combustion chamber of GTE was carried out (Figure 3).

### Table 3. The experimental data

| №  | $\Delta P_a$, kPa | $\Delta P_{ab}$, kPa | $G_{ab}$, g/s | $G_a$, g/s | BAAR | AAFR | $\bar{D}_{12}$, mkm | $\bar{C}_V$ |
|----|-------------------|----------------------|---------------|------------|------|------|----------------|---------|
| 1  | 4                 | 0                    | 0             | 5.2        | 0    | 0.231| 111            | 12.2    |
| 2  | 10                | 0                    | 0             | 5.2        | 0    | 0.413| 45             | 8.5     |
| 3  | 25                | 0                    | 0             | 3.9        | 0    | 0.897| 20             | 4.1     |
| 4  | 25                | 0                    | 0             | 5.2        | 0    | 0.673| 20             | 5.2     |
| 5  | 25                | 0                    | 0             | 7.8        | 0    | 0.449| 22             | 6.7     |
| 6* | 33                | 0                    | 0             | 7.2        | 0    | –    | 13             | 3.2     |
| 7  | 0                 | 32.4                 | 0.37          | 3.9        | 0    | 0.095| 186            | 21.7    |
| 8  | 0                 | 138                  | 0.76          | 4.2        | 0.18 | 0    | 43             | 18      |
| 9  | 0                 | 168                  | 0.8           | 7.9        | 0.101| 0    | 48             | 19.7    |
| 10 | 0                 | 255                  | 1.1           | 3.9        | 0.282| 0    | 50             | 11.7    |
| 11 | 4                 | 280                  | 1.17          | 9.7        | 0    | 0.121| 0.123          | 51      |
| 12 | 5                 | 277                  | 1.16          | 3.9        | 0.297| 0.359| 38             | 7.3     |
| 13 | 25                | 134                  | 0.76          | 3.9        | 0.195| 0.897| 23             | 4.7     |
| 14 | 25                | 145                  | 0.78          | 5.2        | 0.15 | 0.673| 23             | 4.5     |
| 15 | 25                | 165                  | 0.8           | 7.8        | 0.103| 0.449| 23             | 4.2     |
| 16 | 33.1              | 27.5                 | 0.52          | 7.2        | 0.044| 0.583| 17             | 4.0     |

*with blowing air through the front
Figure 3. 3D model of the combined nozzle module prototype with bubbling and pneumatic spraying for a low-emission combustion chamber of GTE.

The experimental research of foamed liquid fuel spraying parameters at the CIAM laser diagnostics experimental setup was carried out. The results of preliminary tests showed that it was possible to improve the fineness of the fuel droplets by 25-30% without significant changes in the flow structure behind the outlet nozzle under conditions simulating the start of the combustion chamber.

Improving the quality of the fuel spraying will lead to an increase in the combustion completeness at low modes, to reduce the emission of harmful substances, and provide an opportunity to shorten the combustion chamber along the axial length, i.e. increase fuel efficiency.

Conclusions
The application field of the method of fuel foaming by air is limited to start and idle modes. The addition of gas and liquid pulse flows provides better stability of the fuel-air spray pattern, while longer fuel stability in the high-speed air flow provides better atomization and the absence of droplets separation by size. A wide range of changes in the fuel flow rate is possible as a result of partial locking of the liquid supply ducts with auxiliary air.

The atomizer module that combines the liquid fuels bubbling and pneumatic spraying methods for GTE low-emission combustion chamber has been designed based on the conducted research.

Improving the quality of the fuel spraying in such a module will increase the combustion efficiency at low modes, reduce the emission of harmful substances, and provide an opportunity to shorten the combustion chamber along the axial length.

It is necessary to continue the research in two directions: 1) conducting more in-depth comprehensive studies of the spraying method by bubbling and optimization of the experimental design; 2) determining the proposed method design features when it is integrated into the system of perspective TFE.

References
[1] Annex 16 2017 Environmental protection to the Convention on International Civil Aviation II (Aircraft Engine Emissions ICAO)
[2] Vasiliev A Yu 2007 Vestnik SGAU 2(13) 54–61