A study on the geometric characteristic influence on the liquid fuel flow in a three-way pressure-swirl atomizer

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Abstract. An important factor that affects the characteristics of combustion processes in the combustion chambers of aircraft engines is the fuel atomization. Semi-empirical methods are usually used to determine the characteristics of liquid fuel atomization by pressure-swirl atomizers. The input data for semi-empirical methods are the geometric parameters of the atomizer, as well as the spray cone angle and the nozzle discharge characteristic. These parameters can be obtained experimentally, which requires the availability of appropriate apparatus and a sample of a pressure-swirl atomizer, which is associated with significant material costs. An alternative way to determine these characteristics is to use numerical methods for modelling two-phase flows. Therefore, it is convenient to use a combination of empirical and numerical methods (hybrid method) to determine the spray parameters of a pressure-swirl atomizer. In this paper, we studied the effect of geometric and operating parameters on spray characteristics using the hybrid method, which includes the volume of fluid (VOF) numerical method and the semi-empirical equation. The calculation results are compared with empirical generalizations and experimental data of such parameters as the discharge coefficient, the air core ratio and the spray cone angle.

The results of this work were compared with the values of such parameters as the air core ratio and the spray cone angle obtained using the proposed method and analytical techniques.

1. Introduction

An important factor that affects the characteristics of combustion processes in the combustion chambers of aircraft engines is the fuel atomization. Semi-empirical calculation methods [1, 2, 3], three-dimensional calculation methods [4, 5, 6, 7, 8, 9, 10] and experimental studies [11, 12, 13] are used to determine the characteristics of liquid fuel atomization by nozzles.

Semi-empirical methods are based on an analytical model of fluid flow and fuel film breakup that uses experimental data to determine unknown coefficients in the model. To use semi-empirical methods, as a rule, it is necessary to specify the geometric parameters of the nozzle, the pressure drop, the spray cone angle, and the discharge characteristic of the atomizer. The last two characteristics are determined either experimentally or as a result of numerical simulation of two-phase flows by computational fluid dynamics methods. To conduct experimental research, it is necessary to manufacture a prototype, as well as the availability of appropriate apparatus and measuring equipment, which leads to significant material costs. Numerical methods allow us to solve this problem of a lack of material resources.
However, reliable and accurate methods of their application are necessary for the effective use of numerical methods.  
Currently, there are two approaches for modeling two-phase flows: the Euler-Lagrange and Euler-Euler methods. In the Euler-Lagrange method, the trajectories and parameters of individual material points are calculated, the size of which can be neglected at certain time intervals. This method is most often applied in two-phase flows simulations, because of its small resource-intensive method relative to the first one [14].

Euler's approach involves modeling the primary breakup of a liquid [7]. One of the most common Euler methods described in existing publications is the Volume of Fluid (VOF) method [15]. In the VOF method, the volume fraction of liquid in cell C is used as a function indicating a two-phase flow. At C = 0, the cell is filled with a gaseous phase (for example, air), at C = 1, the cell is filled with a liquid phase (for example kerosene). The interface between two media from this function is determined at a value of C = 0.5 [16].

In recent years, researchers have been actively developing hybrid methods for calculating spray parameters with atomizers of various configurations. In [5], a method was developed that allows calculating large fluid structures by the Euler–Euler method, and small-scale structures by the Euler–Lagrange method. Good agreement is obtained on the uniformity of the droplet mass distribution with the experimental data. In [7], the VOF method was used to calculate the jet breakup of aviation kerosene in a blowing air stream, where the discrepancy between the experiment results and calculations of Sauter Mean Diameter does not exceed 15%. This method involves the use of data obtained from the calculations by the VOF method in the DPM method. The application of these methods for a plain-orifice atomizer was shown, however, nothing is said about the application of this approach for pressure-swirl atomizers, that is, there is no data on the possibility of estimating the spray cone angle and the distribution of droplets in the spray cone.

Apparently, the three-dimensional calculation of the spraying process by atomizers requires a large computational resource, so the question also arises of how to reduce production costs to obtain spray parameters. In [17], to determine the approximate initial droplet diameter, a calculation was performed with the VOF model in a two-dimensional axisymmetric formulation, then with the DPM model, obtaining good agreement for the Sauter mean diameter. The disadvantages of the two-dimensional formulation for calculating the spray can be attributed to the fact that in such a formulation it is not possible to estimate the spray cone angle for a pressure-swirl atomizer or such a parameter as the uneven distribution of droplets in the spray cone.

In addition, at the design stage of atomizers for combustion chambers of gas turbine engines it is important to determine the breakup form of the liquid film depending on the operating parameters and the characteristics of the atomizer geometry. There are recommendations on the forms of film breakup depending on the Weber number, but they do not take into account the features of the geometric parameters of pressure-swirl atomizers (number of input channels, the ratio of nozzle diameter to its length, etc.), therefore their applicability is limited.

Accordingly, to solve the problem of determining spray parameters, such as the spray cone angle, droplet Sauter mean diameter and uneven distribution of droplets in the spray cone, a combination of Euler-Lagrange methods, Euler-Euler methods (VOF model) and semi-empirical methods can be used. In this case, the VOF method can be used to determine the characteristics of the liquid film primary breakup in pressure-swirl atomizers, such as discharge characteristic, flow coefficient, spray cone angle, and then, nozzle parameters such as nozzle fill factor and the fuel film thickness can be obtained from this data. Thus, the objectives of this study are:

1. Adapt the primary spray calculation method by the VOF method for pressure-swirl atomizers.
2. Calculate the spray angle, nozzle fill factor, and nozzle discharge coefficient by the hybrid method, which includes VOF and a semi-empirical method.
3. Study the dependence of the modes and forms of liquid jet breakup depending on the geometric parameters of pressure-swirl atomizers.
2. A semi-empirical model

To validate the method used to calculate spray parameters from a pressure-swirl atomizer, the method presented in [2] was used. The initial data for this method includes the geometric parameters of the nozzle, flow characteristics, and physical properties of the investigated fluid.

The spray cone angle in this method is defined as:

\[ \alpha = 2 \cdot \arctan \frac{u}{w}, \]

where

\[ u = \frac{2 \cdot \mu \cdot A_e \cdot (1 + S_B)}{1 + S_B} \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho_f}}, \]

\[ w = \sqrt{1 - \Delta s \cdot \mu^2 - \left( \frac{2 \cdot \mu \cdot A_e \cdot (1 + S_B)}{1 + S_B} \right)^2 \cdot \frac{2 \cdot \Delta P}{\rho_f}} \]

axial and tangential flow velocities at the nozzle exit, respectively.

To calculate the discharge coefficient \( \mu \), the following formula is used:

\[ \mu = \frac{1}{\sqrt{\frac{A_e^2}{1 - \varphi_n} + \frac{1}{\varphi_n^2} + \Delta s}} \]

where \( R \) is the swirl radius, \( r_n \) is the radius of the nozzle, \( \beta_c \) is the angle of the inlet channels relative to the nozzle axis, \( \epsilon \) is the deformation coefficient of the inlet stream, determined by the experimental dependence [2], \( n \) is the number of inlet channels, \( f_{in} \) is the area of the inlet channels, \( \varphi_n = 1 - \frac{r_a^2}{r_n^2} \) is the nozzle fill factor, \( r_a \) is the radius of the air core, \( r_n \) is the radius of the atomizer nozzle.

The equivalent geometric characteristic \( A_e \) is a characteristic of pressure-swirl atomizers, and was calculated according to the equation given in [2]:

\[ A_e = \frac{R \cdot r_n \cdot \pi \cdot \sin \beta_c}{(1 + \theta) \cdot \epsilon \cdot n \cdot f_{in}} \]

The complex \( \theta \) for calculation characterizes the effect of the walls inside the swirl chamber on the angular momentum, \( \lambda_{in} \) is the friction coefficient in the swirl chamber, \( R_c \) is the radius of the swirl chamber.

3. Numerical setup

The injector scheme is shown in Figure 1. Numerical simulation of the spray processes was carried out for the pressure-swirl atomizers, presented in table 1. The ratio of the nozzle length to its diameter remained constant at 2. The angle of the inlet channels relative to the nozzle axis is 65°, the number of inlet channels is 3. Overpressure was set at the fuel inlet in the computational domain.

![Figure 1. The injector scheme: 1- spring; 2 – screw; 3- nozzle](image-url)
Table 1. Configuration for pressure-swirl atomizer calculations

| №  | Dn, mm | Inlet gauge pressure, atm. | Ae    |
|----|--------|----------------------------|-------|
| 1  | 0.25   | 10                         | 0.291 |
| 2  | 0.35   | 1-10                       | 0.337-0.468 |
| 3  | 0.40   | 10                         | 0.535 |
| 4  | 0.50   | 0.5-10                     | 0.486-0.689 |
| 5  | 0.75   | 10                         | 1.1   |
| 6  | 1.00   | 10                         | 1.52  |

To simulate the spraying process using the VOF method, a hybrid mesh model was generated, in which the elements are structured in the spraying area and atomizer nozzle. The initial number of elements in the calculation area is about 1 million, but when using the local mesh refinement function in the calculation, the number of elements increased to 2.5 million, with a minimum element size in the nozzle of 12 μm. The generated mesh model is shown in Figure 2.

![Figure 2. A mesh model of the computational domain of the pressure-swirl atomizer](image)

The calculation of a pressure-swirl atomizer by the volume of fluid method (VOF) is implemented in commercial software ANSYS 18.2 [18]. The calculations were performed in a three-dimensional non-stationary formulation, with the k-omega turbulence model [5].

4. Results and discussion

Figure 3 shows the comparison of the p-q curve, calculated by the VOF method, with experimental data of the pressure-swirl atomizer.
Figure 3. The discharge characteristic

The discrepancy between the experimental values of the p-q curve and the values of the simulation by the VOF method does not exceed ± 5%. Figures 4, 5, and 6 show the comparison of the spray cone angle, discharge coefficient and nozzle fill factor obtained using the VOF method, an empirical method from [1] and the hybrid method, which depends on the parameter Ae. The hybrid method is based on the semi-empirical Dittakin's method [2], where the p-q curve obtained by the VOF method was used as the input data.

Figure 4. The dependence of the spray cone angle on the value of the equivalent geometric characteristic

An analysis of Figure 4 shows that when the geometric characteristic values are greater than 0.5, the spray cone angle values obtained in the CFD simulations by the VOF method using the hybrid method and the experimental values agree well with each other, but diverge from the generalized curve [1].
Figure 5. The dependence of the discharge coefficient on the value of the equivalent geometric characteristic

Figure 5 shows that the values of the discharge coefficient obtained by the VOF method and the hybrid method begin to diverge at geometric characteristic values greater than 0.5, while the values obtained using the hybrid method approximate the generalized curve as the value of $A_e$ increases.

Figure 6. The dependence of the nozzle fill coefficient on the value of the equivalent geometric characteristic

The discrepancy between the calculated characteristics and empirical dependencies can be explained by the fact that at small values of the geometric characteristic there is no air vortex inside the nozzle of the atomizer, which can be seen from Figure 6. This means that there is a conversion stage in which an air vortex is formed in the nozzle. It can be deduced from Figure 6 that this mode is in between values of the atomizer geometric characteristic of 0.45 ... 0.7.

To analyse the features of the conversion stage, we considered the pictures of fuel atomization of the regimes that are in the specified range at a pressure drop of 10 atm. (Figure 7). It can be seen from the figure that with a nozzle diameter of 0.35 mm ($A_e = 0.468$) no air vortex is formed inside the nozzle, whereas with a nozzle diameter of 0.5 mm ($A_e = 0.689$) the air vortex is present. This circumstance confirms that to obtain reliable results, it is necessary to use methods that combine three-dimensional calculation methods and semi-empirical methods.
5. Summary
A computational and experimental study of the dependence of the characteristics of the primary spray was carried out. The results are as follows:
- a hybrid methodology was developed for calculating the spray cone angle, discharge characteristic, and nozzle fill factor, including the VOF numerical simulation method and semi-empirical method;
- at values of the geometric characteristics greater than 0.5, the values of the spray cone angle obtained in CFD VOF method, using the hybrid method, and the experimental values have a good agreement with each other;
- with a nozzle diameter of 0.35, there is no air vortex inside the atomizer nozzle, which is not taken into account in semi-empirical methods; therefore, to obtain reliable results, it is necessary to use methods that combine three-dimensional calculation methods and semi-empirical methods.

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References
[1] Vitman L A, Katsnel'son B D and Paleyev I I 1962 Raspylivaniye zhidkosti forsunkami (Leningrad: Ripol Klassik)
[2] Dityakin Y F , Klyachko L A, Novikov B V and Yagodkin V I 1977 Raspylivaniye zhidkostey (Moscow: Mashinostroyeniye)
[3] Didenko A A 1996 Issledovaniye kachestva raspyleniya topliva i yego vliyaniya na kharakteristiki kamer sgoraniya malorazmernykh GTD Ph.D. thesis (Samara: Samara State Aerospace
University)

4. Sipatov A M, Karabasov S A, Gomzikov L Y, Abramchuk T V and Semakov G N 2015 Modelirovaniye protsess s raspyla s ispol'zovaniem adaptivnykh setochnykh modeley Vychislitel'naya mekhanika sploshnykh sred vol 2(45) (Perm': Permskiy federal'nyy issledovatel'skiy tsentr UrO RAN) pp 93-101

5. Kutsenko Y G 2017 Metody raschota i analiza dlya modelirovaniya protsess s raspyla zhidkogo topliva Sbornik trudov X Mezhdunarodnoy nauchno-tekhnicheskoy konferentsii (Samara: Samara University) pp 32-3

6. Kazimardanov M and Zagitov R 2019 Numerical simulation of kerosene atomization in injector of a gas turbine engine High-Energy Processes in Condensed Matter AIP Conf. Proc. 2125 ed Vasily Fomin (Novosibirsk AIP Publishing,) pp 030050-1-7

7. Inoue C, Shimizu A, Watanabe T, Himeno T and Uzawa S 2015 Numerical and experimental investigation on spray flux distribution produced by liquid sheet atomization Turbo Expo: Power for Land, Sea, and Air (Vol. 56697, p. V04BT04A022). American Society of Mechanical Engineers

8. Herbert D A, Schmidt D P, Knaus D A, Philips S and Magari P 2008 Parallel VOF spray droplet identification in an unstructured grid. ILASS Americas, 21st Annual Conf. on Liquid Atomization and Spray Systems, Orlando, Florida.

9. Strokach E A 2017 Chislennoye modelirovaniye rabochego protsess v kamere sgoraniya raketnogo dvigatelya maloy tyagi s tsentrobezhnymi forsunkami Ph.D. thesis (Moscow: Moscow Aviation Institute)

10. Sun Y, Alkhedhair A M, Guan Z and Hooman K 2018 Numerical and experimental study on the spray characteristics of full-cone pressure swirl atomizers Energy vol 160 (Amsterdam: Elsevier) pp 679-92

11. Fischer A A, Andrade J C and Costa F 2017 Spray Cone Angles by a Pressure Swirl Injector for Atomization of Gelled Ethanol Proc. of COBEM-2017 (Brazilian Institute for Space Research, Cachoeira Paulista)

12. Ghate K and Sundararajan T 2019 Influence of Convergence Angle on Hollow Cone Spray Characteristics Proc. of the 6th International Conf. of Fluid Flow, Heat and Mass Transfer (Avestia Publishing, Ottawa).

13. Sforzo B A, Kastengren A L, Matusik K E, Gomez del Campo F and Powell CF 2019 X-Ray Phase Contrast Imaging of Liquid Film and Spray Development Inside an Aircraft Engine Swirler Journal of Engineering for Gas Turbines and Power 141 American Society of Mechanical Engineers

14. Yun A A and Krylov B A 2007 Raschet i modelirovaniye turbulentnykh techeniy v teploobmennikakh, smeshivaniye, khimicheskiye reaktii i dvukh faznyye protsessy v programnykh kompleksakh Fastest-3D (Moscow: Izdatel'stvo MAI)

15. Hirt C W and Nichols B D 1981 Volume of Fluid (VOF) method for the dynamics of free boundaries Journal of Computational Physics vol 39 (New York: Academic Press) pp 201-225.

16. Hrabryy A I 2014 Chislennoye modelirovaniye nestationarnykh turbulentnykh techeniy zhidkosti so svobodnoy poverkhnost'yu Ph.D. thesis (St. Petersburg: St. Petersburg State Polytechnic University)

17. Verma N, Manoj Kumar K, Ghosh A 2017 Characteristics of aerosol produced by an internal-mix nozzle and its influence on force, residual stress and surface finish in SQCL grinding Journal of Materials Processing Technology vol 240 (Amsterdam: Elsevier) pp 223-32

18. Ansys Inc. http://www.ansys.com/