The effect velocity and direction of swirling air flow on the formation spray downstream of pressure swirl nozzle

A A Sviridenkov and E I Sokolova

Central Institute of Aviation Motors named after P.I. Baranov, Russia

aasviridenkov@ciam.ru

Abstract. One of the methods for generation a finely dispersed spray for pilot nozzles, used in modern aircraft engines widely, is co-rotating or counter-rotating directed relative to the direction of movement of the fuel film, air flow swirl. Therefore, it is interesting to investigate the shape of the liquid film and its disintegration at low fuel consumption. In the present work, the influence of the speed and direction of the air flow on the main characteristics determining the dispersion and shape of the spray pattern downstream the pressure swirl nozzle was investigated. The mathematical model of the film motion in a curvilinear coordinate system associated with the film surface to obtain the basic characteristics of the spray was used. The main attention was paid to the spraying characteristics in the initial phase of the formation of the spray at the calculations carried out according to this model. Calculations showed that the swirling air flow helps to open the entire cone spray angle, however, the initial angle of the spray is smaller than in the absence of air flow near the nozzle with opposite swirling. The work also showed that swirling air flow reduces the thickness of the fuel film in the immediate vicinity of the nozzle almost the same, regardless of the direction of its rotation. The effect of the swirling air flow on the average sizes of atomized fuel droplets based on the calculation of the thickness of the fuel film, its speed and the cone angle of the spray data were obtained. The results are compared with the available experimental date.

1. Introduction

The airblast atomizers are widely used to create fine atomization spray in various sectors of industry. They are simple to manufacture and the characteristics of the spray created by them are easy to obtain using modern calculation methods. The ongoing stricter of ICAO requirements to limit emissions of harmful substances into the atmosphere, as well as environmental safety, necessitate the organization of new constructive methods of burning fuel. Recently, combustion chambers having coaxial burners, consisting of peripheral main airblast nozzles with preliminary lean mixing, and a central pilot pressure swirl nozzle, with an air swirl located around it, are widely used. Such a scheme for organizing atomization and subsequent combustion of fuel made it possible to satisfy the existing emission standards for large turbofan engines with a margin. The shape of the liquid film from the orifice of a pressure-swirl atomizer is a cone at fuel supply pressures exceeding the critical value of the pressure difference. The shape of the liquid film varies from a cone to a tulip and, finally to an onion bubble, as the fuel supply pressure decreases. When the liquid film breaks down into a tulip and onion, the spray quality is significantly impaired. The introduction of swirling air around the body of the pressure swirl nozzle can improve atomization, especially at low fuel supply pressures.
An analytical solution describing the shape of a liquid film of an ideal liquid downstream a pressure swirl nozzle was obtained in [1]. It was shown that for small values of the Weber criterion \( W_{e1} = 0.5 \rho_1 w_{0g} h_0 / \sigma \), the film takes the form of a bubble, breaking at the beginning of the second wave. Here \( \rho_1 \) is the fluid density, \( w_{0g} \) is the peripheral fluid velocity at the average radius of the annular jet in the atomizer nozzle, \( h_0 \) is the thickness of the fluid film at the nozzle exit, and \( \sigma \) is the surface tension coefficient. With an increase in the Weber number, the place of the film break-up is shifted to the nozzle, and another shape is formed in the form of a tulip and the film breaks up during the first wavelength. The behavior of the axis of a symmetric hollow liquid film in the presence of a pressure difference between its internal and external volume bounded by a liquid film theoretically and experimentally was studied in [2]. The developed mathematical model of the behavior of a rotating ring film of a viscous liquid, based on the equations of motion of a liquid film in the coordinate system associated with the surface of the film, made it possible to determine the conditions for the breakup of a liquid sheet. By numerically solving the system of equations and experimentally was analyzed the influence of the pressure drop on the film surface and the properties of the liquid on the boundary of the transition of a liquid film in the form of "onion" into a disintegration spray. The calculation and experiment for the transition boundary show the same trend, however, the experimental boundary is slightly biased towards higher values of the mass flow rates of air and liquid. In [3] it was shown that the swirling of the air surrounding the nozzle in the same direction as the swirling of the fuel film allows the fuel spray opening. In this case, air increases the swirl of the film. For counter-rotational swirling air the spray opening is worsens, since the fuel swirl in this case decreases. The addition of an axial velocity component weakly improves the spray pattern. Dependencies are obtained in the work, which make it possible to determine the boundaries of the spraying area for any nozzle if the critical flow rate for any one fuel, for example, kerosene, is known for it. Improving the quality of atomization of a pressure swirl nozzle by creating swirling air movement around a liquid film of onions or tulip shape formed at very low fuel supply pressures (or near the lower limit of fuel consumption) was experimentally studied in [4]. The shape of the liquid film from the hole was observed for water and kerosene at injection pressures of 100 kPa and below, where the liquid film at the outlet of the pressure swirl nozzle had the shape of onion or tulip. Two types of air swirls were mounted coaxially with the nozzle body. The tests were carried out with swirl pressure differences up to 12% of the pressure in the chamber, although the normal pressure drop is about 4% in gas turbine combustion chambers. The threshold pressure drops for the transition between the onion and cone states and the tulip and cone states were defined as functions of the fluid supply pressure for each air swirl. Hysteresis was detected in the transitions: once established with an increase in the air pressure drop, the cone shape continued for some time until a very low pressure drop of swirling air was achieved with a decrease in pressure drop of swirling air. The threshold value of the air pressure drop for transitions from the state of the onion (or tulip) to the cone stage was lower for the case of joint rotation than for the case of the opposite rotation. Another interesting phenomenon was discovered: the imposition of external influences, such as the impact of air jets from small holes on the onion bubble, led to an instant transition. The difference in air pressure required for the transition of the shape of the spray from one state to another can be significantly reduced by external exposure. The critical pressure drop of swirling air is less for kerosene than for water, and a pressure drop of 1.5% is enough to transfer kerosene even at an injection pressure of 10 kPa.

In the present work the effects of imparting co-rotational and counter-rotational swirling air on the main characteristics, determines the dispersion and shape of the spray pattern downstream a pressure swirl nozzle was investigated. We used a mathematical model of the film motion in a curved coordinate system associated with the film surface [5, 6]. The model assumes that the swirling fluid flow is one-dimensional and stationary. The fluid is considered incompressible with a zero pressure gradient in the direction of movement of the film and in the tangential direction. Differential values pressure in the direction normal to the film surface is determined from the condition of equilibrium of pressure forces and surface tension. The influence of viscosity forces on fluid motion is neglected, but the viscous interaction at the gas-liquid interface is taken into account. Since in practice the film
thickness is much smaller than the radius of the spray jet, a change in speed in the circumferential and normal directions can be neglected. Under these assumptions, one can write the equations of conservation of mass and momentum taking into account gravity, in which all variables are a function of one coordinate, measured along the surface of the film. These equations can be integrated and the dependences of the main parameters determining the spraying quality, namely the thickness and speed of the film, as well as the cone angle of the spray, as a function of the distance from the pressure swirl nozzle, can be obtained. In the calculations carried out according to this model, the main attention to the spraying characteristics in the initial phase of the formation of the spray was done.

2. Result of research

Investigations of the spray were carried out for a pressure swirl atomizer with a nozzle orifice diameter of 0.59 mm and a kerosene flow rate of 0.67 g/s. The root angle of the spray was 90°. The film of fuel at the outlet of the nozzle got into either a resting medium or into a swirling air stream. The direction of rotation of the swirling air relative to the liquid film corresponded to the direction of rotation of the film at the outlet of the pressure swirl nozzle or was opposite to it. The axial and rotational components of the air flow velocity in the present research were considered the same. The spray shape for these conditions is shown in Figure 1.

As follows from Figure 1a, in a quiescent medium the spray represents a system of bubbles, with the length and thickness of each of them decreasing as the film moves downstream. When the film enters the swirling air stream with the axial and rotational velocity components $U_a = W_a = 14$ m/s, the length and thickness of the waist of the liquid film increases. A further increase in air velocity to 55 m/s leads to the full opening of the spray. With a change in the direction of the air flow to the opposite relative to the rotation of the liquid, a change in the film configuration occurs. The viscous interaction of liquid and air leads to a decrease in the rotational component of the film velocity at the...
exit. And, as a result, the spray near the nozzle exit narrows. This is especially evident at high speeds of the counter-rotating air flow. Next, we consider the change in the thickness and velocity components of the liquid film of the flow cases considered above. Figure 2a shows the change in the film thickness downstream of the nozzle at a distance of up to 10 nozzle diameters given that it does not break, and figure 2b in the initial section of the film motion.

![Figure 2](image)

**Figure 2** The influence of air flow on the change on the relative film thickness
black line - without air, red - air velocity $U_a = 14 \text{ m/s}$, blue - $U_a = 55 \text{ m/s}$, co-rotation; purple - air velocity $U_a = 55 \text{ m/s}$, green - $U_a = 55 \text{ m/s}$, the counter-rotation

The results of calculations of the film thickness showed that at a distance of 10 diameters of the nozzle of the nozzle, the minimum film thickness is observed at air speeds of 55 m/s and does not depend on the direction of rotation of the air. For a velocity of $U_a = W_a = 14 \text{ m/s}$, the swirl reduces the thickness of the liquid film, and the opposite swirl has a weak effect on the thickness of the film at this distance. Near the nozzle, a swirling air flow reduces the thickness of the fuel film downstream the nozzle, in the initial section, almost the same, regardless of the direction of its rotation. With further movement of the liquid film downstream for air velocities $U_a = W_a = 55 \text{ m/s}$, a significant decrease in the film thickness occurs, but for air velocities $U_a = 55 \text{ m/s}$, $W_a = -55 \text{ m/s}$ there is a range of distance from the nozzle, on which the film thickness is even greater than in the absence of air flow. For air velocities $U_a = W_a = 14 \text{ m/s}$, the film thickness is less than in the absence of air flow, and air speeds $U_a = 14 \text{ m/s}$ the film thickness is greater.

The change in the components of the velocity of the liquid film is shown in Figure 3.

In the absence of air stream, a gradual decrease in the axial and rotational components of the velocity downstream occurs. Also, in the dependences of the velocity change, local minima of the axial velocity component and local maxima of the rotational velocity component are observed. For the velocity $U_a = 14 \text{ m/s}$ and $W_a = \pm 14 \text{ m/s}$, as well as $U_a = 55 \text{ m/s}$ and $W_a = \pm 55 \text{ m/s}$, the air flow accelerates the film in the axial direction. The direction of rotation of the film changes to the opposite for values of air velocity $W_a = -55 \text{ m/s}$ at the axial distance of $X / D_0 = 0.4$ and $X / D_0 = 2.5$ for $W_a = -14 \text{ m/s}$. Further downstream, the film swirls in the direction of air flow. Changing the direction of rotation of the film at a small distance from the nozzle of the injector is important for studying the propagation and break-up of the sheet of a pressure swirl nozzle falling into a swirling air flow.
In the absence of air flow, a gradual decrease in the axial and rotational components of the velocity downstream occurs. Also, in the dependences of the velocity change, local minima of the axial velocity component and local maxima of the rotational velocity component are observed. For the velocity $U_a = 14 \text{ m/s}$ and $W_a = \pm 14 \text{ m/s}$, as well as $U_a = 55 \text{ m/s}$ and $W_a = \pm 55 \text{ m/s}$, the air flow accelerates the film in the axial direction. The direction of rotation of the film changes to the opposite for values of air velocity $W_a = -55 \text{ m/s}$ at a distance of $X/D_0 = 0.4$ and $X/D_0 = 2.5$ for $W_a = -55 \text{ m/s}$. Further downstream, the film swirls in the direction of air flow. Changing the direction of rotation of the film at a small distance from the nozzle of the atomizer is important for studying the propagation and break-up the sheet of the pressure swirl nozzle falling into a swirling air stream.

The fineness of liquid atomization was estimated on the basis of data on the sheet thickness and the relative air and film velocity at the place of the sheet disintegration in accordance with model [7]. The study showed that the counter-rotating atomizer reduces the length break-up of the sheet compared with co-rotating atomizer. The possibility of such a phenomenon was indicated in [8]. With the opposite swirl, the sheet disintegration is shifted to the nozzle atomizer, where the film thickness is maximum value. This change in the length of the break-up of the fuel film largely explains the well-known fact that, despite the increase in the relative velocities of the liquid and air for counter-rotating atomizer, the size of the droplets of atomized fuel does not decrease compared with counter-rotating atomizer, but may increase. This is especially true for relatively small differences in air and fluid velocities. As noted above, the direction of rotation of the liquid sheet can occur at small distances from the nozzle of the injector, where the liquid film has not yet disintegrated. This can also affect the size of the droplets formed during the break-up of the film. The calculation of the fineness of water spraying was carried out for conditions close to those presented in the experimental work [4]. The study was conducted for a drop pressure of water at the nozzle of 40 kPa. Based on the presented flow characteristics of the nozzle and its known diameter, an estimate was made of the thickness of the water film at the nozzle exit. The study showed the following results. The droplet size of $D_{32}$ was 320$\mu$ in the absence of atomizing air. When the air pressure drop across the swirler was 2 kPa, the droplet size was 180 $\mu$ for co-rotating atomizer and 170 $\mu$ for the counter-rotating atomizer. An increase in air differential of up to 4 kPa reduces droplet size to 92$\mu$ for co-rotating atomizer and 86$\mu$ for counter-
rotating atomizer. Qualitatively, these calculated of droplet sizes are in reasonable agreement with the obtained experimental data [4].

**Summary**

Calculations showed that the swirling air flow helps to open the entire spray; however, near the nozzle of injector with opposite swirling, the angle of the spray is smaller than in the absence of air flow. The work also showed that swirling air flow reduces the thickness of the fuel film downstream the nozzle in the initial section almost the same, regardless of the direction of its rotation. Based on the results obtained on the thickness of the fuel film, its speed and the angle of the spray, data were obtained on the effect of the swirling air flow on the average sizes of atomized fuel droplets. The results obtained are compared with the available experimental data. The results confirm that the imposition of a swirl airflow around the onion bubble leads to a noticeable improvement in atomization. The direction of the air swirl relative to the direction of the swirl transmitted to the fluid flow does not have a noticeable effect on spraying. The droplet size was smaller for a co-rotating atomizer, although the relative air-liquid velocity was higher for a counter-rotating atomizer. Changing the direction of rotation of the film for counter-rotating atomizer at a small axial distance from the nozzle of the injector is reduces the condition for break-up of the sheet falling into a swirling air flow. It is likely that a thinner liquid film is formed before sheet break-up in the case of a co-rotation atomizer.

**References**

[1] Borodin VA and Dityakin Y F On the shape of the liquid film produced by a centrifugal nozzle 1960 Izv. Akad. Nauk SSSR Mekh. Mashinostr 2

[2] Gaissinski and AL 2017 Coarse and Fine Atomization Regimes in Miniature Airblast Atomizer, ISABE-2017-22525

[3] Maiorova A I, Vasil’ev A Yu, Sviridenkov A A and Chelebyan O G The atomization and burning of biofuels in the combustion chambers of gas turbine engines 2017 Journal of Physics: Conference Series, Vol 891, conference 1 012221, DOI https://doi.org/10.1088/1742-6596/891/1/012221

[4] Hanajima S and AL Onion-to-Cone Transition of the Liquid Film from a Pressure-Swirl Atomizer by Imparting Swirl Air and its Hysteresis 2018 ICLASS, 14th Triennial International Conference on Atomization and Spray Systems

[5] Chuee S G Numerical Simulation of Nonswirling and Swirling Annular Liquid Jets 1993 AIAA Journal 31 pp 1022-27

[6] Ibrahim .A., McKinney, T. R. Injection Characteristics of Non-Swirling and Swirling Annular Liquid Sheets 2004 52nd JANNAF Joint Propulsion Meeting

[7] Senecal, P.K., Schmidt, D.P., Nouar, I.Rutland, C.J., Reitz, R.D. and Corradini, M.L., Modeling High Speed Liquid Sheet Atomization 1999 Int. J. Multiphase Flow 25, 1073 – 1097.

[8] Levy Y, Sherbaum V., D. Levin, V. Ovcharenko Airblast Swirl Atomizer for small Jet Engining, Proceedings of ASME Turbo Expo 2005, GT 2005-68314