Research of the dynamics of two-phase flows by optical methods PIV/IPI

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Abstract. The paper describes conditions and experimental results of the dynamics of two-phase flows research by optical methods PIV/IPI. Studies were carried out for the finely dispersed flow generated by the centrifugal atomizer. Such atomizer is necessary for the implementation of certification of aircraft engine critical mode under rain conditions: height of 6100 m, the Mach number \( M = 0.8 \). The flow parameters were measured for 9 modes of liquid pressure in the nozzle from 0.2 to 1.0 MPa in increments of 0.1 MPa. Velocity vectors obtained for these pressure modes shown that maximum velocity of the droplets is achieved nearby the nozzle section and ranges from 20 to 30 m/s. Increasing the pressure reduces the difference between velocities at peripheral and axial regions of the flow.

1. Introduction

Two-phase mixtures are particular phenomena in engineering and the list of industrial facilities using two-phase flows is extremely wide. It contains steam boilers, evaporators, gas and oil pipelines, liquid atomization devices and much more [1, 2]. Better understanding of the processes occurring in two-phase mixtures requires both experimental studies and the development of computational models. Since a strict mathematical description of two-phase flows is extremely difficult due to the complexity of the definition of interfacial surfaces. Usually empirical or semi-empirical relationships obtained from the results of experimental studies is used in engineering practice [3, 4].

To obtain the most reliable research results, optical non-contact measurement methods, such as particle image velocimetry are used. They provide fixation of the instantaneous velocity values without additional flow turbulization and corresponding blunders. This work describes the optical investigation of the two-phase flow by methods of particle image velocimetry (PIV) and interferometric particle imaging (IPI) [5-7].

There was carried out a study of finely dispersed flow (droplets’ size of about 500 \( \mu \)m) generated by the centrifugal atomizer. Such atomizer is necessary for simulation rain conditions and implementation of certification of aircraft engine critical mode at the height of 6100 m and value of Mach number \( M = 0.8 \). Certification in ground conditions, where the droplets are in undisturbed air (height of 0 m, Mach number \( M = 0 \)), usually requires the formation of a flow of large droplets with a median diameter of 2.66 mm. The nozzle for these modes has already designed and described in paper [8]. The same nozzle does not allow testing in both modes. Therefore, it is necessary to develop and study a new nozzle designed to form finely dispersed air-water mixture.

Vectors of the velocity and sizes of droplets were obtained by using optical methods of PIV and IPI, respectively. Also, as a result of the studies, the ranges of the spray angle, the uniformity of the spray and the pressure/flow characteristic curves are determined.
2. Test Stand

To experimentally study the parameters of two-phase flow, a test stand has been designed and installed, the scheme of which is shown in figure 1.

![Test stand scheme](image)

Figure 1. Test stand scheme.

The flow parameters were measured for 9 modes of liquid pressure in the nozzle from 0.2 MPa to 1.0 MPa in increments of 0.1 MPa.

For implementation of PIV and IPI methods, laser (532 nm), 2 high-speed cameras and optical amplifier were used. Processing of images was carried out in the program Actual Flow. Measurement of instantaneous velocity by PIV in the cross-section of the two-phase flow was based on the definition of the movement of an ensemble of particles during fixed time interval [9, 10]. IPI method was based on the interference of the reflection and refraction of glare points. The technique utilized the interferometry pattern created from a particle illuminated by a laser sheet. The particles must be transparent, homogeneous and spherical like water droplets in two-phase flow [11, 12].

3. Experimental results and their discussion

The photos taken with the high-speed camera (figure 2) show standard images of sprays from centrifugal nozzle: plumes in the form of a hollow cone. The droplets on the diameter of the plume are distributed nonuniformly – more drops fall on the periphery of the flow. Increasing pressure in the nozzle leads to fact that nonuniformity becomes more pronounced. As the droplets are removed from the nozzle section, the nonuniformity becomes less and the cone is filled with droplets.

![Photographs of the spray plumes](image)

Figure 2. The photographs of the spray plumes.
Figure 3 shows vector distributions of flow velocity under different pressures in range from 0.2 MPa to 1.0 MPa. Figure 4 shows locations of three characteristic cross-sections at distances of 10 mm, 100 mm and 200 mm from the nozzle section. They both have the same palette shown in figure 4.

Figures 5, 6 and 7 show velocity dependences on dimensionless radius of the plume $\overline{R}$ which is equivalent to the coordinate $x$ divided by nozzle diameter $d_0$, for three characteristic cross-sections (shown in figure 4). Values of pressure are equal to 0.4 MPa in Figure 5, 0.7 MPa in figure 6 and 1.0 MPa in figure 7.

These graphs show that the maximum velocity is achieved nearby the nozzle, i.e. at a distance of 3 nozzle’s diameters (10 mm). In the middle part of the flow (100 mm cross-section), the velocity maxima on the periphery and the minimum on the axis of the flow are visible. This is typical situation for centrifugal nozzles’ atomization. The section of 200 mm from the nozzle is characterized by a velocity field with less pronounced maxima. Increasing pressure leads to situation when the limiting velocities at the periphery in the middle and lower sections of the plume become more nonuniform.
Figures 8-11 show the distribution of the mass fraction of the droplets by diameter \( g \) (figures 8 and 10) and the corresponding curves of the relative mass of the droplets \( S \) with different diameter formed by the centrifugal nozzle (figures 9 and 11). Since the flow pattern did not differ qualitatively with increasing pressure, so the dependencies only for two pressure modes of 0.2 MPa and 1.0 MPa are presented as examples.

**Figure 5.** Velocity dependences on the dimensionless radius of the spray plume \( \bar{R} \) at a pressure of 0.4 MPa: 1 – cross-section 200 mm; 2 – cross-section 10 mm; 3 – cross-section 100 mm.

**Figure 6.** Velocity dependences on the dimensionless radius of the spray plume \( \bar{R} \) at a pressure of 0.7 MPa: 1 – cross-section 200 mm; 2 – cross-section 10 mm; 3 – cross-section 100 mm.

**Figure 7.** Velocity dependences on the dimensionless radius of the spray plume \( \bar{R} \) at a pressure of 0.4 MPa: 1 – cross-section 200 mm; 2 – cross-section 10 mm; 3 – cross-section 100 mm.

**Figure 8.** Droplets diameter distribution (pressure in the nozzle 0.2 MPa).

**Figure 9.** Distribution of the relative mass of droplets (pressure in the nozzle 0.2 MPa).
It can be seen that the formed flow at a pressure of 0.2 MPa contains the maximum number of droplets with the largest mass (figure 8). The bulk of the droplets are concentrated in the range of diameter from 0.5 mm to 0.8 mm. The median diameter obtained in this mode is $d_m = 0.649$ mm (figure 9).

In a percentage correlation (figure 10) there is a dominating number of droplets with a diameter of 0 to 0.2 mm. Therefore median diameter corresponds to the part of the graph with minimum number of droplets but their maximum mass.

The increase in pressure in the nozzle does not lead to a significant change in the droplet spectrum and median diameter ranges from 0.625 mm to 0.660 mm. Pressure mode of 1 MPa defines a median diameter $d_m = 0.656$ mm. In a percentage correlation (figure 11) there are more small droplets than under conditions of 0.2 MPa.

![Figure 10. Droplets diameter distribution (pressure in the nozzle 1.0 MPa).](image1)

![Figure 11. Distribution of the relative mass of droplets (pressure in the nozzle 1.0 MPa).](image2)

### 4. Conclusion

Using the methods of optical flow diagnostics (PIV/IPI), experimental studies of two-phase flow formed by a centrifugal nozzle for conditions $H = 6100$ m, $M = 0.8$ were performed. Studies have shown that the plume of droplets formed by the nozzle is unevenly distributed over the cross sections. Increase in pressure (more than 0.6 MPa) leads to the situation when circumferential and radial nonuniformities become more pronounced. However, the overall pattern of the flow from the centrifugal nozzle with a lack of droplets in the axial region and an excess at the periphery remains constant.

Distributions of velocity vectors obtained for different pressure modes shown that maximum velocity of the droplets is achieved nearby the nozzle section (10 mm below it and ranges from 20 to 30 m/s). Increasing the pressure reduces the speed difference between the periphery and the axis of the flow.

The formed spectrum contains droplets in the range of diameters from 0 to 0.9 mm. The bulk of the liquid is concentrated in large drops. Therefore, increase in the nozzle’s pressure from 0.2 MPa to 0.7 MPa defines change in the median diameter from 0.625 mm to 0.660 mm.

### Acknowledgments

This work was financially supported by RFBR (Russian Foundation for Basic Research) grant No. 18-31-00399 “Experimental and theoretical investigation of gas and two-phase swirling flows to increase the efficiency of vortex ejectors and to adapt it for perspective technical systems.”

### References

[1] Leonov A, Chudanov V and Aksenova A 2013 *Methods of direct numerical simulation in two-phase fluids* (Moscow: Nauka)

[2] Malyshev A, Mamchenko V and Kisser K 2016 *Heat transfer and hydrodynamics of two-phase flows of coolant* (St. Peterburg: ITMO)
[3] Barilovich V B 2009 *Fundamentals of therm gas dynamics of two-phase flows and their numerical solution* (St. Petersburg: SPbPU)

[4] Barvinok V and Vashukov Yu 2012 *Methods of experimental research of technological processes in production of aircrafts* (Samara: SNACU)

[5] Akhmetbekov E, Bilsky A, Lozhkin Yu, Markovich D and Tokarev M 2006 Control system of experiment and processing data obtained by methods of particle image velocimetry (Actual Flow) *Computational methods and programming* 7 79-85

[6] Zhdanova A, Zabelin M, Nyashina G and Strizhak P 2014 Particle image velocimetry of water sprays motion through high-temperature gases *Fundamental Research* 9(6) 1225-29

[7] Lin J, Foucaut J-M, Laval J-P, Perenne N and Stanislas M 2008 Assessment of different SPIV processing methods for an application to near-wall turbulence *Topics in Applied Physics* 112 191-221

[8] Guryanov A and Kalinina K 2018 Study of the nozzle for rain simulation at certification of aviation engines *MAI Journal* 25(1) 18-27

[9] Wienke B 2005 Stereo-PIV using self-calibration on particle images *Experiments in Fluids* 39 267-80

[10] Lecordier B and Trinit’e M 2006 Accuracy assessment of image interpolation schemes for PIV from real images of particle *13th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics* 10 181-93

[11] Jasikova D, Kotek M, Tadeas L and Kopecky V 2012 The study of full cone spray using interferometric particle imaging method *EPJ Web of Conferences* 25 01033

[12] Bilsky A, Lozhkin Yu and Markovich D 2011 Interferometric technique for measurement of droplet diameter *Thermophysics and Aeromechanics* 18(1) 1-12