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Shadow Visualization of Water Droplets Breakup Process in a Laval Nozzle Two-Phase Flow

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Abstract

The results of an experimental study of an air-droplet flow in a flat supersonic Laval nozzle of a periodic-acting wind tunnel are presented. The droplets were fed into the flow using fine spray nozzles installed in the pre-chamber. The working part of the wind tunnel has a rectangular cross-section with dimensions of 70x98 mm. The Mach number at the nozzle exit varied in the range 2,0-3,0 due to the mechanism of compression of the nozzle critical section, the total pressure in the pre–chamber was 450-550 kPa, and the total temperature was 288-298 K. The initial concentration of the dispersed (liquid) phase in the flow and the initial droplet size distribution were varied by changing the pressure drop at the spray nozzles. When studying the dynamics of droplet crushing in the critical section of the nozzle, the SSP (shadow photography) laser method was used, which includes: a flow illumination system based on a Beamtech dual-pulse Nd:YAG laser with a wavelength of 532 nm, a 7-joint optical arm for delivering laser radiation, a light-scattering screen for creating a backlight with alcohol solution of rhodamine phosphor, a digital CCD camera with a frame rate at full resolution up to 15 Hz, an Infinity K2 DistaMax microscope lens and the synchronization processor. A series of snapshots of the instantaneous state of the air-droplet flow in the critical section and in the expanding part of the Laval nozzle were obtained.

Keywords: wind tunnel, shadow method, supersonic flow, water breakup process.

1. Introduction

In engineering practice, the traditional method of spraying liquids is the use of nozzles. The following types of nozzles are distinguished: jet, centrifugal, pneumatic (two-phase), impact, mechanical, acoustic, etc. Commercial companies often use their own terminology like slot, rotating, ultrasonic nozzles etc.

The process of forming a fine spray is described quite well in the literature for various types of nozzles [1-3]. In mechanical (jet, centrifugal) and pneumatic (air, steam) nozzles, the fragmentation of the liquid sheet flowing from the nozzle occurs under the action of hydrodynamic forces caused by the difference in the speeds of the liquid sheet and the surrounding environment, with the formation of individual clots in the form of threads and their subsequent breakup into droplets. In some cases, multi-faceted secondary breakup of the droplets with the carrier gas flow takes place.

The process of liquid droplets breakup in nozzles causes the existence of a certain distribution of droplets by diameter, and the range of droplet sizes can be quite wide – from fractions to hundreds of micrometers. As numerous studies have shown [4], in result of mechanical spraying of liquids by the most common centrifugal nozzles, the range of droplet sizes is close to a lognormal distribution.

Using the properties of gas-droplet flows with a low mass concentration (up to 1%) of the liquid phase can solve the problem of reducing aerodynamic heating. It is known that when initially compressed gas expands in a channel, its thermodynamic temperature decreases due to the transition of the internal energy of the gas into the kinetic energy of the flow. The question arises: is it possible to create conditions in the flow under which the streamlined wall temperature would be close to the minimum temperature in the system – the flow thermodynamic temperature. The solution to this problem is possible through the use of the properties of gas-droplet flows. In the case of a low mass concentration (up to 1%), the liquid phase has virtually no effect on the properties of the carrier flow, while the droplets can cool down to the flow thermodynamic temperature [5-8]. By organizing the precipitation of cooled droplets on the wall, it is possible to achieve a decrease in the surface temperature.

There are both experimental and numerical works devoted to this issue in the literature. In [9, 10] it was experimentally shown that the expansion of wet water vapor in a nozzle (steam with water droplets with a humidity of up to 4,5%) leads to a decrease in the nozzle wall temperature compared to the case of superheated steam flow. In [9] the temperature recovery factor took the values r = 0,7 in wet steam and r = 0,9–0,8 in superheated steam depending on the initial degree of superheating. In [10] it was shown that the adiabatic wall temperature depends on both the initial humidity and the initial size distribution of the droplets. For droplet diameters d > 70 μm and an initial moisture content of more than 2%, the droplets deposit on the wall, forming a liquid film with a temperature equal to the saturation temperature. In [11-14] it is numerically shown that the presence of even a small concentration of droplets (less than 3%) in the main air flow can lead to a significant decrease in the adiabatic temperature of the streamlined wall.

As a result of previously conducted experimental studies [7, 15, 16], a system for preparing and injecting liquid into a supersonic flow through a single- and multi-nozzle system in the prechamber of the wind tunnel was created and debugged. A series of thermal imaging measurements of the cooling rate of a plate streamlined by supersonic air and air-droplet flows were performed. The effects of ice build-up on the streamlined wall with a temperature decrease of 10-13 C compared to a single-phase flow were detected. Flow pattern visualization showed a preferential focusing of particles in the central part of the channel after passing the wind tunnel nozzle. A method of aerodynamic focusing of droplets along the shock wave front was tested when a shock wave generator wedge was installed in front of the model. When varying the Mach numbers of the incoming flow, a regime of maximum temperature decrease of the entire surface of the streamlined plate was detected at Mach numbers less than 2,5, while for higher Mach numbers, cooling of only the leading edge of the plate was observed.

The aim of this work is to study the dynamics of droplet breakup and histograms of droplet size distribution in the critical section and in the expanding part of a supersonic wind tunnel nozzle in the range of Mach numbers at the nozzle exit section M_∞ = 2,0-3,0.

2. Methodology and equipment of experimental study

Most modern methods for determining the dispersion composition of particles/droplets suspended in the gas phase, providing detailed information on their sizes, are based on optical measurements. Optical methods are very common, as they are contactless (they do not disturb the carrier medium and do not affect the particles).

In this work, we used the panoramic shadow laser method SSP (shadow photography) [17-21], which includes: a flow illumination system based on a Beamtech dual-pulse Nd:YAG laser with a wavelength of 532 nm, a 7-joint arm for delivering laser radiation, a light-scattering screen for creating background illumination with an alcohol solution of rhodamine phosphor, a digital CCD camera with a frame rate at full resolution of up to 15 Hz, an Infinity K2 DistaMax microscope lens and a Polis SP-10.0PS synchronizing processor. Digital analysis of the shadow image of droplets allows us to determine the position and boundary of the object at the moment of background illumination by the laser (Fig. 1), which is important in the problems of thermal and gas dynamic state of a two-phase flow.

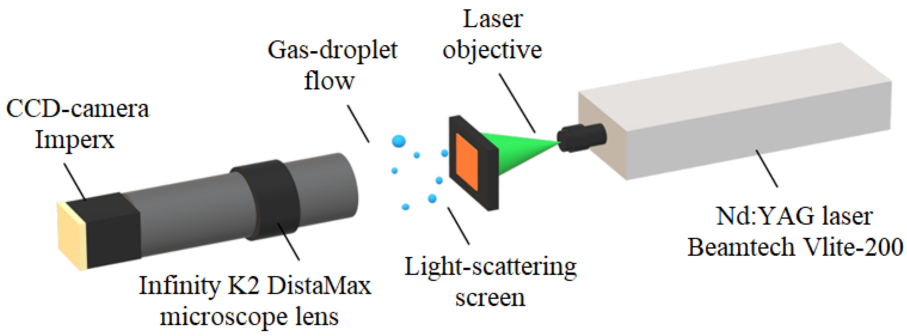

Fig. 1. Methodology for measuring the size distribution of water droplets sprayed by a centrifugal nozzle.

Experimental studies were conducted on the supersonic continuous-action wind tunnel AR-2 (Fig. 2). The working channel of the wind tunnel has a rectangular cross-section with dimensions of 70×98 mm. The supersonic nozzle is formed by two flat flexible plates, providing the possibility of operation at Mach numbers from 2,0 to 3,0 due to the compression of the critical section using an electric drive.

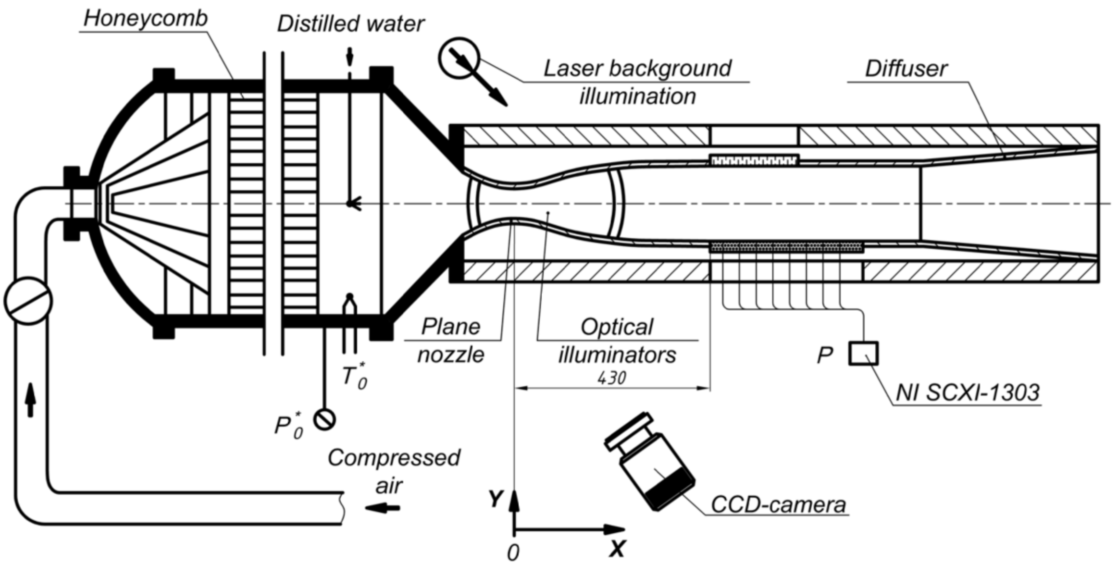

Fig. 2. Scheme of the experimental installation: T_0^* – total temperature of the incoming flow, K; P_0^* – total pressure in the pre-chamber, Pa; P – static pressure on the wall, Pa.

In the central part of the pre-chamber, at a distance of 300 mm from the beginning of the narrowing zone, centrifugal nozzles were placed. The average size of water droplets in the spray created by the nozzle (according to the manufacturer information) was from 60 to 110 µm with a change in pressure drop from 1000 to 300 kPa, respectively. Distilled water was supplied to the centrifugal nozzles through a separate system consisting of a tank with distilled water under pressure (the water pressure in the tank was pumped and maintained at a given level by a pneumatic system), a flow meter and connecting tubes.

3. Results of experimental study

At the first stage of research a series of measurements of the water droplet diameter distribution during water spraying into the atmosphere by a centrifugal nozzle were carried out. The obtained histograms were compared with the data from the nozzle manufacturer Lechler. A series of images of the instantaneous state of the droplets near the spraying nozzle edge

(Fig. 3, left) and at a distance of 30 mm (Fig. 3, right), as well as up to 100 mm from the nozzle edge for comparison with the manufacturer's data were obtained using the panoramic shadow method. The obtained images allow us to estimate the cone angle of the spray torch being formed, the predominant mechanism of droplet fragmentation, and the statistics collected from thousands of frames allow us to construct histograms of the droplet size distribution (Fig. 4). For example, with a pressure drop of 900 kPa, the average Sauter diameter of droplets during spraying into the atmosphere was about 70 μm, while according to the manufacturer's data, it was 66 μm.

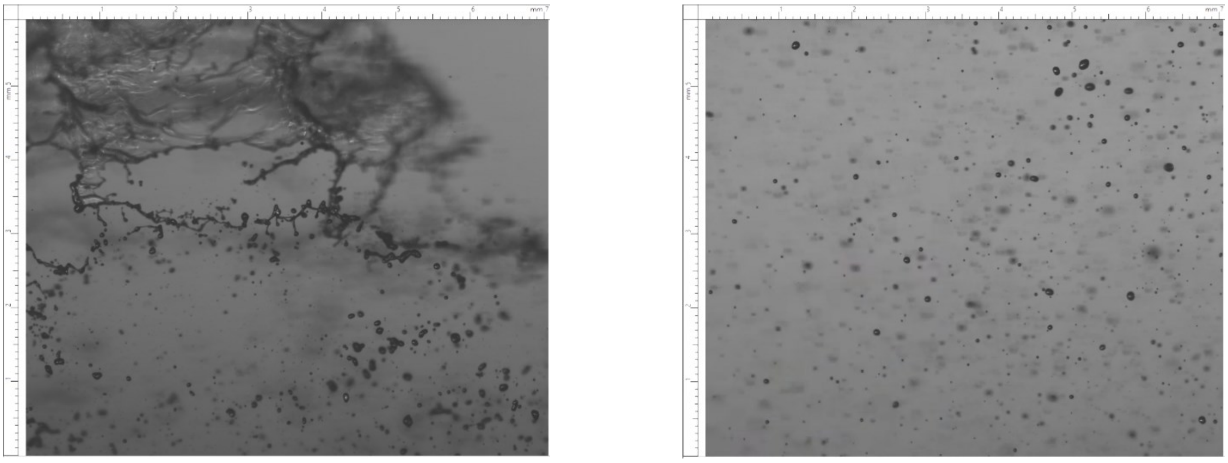

Fig. 3. Water fragmentation into droplets and determination of the spray cone angle (left), formed fine spray at a distance of 30 mm from the nozzle edge (right).

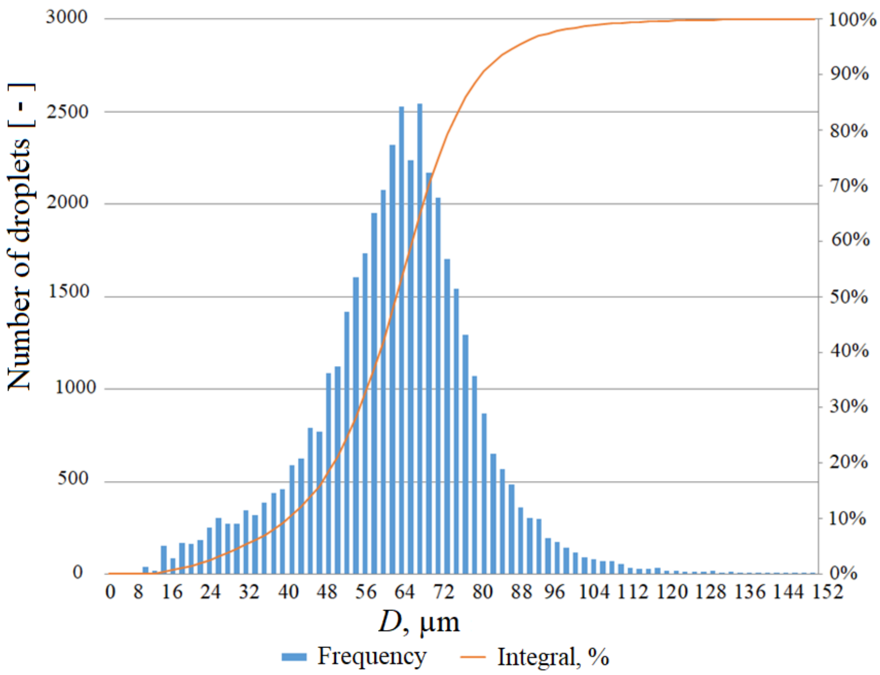

Fig. 4. Histogram of droplet diameter distribution when spraying water into the atmosphere with a centrifugal nozzle at a pressure drop of 900 kPa.

A series of images of the instantaneous state of the air-droplet flow in the critical section and in the expanding part of the wind tunnel nozzle were obtained (Fig. 5). The SSP method obtained a lognormal droplet size distribution with a characteristic Sauter diameter of about 20 μm at the wind tunnel nozzle exit section (Figs. 6, 7). In this case, the average droplet diameter and size distribution were practically independent of the pressure drop on the centrifugal nozzle in the studied wide range from 200 to 1300 kPa and the change in the Mach number in the range from 2,0 to 3,0.

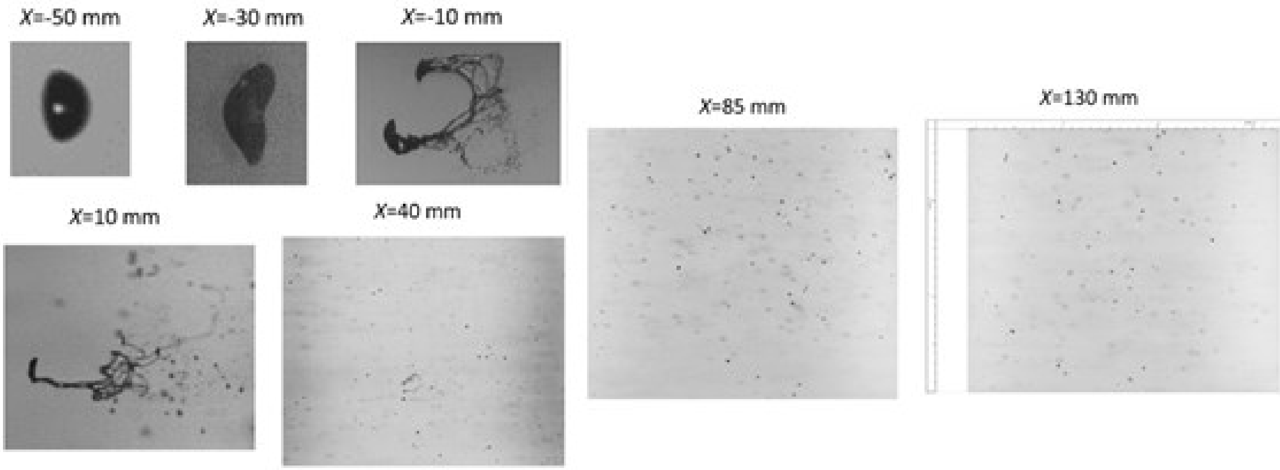

Fig. 5. SSP visualization of the process of water droplet breakup during flow through a Laval nozzle (X=0 mm corresponds to the critical nozzle section of the wind tunnel).

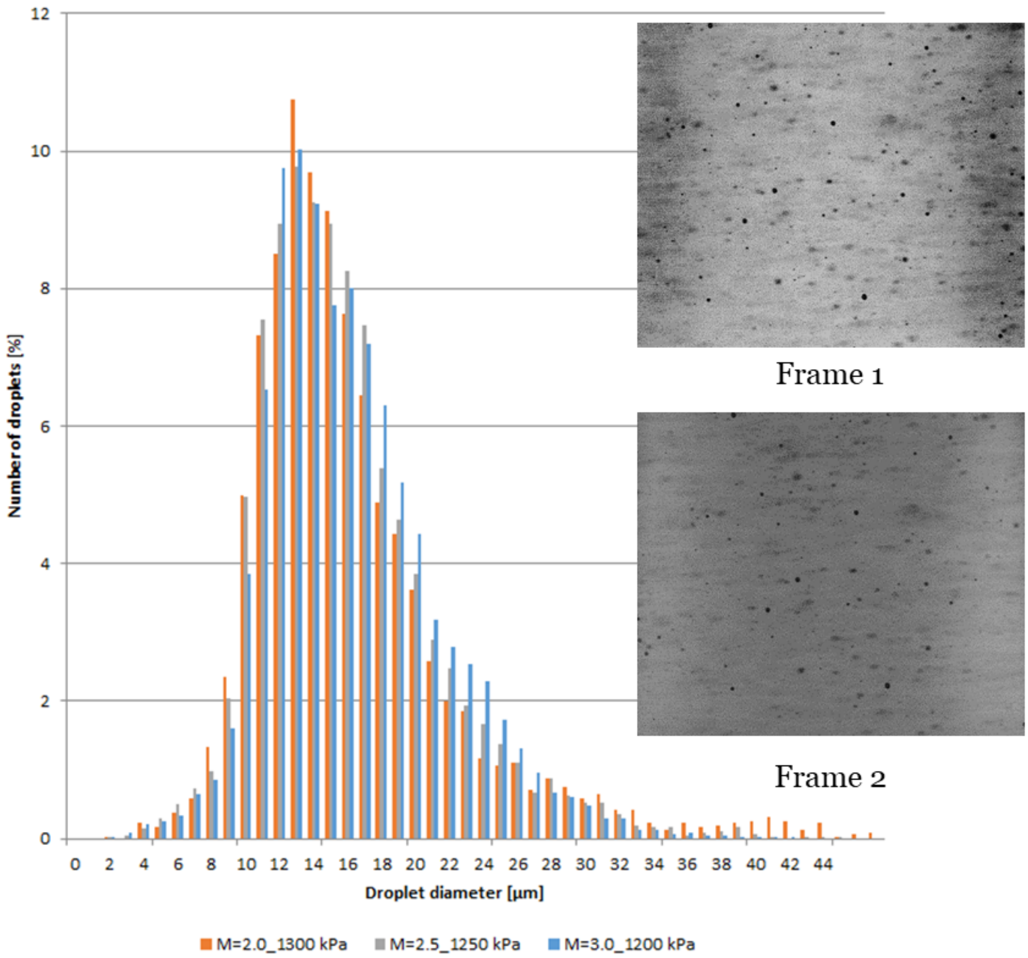

Fig. 6. Distribution of water droplets by diameter in a supersonic flow at a Mach number M_∞ and a water pressure drop at the centrifugal nozzle ΔP: M_∞ =2.0, ΔP = 1300 kPa; M_∞ =2.5, ΔP = 1250 kPa; M_∞ = 3.0, ΔP = 1200 kPa.

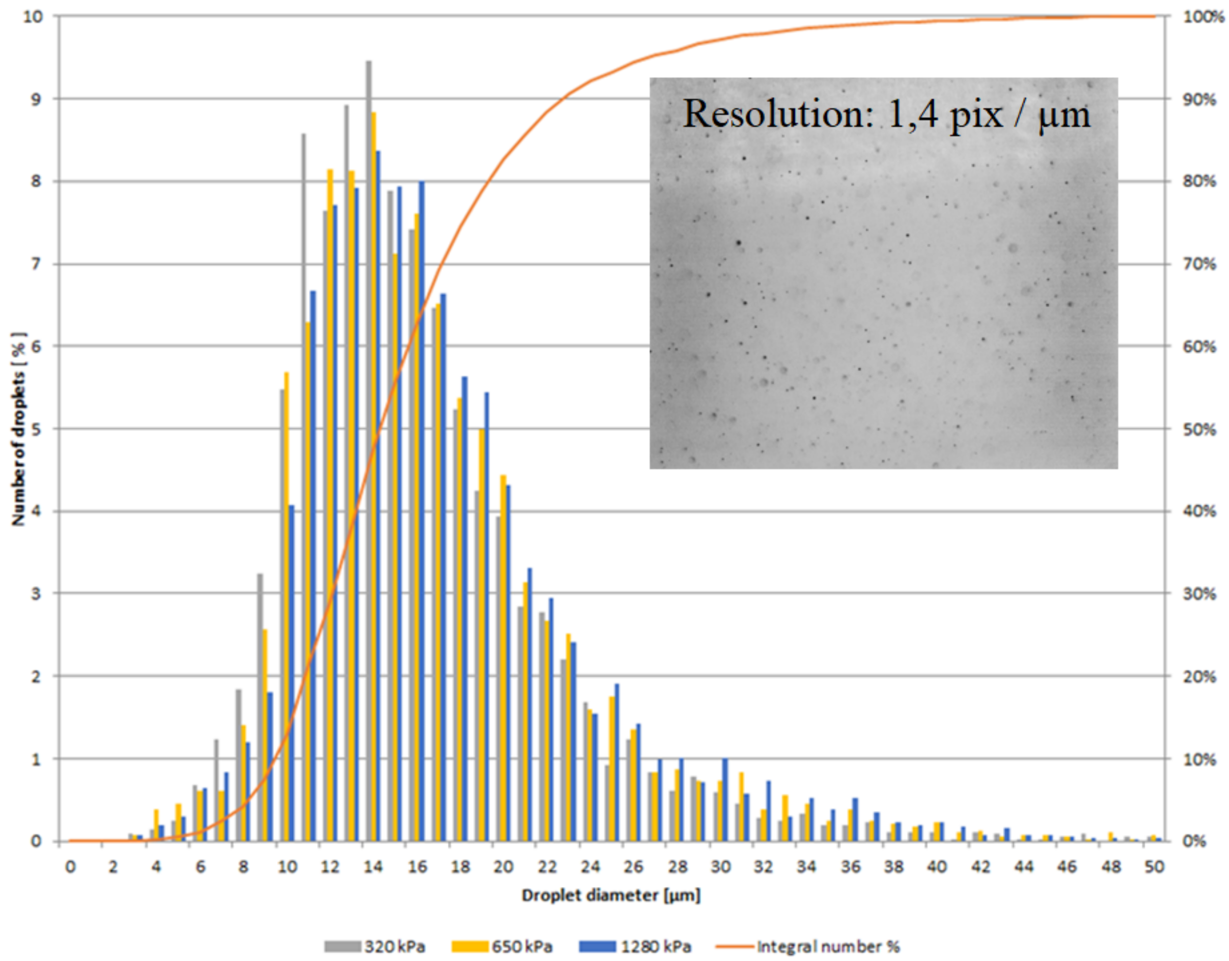

Fig. 7. Comparison of droplet diameter with changing water pressure drop at the centrifugal nozzle ΔP = 320; 650 and 1280 kPa.

4. Conclusion

A series of images of the instantaneous state of droplets near the centrifugal nozzle edge and at a distance of up to 100 mm from the edge were obtained using the panoramic shadow method. The agreement with the nozzle manufacturer's data was obtained within 6% for water pressure drops at the nozzle up to 900 kPa. The dynamics of the air-droplet flow in a flat supersonic wind tunnel nozzle was studied. The SSP method established the average Sauter diameter of droplets at the nozzle exit section to be ≈20 µm. A series of images of the instantaneous state of the air-droplet flow in the wind tunnel critical section area and in the expanding part of the nozzle were obtained. The average droplet diameter and size distribution histograms changed little with an increase in the water pressure drop at the nozzle up to 1300 kPa and a change in the Mach number in a wide range from 2,0 to 3,0.

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List of designations

SCXI – Signal Conditioning eXtensions for Instrumentation (National Instruments);
SSP – shadow photography;
CCD – charge-coupled device;
M – Mach number, -;
P – pressure, Pa;

T – temperature, K;
X, Y – coordinates, m.
Indexes:
0 – stagnation parameter;
∞ – free flow parameter.

References

1. Vitman L.A., Kacnel'son B.D., Paleev I.I. Spraying liquid with nozzles / Ed. by Kutateladze S.S. State Power Agency, Leningrad. 1962. 264 p. [in Russian]
2. Droplets and Sprays. Applications for Combustion and Propulsion // Ed. by Basu S., Agarwal A.K., Mukhopadhyay A., Patel C. Springer Nature Singapore Pte Ltd. 2018.
3. Piskunov V.N. Aerosol dynamics. Moscow: FIZMATLIT, 2010. 296 p. [in Russian]
4. Varaksin A.Yu. Fluid dynamics and thermal physics of two-phase flows: Problems and achievements // High Temperature, 2013, V. 51, I. 3, Pp. 377–407.
5. Leontiev A.I., Lushchik V.G., Makarova M.S., Popovich S.S. Temperature Recovery Factor in a Compressible Turbulent Boundary Layer // High Temperature. 2022. Vol. 60. Pp. 409-431.
6. Leont'ev A. I., Osiptsov A. N., Rybdylova O. D. The boundary layer on a flat plate in a supersonic-gas-droplet flow: Influence of evaporating droplets on the temperature of the adiabatic wall // High Temperature. 2015. V. 53. N. 6. Pp. 866–873.
7. Popovich S.S., Vinogradov Yu A., Zditovets A.G., Kiselev N.A., Medvetskaya N.V. Measurement of the adiabatic wall temperature of a flat plate in a supersonic air-droplet flow // Fluid Dynamics. 2020. V. 55, N. 5. P. 701–707.
8. Zditovets A.G., Kiselev N.A., Popovich S.S., Vinogradov U.A. Adiabatic wall temperature in the supersonic flow of moist air with spontaneous condensation // Experimental Thermal and Fluid Science. 2024. V. 150. N. 111057.
9. Zhukovskiy V.S., Madiyevskiy V.A., Reznikovich K.I. On the intrinsic temperature of the wall in a flow of supersaturated steam // High Temperature. 1966. V. 4. N. 3. Pp. 399-406.
10. Ignatievskaya L.A. Study of a two-phase boundary layer on a flat wall // Ph. D. thesis, Moscow Power Engineering Institute, 1971.
11. Azanov G.M., Osiptsov A.N. The effect of fine evaporating droplets on the adiabatic-wall temperature in a compressible two-phase boundary layer // Fluid Dynamics. 2016. V. 51. N. 4. Pp. 498–506.
12. Golubkina I.V., Osiptsov A.N. The effect of admixture of non-evaporating droplets on the flow structure and adiabatic wall temperature in a compressible two-phase boundary layer // Fluid Dynamics. 2019. V. 54. N. 3. Pp. 349–360.
13. Golubkina I.V., Osiptsov A.N. Compressible gas-droplet flow and heat transfer behind a condensation shock in an expanding channel // International Journal of Thermal Sciences. 2022. V. 179.
14. Golubkina I.V., Osiptsov A.N. Steady gas-droplet flow pattern and heat transfer behind the point of incidence of a shock wave on a flat wall // Fluid Dynamics. 2023. V. 58. N. 4. Pp. 555–568.
15. Popovich S.S., Zditovets A.G., Kiselev N.A., Vinogradov Y.A. Experimental study of the shock wave influence on adiabatic wall temperature in a supersonic air-droplet flow // Journal of Physics: Conference Series. 2020. DOI: 10.1088/1742-6596/1683/2/022064
16. Popovich S.S., Zditovets A.G., Vinogradov Y.A. Experimental investigation by the shadow method of water droplets breakup in an adjustable supersonic nozzle // 22nd International Conference on the Methods of Aerophysical Research (ICMAR 2024), Novosibirsk, 2024. P. 148-149.
17. Bilsky A.V., Lozhkin Y.A., Markovich D.M. Application of IPI technique to study spray flows // 11th International conference OMFI, 2011.

18. Gobyzov O.A., Lozhkin Y.A., Ryabov M.N., Markovich D.M. Experimental study of submillimeter droplets dynamics and breakup in continuous supersonic flow terminated by shock wave // EPJ Web of Conferences. 2016. V. 114. N. 02031.

19. Poplavski S.V., Boiko V.M., Gobyzov O.A., Ryabov M.N., Bilsky A.V. Experimental Study of the Breakup of Microdrops and Drops of Natural Size in Gradient Flows // International Conference on the Methods of Aerophysical Research ICMAR, 2018. AIP Conf. Proc. N. 2027.

20. Bilsky A.V., Gobyzov O.A., Markovich D.M. Evolution and recent trends of particle image velocimetry for an aerodynamic experiment (review) // Thermophysics and Aeromechanics. 2020. T. 27. № 1.

21. Znamenskaya I.A. Methods for Panoramic Visualization and Digital Analysis of Thermophysical Flow Fields // Scientific Visualization. 2021. V. 13. N. 3. Pp. 125-158.