Superheated Water Atomization: Some New Aspects of Control and Determining Disperse Characteristics of Atomization Plume in Micron and Submicron Ranges of Droplet Size.*

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Abstract. New experimental data on superheated water atomization is presented. It is shown that in contrast to the case of short cylindrical nozzles, which provide bimodal water-droplet sprays, the application of divergent nozzles makes it possible to obtain one-modal water atomization with droplets of about micron diameter being obtained. This fact is due to changes in the mechanism of superheated water jet fragmentation and it is very important for engineering applications. A modified experimental technique for processing integral monochromatic scattering indicatrix was developed and tested. In addition, a new calculation code was worked out for calculating atomized water drop-size distribution (on the basis of Mi theory) in micron and submicron ranges.

1. Introduction
Wide application prospects of finely atomized superheated water and some other liquids in different modern technologies determine the urgency of their further investigations. These prospects are connected with very intense heat transfer between small droplets and carrying gases. This technology can be efficiently used for water injection in different combined-cycle power units with wet working liquid compression and wet regeneration of the waste-gases heat [1, 2], in spray-cooling [3], in new efficient fire-fighting and smoke-capturing technologies [4].

An efficiency of the finely atomized liquids application depends significantly on their disperse characteristics. That is why it is important to provide a possibility of reliably obtaining the required small droplet size.

Jet discharge from short nozzles has been studied for a long time. V.P. Skripov and coworkers were first in this way [5]. Their studies concerned with bubble nucleation and growth, developing hydrodynamic instability in jets during metastable superheated liquid flashing as a result of quick pressure drop, pulse heating and some other actions. Rather large investigations in this direction were also conducted abroad [6-9]. Shapes of flashing jets, their evolution, effect of inlet parameters of the flashing liquid on this process, temperature fields in atomized sprays, and, in some cases, droplet dispersion in them were studied. In the works of A.A. Avdeev and D.A. Labuntsov [10, 11] the theoretical analysis of the processes that lead to flashing boiling and the behavior and interaction of phases in discharging high-velocity two-phase jets, as well as the shape of jets and the diversity of wave formations that accompany metastable liquid discharge are considered. The comprehensive review and analysis of state-of-the-art of the problem under consideration can be found in the recently published monograph of A.A. Avdeev [12]. We should point out that the amount of publications concerning droplet size distribution in flashing-liquid sprays and their dependence on jet discharge conditions is very limited although these data are of primary importance for choosing atomizing technology and reliably constructing atomizing systems.

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An efficiency of finely atomized liquids application depends significantly upon their disperse characteristics. That is why it is important to provide a possibility of controlling liquid atomization process to obtain required droplet size and to have suitable technique for quick and reliable droplet size measurements in experiments and during apparatus testing.

The first references about highly disperse atomization of superheated water were in “Kema” publications [13]. But they contained no description regarding droplet size measurements technique, although obtaining of practically monodisperse atomized superheated water with 2- micron droplet size was declared. Atomized superheated water disperse characteristics have been studied in the Joint Institute for High Temperatures of RAS (JIHT RAS) [14, 15].

2. Unit description, methodic and experimental conditions.

The droplet size distribution in finely atomized superheated metastable water was studied at the experimental unit “Raspyl” [16, 17]. It is used for investigation of finely atomized two-phase droplet-air flows with relatively small liquid faze fraction, which is typical for atomized water injection into GTU compressors and over object of modern equipment. The nozzles, used in experiments, were supplied from feeding tank by water with temperature changing from 170 to 240°C at pressures 4 - 8 MPa. The feeding tank has a system of heating elements and measuring system for keeping necessary inlet temperature and pressure stability. The temperature, flow rate and pressure distribution of two-phase flow is also measured in the experimental zone. The flow disperse characteristics measurement was carried out by means of its monochrome scattering level determination at various angles (fig 1) by methodic, which was described in [16, 17].

The water temperature control at the atomizing nozzle inlet within range 170-240°C allowed to change submicron droplets (0.1-2 μm) ratio to overall water flow rate. This ratio varied at the above temperature range from 40 to 75%. As for nozzles with bimodal droplet size distribution micron mode droplets sized varied from 2.0 to 25μm.

At the above mentioned pressure level at the nozzle inlet the injected water flow rate was changing from 5.7 - 6.5 to 8.7 - 9.3 g/c, what depends upon T₀. The mass fraction under these conditions was about 4.5-8% and it approximately 2-4 times exceeds the typical values for compressor water injection. As for long nozzles experiments, initial pressure P₀ and temperature T₀ (the main parameter, which determines the level of water superheating and, therefore, a degree of water atomization) varied from 4.0 to 8.0 MPa and from 20 to 280 °C, respectively. It was shown in experiments that if the water temperature is lower than 170°C, the atomized water spray consisted of micron size droplets (from 5 to 30 μm). These figures are typical for cold water atomization by commonly used technologies [18]. The more the temperature exceeds 170°C value, the greater the fraction of submicron droplets is, with droplet diameter varying from 0.1 to 1 μm. At T₀ = 270°C a share of fine droplets reaches 70% (fig.2a). Such a bimodal distribution of droplets by size is due the superposition of two processes [19]: the first is flashing of the superheated water in the jet volume; while the second is the development barocapillary instability at the jet surface [20].

The above JIHT RAS articles describe the results of investigations of superheated water atomization during its discharge through relatively short converging nozzles, with the metastable water residence time in the nozzle being 20-30 μs. As estimations show, such a time is enough for micro bubble nucleation and growth up to 6 - 7 micron size. At the nozzle outlet, water is atomized during 10 – 20 μs due to action of both of these processes. Relatively large liquid structures, which contain a lot of quickly growing bubbles, are disintegrated into smaller ones (mainly of submicron size).

An indirect confirmation of such superheated water atomization physical model with the flashing process being dominated is a droplet plume shape (fig.3). Plume sharply expands at the nozzle outlet quite immediately at a distance about 1-2 mm. But later the expansion angle significantly decreases down to 10 - 13 deg.
The second alternative allows to obtain more complicated shape of nozzle expanding part with variable diverge angle along the nozzle length.
The tests were conducted in the following range of superheated water parameters: temperature at the nozzle inlet: 140 - 240°C; a pressure: 3.3 -5.5 MPa; and the flow rate from 28 to 95 g/s.

3. Results analysis.

A modified monochrome scattering indicatrix measurement technique was realized in the experiments. The atomized droplet plumes disperse characteristics analysis was based on this technique. Laser beam scattering indicatrix measurements were complicated by large optical thickness of the flow. This could lead to remarkable error in radiation intensity measurements due to secondary scattering in the droplet plume [28]. To minimize the effect of secondary (multiple) scattering a special well-streamlined conical barrel have been designed and tested. It significantly decreased the ray length. But such barrel application is limited by its relatively large cross dimensions in comparison with plume diameter. It may cause noticeable perturbations of the flow being investigated. More effective multiple scattering correction technique with no flow disturbance consists of measuring integral laser ray weakening while crossing the entire atomization plume under various angles. Such a method has been used in experimental data analysis.

New calculation code (based on the Mi theory [21-25]) was developed for determining atomized water droplets distribution by size from monochrome scattering indicatrix measurements. Investigations conducted with superheated water earlier revealed bimodal [26] shape of such distribution. This fact made it possible to propose an automated simplified iteration procedure for solving inverse light scattering problem.

The previews investigations revealed bimodal and one-modal type of droplet size distribution in atomization plume. It gave a chance for numerical solution optimization for inverse scattering problem. This problem requires determining atomization plume droplet size distribution (with necessary accuracy) proceeding from integral scattering indicatrix.

The droplet size range under consideration (from r1~0.1μm to r5~10 μm) is divided into two zones: submicron mode (from r1~0.1μm to r3~1 μm) and micron mode (from r3~1μm to r5~10 μm). These zones significantly differ in scattering indicatrix values at small and big angles. The range borders are revised in the following solution.

The curve of relative droplet volume fraction increment distribution vs droplet diameter is described by system of four cube splines in the following intervals: from the beginning of the interval (y1=0, r1) to the first interval maximum (y2, r2), then from first interval maximum to minimum (y3, r3), then from minimum to the maximum of second interval (y4, r4), and from second interval maximum to the end of second interval (y5=0, r5).

Such approximation selection allows to design asymmetric distributions of the considered function, which remains smooth, without break of first and second derivatives.

At the end of interval the values of the function and its first derivative are summed to be zero (the condition of natural spline). At the same time the end points of the considered range may change because of the experimental parameters and nozzle characteristics. In the conjugation points the first and second left and right derivatives are correspondingly equal.

This approximation leads to the obvious system of sixteen linear equations with twenty one unknowns. Earlier assumed values of r2, r3, r4 and y2, y3, y4 are unknowns as well.

This system is complemented by integral equations (1) in five points of the integral angle scattering function curve.

$$I_\theta = \int_{r_1}^{r} i_\theta(r) y(r) \, dr$$

(1)

here: I_\theta – relative integral (in the range of droplet radius changing from r1 to r5 at the scattering angle 0; i_\theta(r) – relative scattering indicatrix value for droplet diameter r at the scattering angle 0.

This value is calculated according the bellow described calculating code based on the Mi theory.

y(r) – value of interpolating spline function corresponding to the droplet radius r.
The intensity of monochrome radiation (\( \lambda = 532 \text{ nm} \)), which was scattered by spherical particle was carried out according the following equations (based on Mi theory).

\[
I = \frac{I_0 (i_1 + i_2)}{2k^2 r^2}
\]

(2)

Where: \( I \) – light intensity in medium after spherical particle placing in, \( Wt/m^2; I_0 \) – light intensity before spherical particle placing in, \( Wt/m^2; k \) – wave number, \( 1/m; r \) – distance from the particle, \( m; i_1 \) – amplitude function (3); \( i_2 \) – amplitude function (3). Where \( S_1 \)– amplitude function (5); \( S_2 \)– amplitude function (6); \( \lambda \) – wave length (m).

\[
k = \frac{2\pi}{\lambda},
\]

\[
i_1 = |S_1|^2
\]

(3)

\[
S_1(\mu) = \sum_{n=1}^{\infty} \frac{2 + 1}{n(n + 1)} [a_n \pi_n(\mu) + b_n \tau_n(\mu)]
\]

(4)

\[
S_2(\mu) = \sum_{n=1}^{\infty} \frac{2n + 1}{n(n + 1)} [b_n \pi_n(\mu) + a_n \tau_n(\mu)],
\]

(5)

where: \( a_n \) (7); \( b_n \) (8); \( \pi_n \) (9); \( \tau_n \) (10); \( \mu \) – parameter \( \mu = \cos(\Theta) \), \( \Theta \) – scattering angle.

\[
a_n = \frac{\psi_n'(y)\psi_n(x) - m \psi_n(y)\psi_n'(x)}{\psi_n'(y)\zeta_n(x) - m \psi_n(y)\zeta_n'(x)},
\]

(7)

\[
b_n = \frac{m \psi_n'(y)\psi_n(x) - \psi_n(y)\psi_n'(x)}{m \psi_n'(y)\zeta_n(x) - \psi_n(y)\zeta_n'(x)},
\]

(8)

where: \( \psi \) и \( \zeta \) – Ricatti- Bessel function (Bessel – \( \psi_n(z) = \frac{\pi}{2} J_{n+1}^{(2)}(z) \), Hancel 2-d type – \( \zeta_n(z) = \frac{\pi}{2} H_{n+1}^{(2)}(z) \); \( x \) – parameter \( x = ka \); \( y \) – parameter \( y = mka \); \( a \) – particle radius, (m); \( m \) – refraction coefficient (for water droplet and visible light \( dr = m = 1,33 \)).

\[
\pi_n(\cos(\Theta)) = \frac{1}{\sin(\Theta)} P_n^{(1)}(\cos(\Theta)),
\]

(9)

\[
\tau_n(\cos(\Theta)) = \frac{d}{d\Theta} P_n^{(1)}(\cos(\Theta)),
\]

(10)

where \( P_n^{(1)}(\cos(\Theta)) \)– Legendre polynomials .

\[
\int_{r_1}^{r_2} y(r) dr = 1
\]

(11)

The condition (11) must be fulfilled in the process of integral equation system solution. The system of sixteen linear equations for spline coefficients is solved analytically with above five pre-determined
parameters. As a result we have a smooth approximating curve for integral intensity of scattering radiation which coincides with experimental one with demanded accuracy. Thus the size droplet distribution can be determined for considered atomization plume. And iteration procedure for such determining requires much less time than in hand selection (fitting) which was used earlier.

The experiments with “long” diverging nozzles have shown that the nozzle geometry and length affect significantly on atomization process. It became possible to provide atomization with a great share of submicron droplets at following inlet water parameters: \( T_0 = 200^\circ C \) and \( P_0 = 3.7 \text{MPa} \). At the same time at short atomizing nozzles, which were several millimeters long, bimodal droplet distribution took place even at higher inlet parameters of water: \( T_0 = 270^\circ C \) and \( P_0 = 8.0 \text{MPa} \).

It should be pointed out that even a small difference in the nozzle geometry can change atomization characteristics. For example the increase in diverge angle from 12 to 15 deg. leads to the change in atomization characteristic from practically monomodal distribution (fig2b) to bimodal one, which is similar to that shown in (fig2a) The only submicron size droplet presence in the atomization plume after relatively long nozzles with diverges section may be explained by two simultaneous processes: the first is intensification of flashing and the other is auxiliary droplets defragmentation while pushing the walls in diverge section.

4. Conclusions
It is experimentally shown that a change in the shape of the atomizer nozzle from the short cylindrical to the extended with expanding exit section provides obtaining single-mode droplet distribution by size, when atomizing superheated water. When this happens, the droplet dimension is about one micrometer. This fact is very important from practical sense.
Figure 2. Droplet distribution over size in sprays. a) cylindrical nozzle (Fig. 2a). $P_0 = 5.3$ MPa, $T_0 = 202^\circ$C, $G = 7$ g/s; b) nozzle with expanding exit section (Fig. 2b) $P_0 = 3.2$ MPa, $T_0 = 204^\circ$C, $G = 74.2$ g/s.
Figure 3. Superheated water droplet plume (outlet diameter 8 mm).

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