Perspectives of Reaching Mono- and Bimodal Droplet Size Distribution of Atomized Superheated Water in Micron and Submicron Ranges*

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Abstract. New experimental data on superheated water atomization are presented. It is shown that the new nozzle design with expanding relatively long duct provides droplet size distributions which differs much from those in the case of short conic nozzles (at the same inlet temperatures). Mass fraction of submicron mode is significantly greater — up to practically mono-modal submicron distribution. The new method of result data treatment is proposed. According to it the submicron mass fraction is function of dimensionless parameter, which is the vapor clusters surface tension ratio to chemical potential of “explosive” phase transformation.

1. Introduction

The importance of finely atomized superheated water (and some other liquids) producing and its investigation is determined by high level heat transfer of finely atomized superheated water plumes of micro-droplets as with surrounding gas flows so with droplet deposition surfaces. Such atomization technology may be efficiently used for water injection in various gas turbine combined-cycle power units with wet compression and wet regeneration of the waste-gases heat, in spray-cooling, in new efficient fire-fighting and smoke-capturing technologies. Efficiency of the finely atomized liquids application increases significantly with droplet size decreasing. Jet discharge from short nozzles has been studied for a long time (for example [1] and others).

A number of investigations devoted to short converging nozzles have been undertaken recently in Germany and Brazil [2-5]. A shape of flashing plumes, their evolution and effect of inlet liquid parameters on the process, and, in some cases [6], droplet size dispersion were studied. Model liquids were primary organic: isooctane, acetone, spirit and others. The theoretical analysis of flashing process (“explosive boiling”) was done in [7-9]. In these works the theoretical analysis of the processes that lead to flashing boiling is given, taking into account behavior and interaction of phases in discharging high-velocity two-phase jets. At the same time publications concerning droplet size distribution in flashing-liquid sprays and their dependence on jet discharge conditions are rather rare. As for “long” nozzles such publications are practically absent. So the results of this work and approach to their unified treatment, taking into account the above applications, are new and actual.

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A certain quantity parameter was chosen in this paper as criteria of full flashing atomization. It is submicron droplets mass fraction, which is determined by measurement of monochrome scattering level in a wide range of scattering angles for various droplet diameters in atomization plumes.

The first stage of the problem study in JIHT is reflected in [10-13]. It was devoted to atomization by short constricting nozzles. The investigations in this work deal with nozzles with relatively long diverge part after the nozzle throat.

2. Unit description and experimental conditions
The droplet size distribution in finely atomized superheated water plume was studied at the experimental unit “Raspyl” [12, 13]. Unlike short (5-6 mm) constricting nozzles, which were studied earlier the present experimental nozzles had a relatively long (about 30 mm) diverge part after the nozzle throat with diverge angle of 12-15°. Such nozzle geometry is close to Laval’s nozzle design.

Besides measurement of initial parameters $P_0$, $T_0$ and water flow rate there were flow temperature and pressure measurements in several cross-sections along diverge part of the nozzle [14].

The flow disperse characteristics determination (for micron and submicron droplet size) was carried out by plume monochrome scattering level measurement at various angles (up to 45°) by technique described in [10-14]. It is based on Mi theory, and for rather dense plumes of atomized water it is important to take into account secondary multilateral scattering [6] especially at big angles. So measurement of integral laser ray attenuation at various angles is used for treating experimental data.

3. Experimental results and their brief analysis
Initial atomized superheated water flow parameters varied in the experiments with “long” nozzles as follows: inlet temperature was changing from 140 to 240°C, the range of pressure changing was 3.3-3.9 MPa. There were two nozzle throat diameters: $d_0=0.6$ mm and $d_0=1.6$ mm.

As for excess pressure distribution along the nozzle, significant pressure drop is observed in its first part from initial pressure $P_0$ to approximately 150-250 KPa (excess pressure) at one-third of the diverge zone, then up to -20 Pa at the second one-third. In the third part of the diverge zone there is a slow pressure increase to practically zero excess pressure (figure 1).

![Figure 1. Static excess pressure distribution along nozzle diverge zone. Experiments at various inlet temperatures $T_0=170$, 200 and 240°C ($d_0=0.6$ mm).](image)

According to thermocouple measurements, flow temperature in the nozzle diverge part at the nozzle throat is about 130-140°C and it is about 85-75°C in the last one-third part of the nozzle ($d_0=0.6$ mm), while $T_0$ varies from 170 to 240°C. The temperature of atomized superheated water plume was about 80-90°C at the nozzle exit for all regimes. The simultaneous measurement of dynamic pressure
showed an increase from 0.04 to 0.065 MPa with the inlet temperature increase from 140 to 240°C. This data is in a good agreement with flow rates measurements if vapor fraction is determined as an equilibrium one (calculation estimates). So two-phase flow rate is about 150 m/s at inlet temperature $T_0=200^\circ$C.

The experiments with “long” nozzles show that geometry of such nozzles with relatively long diverge zone leads to significant increasing of the flow dispersion level (figure 2). Achieving great submicron droplets fraction in “long” nozzles with relatively long diverge zone (“Laval - type” nozzle) became possible at inlet water parameters $T_0=200^\circ$C and $P_0=4.0$ MPa. As it follows from figure 2, submicron droplets mass fraction increases from 0.35 to 0.6 with inlet temperature growth from 170 to 240°C for short constricting nozzles. As for “long” nozzles it is greater: 0.8–0.9 under the same conditions.

The example of such droplet size distribution for superfine atomization (practically to submicron size droplets – “full flashing atomization”) is given in figure 3. Obviously the main cause of such great level of atomization in “Laval” nozzles is more full development of the “explosive boiling” process in comparison with short nozzles [11, 12, 15] and two-phase flow transformation in diverge nozzle zone.

As for atomization plume geometry there is also a significant difference for “short” and “long” nozzles. Atomization plume in short nozzles sharply expands just after the nozzle exit (1-2mm) [11, 12, 15]. Similar atomization plumes were observed for various superheated liquids in other works [1-5]. “Long” nozzles atomization plume differs significantly by its form from short nozzles plumes; diverge

![Figure 2. Submicron mode mass fraction with droplet diameter less than 1μm in atomization plume vs. its inlet temperature $T_0$ for various nozzle geometry. 1-“short” constricting nozzles; 2 - “Laval”-type nozzle $d_0 = 1.6$ mm; 3 - “Laval”-type nozzle $d_0 = 0.6$ mm.](image)

![Figure 3. Droplet size distribution in atomized superheated water plume in “long” nozzle with diverge part. $P_0=3.9$ MPa, $T_0=240^\circ$C, $G_w=74.2$ g/c; $d=0.6$ mm.](image)
angle is about $12^\circ$ and it does not change much. It indicates indirectly that nucleation and droplet defragmentation processes take place mainly in the nozzle volume.

4. Experimental results treatment

The nucleation processes in accelerating metastable boiling water flow were numerically analyzed. The mutual influence of quick vapor phase growth parameters on two-phase flow were taken into account according to experimental conditions. Model included conservation equations for mass, impulse and energy and equations for nucleation rate [16]. The experimental pressure distribution in nozzle diverge zone was used.

Solving the system showed that saturation pressure point, corresponding to inlet temperature, is not obtained in a nozzle constricting zone at experimental parameters. “Explosive boiling” takes place at a certain distance from a nozzle throat in a nozzle diverge part and there is a sharp peak in nucleation rate. After this nucleation process is practically stopped. After “explosive boiling” the state of the two-phase flow changes; the foam liquid flow containing bubbles transforms into vapor flow containing micron and mainly submicron droplets ("full flashing atomization"). It corresponds to [5, 8] problem insight.

As it was mentioned above, in the constricting nozzle zone as in short nozzles so as in “long” nozzles the saturation point corresponding to inlet temperature $T_0$ is not reached under the above conditions. It means that external regime of atomization according to classification [16] takes place. It is characterized by multilateral influence of various factors. Main of them are aerodynamic forces [1] and "explosive boiling" in the formed and breaking down liquid fragments [15].

The flashing process in long nozzles may be more effective and after reaching the certain superheating level the process of liquid defragmentation is fully determined by “explosive boiling”. The problem is to determine this critical level of overheating. According to hypothesis stated in [5] the initial expanding angle of atomized superheated liquid plume for short conic nozzle completely depends upon nucleation process characteristics. It should be noted that in [5] reaching the full diverge angle after the nozzle is interpreted as “full flashing”.

Nevertheless that JIHT previous experiments confirm generally in reaching the full diverge angle at the inlet temperature of about 200°C at the short conic nozzles, at the same time the droplet size distribution remains bimodal under these conditions, mass fraction of micron droplets being about 60% (figure 2) [10–13]. That is why the term “full flashing atomization” up to our mind should be interpreted as reaching practically mono-modal droplet size distribution in submicron range.

Following [5] let us introduce some definitions. The superheating level is defined as difference between inlet temperature $T_0$ and saturation point temperature corresponding to outlet pressure $T_{\text{sat}}(P_o)$. Parameter $R_p$ is defined as saturation pressure (at inlet temperature) ratio to outlet pressure:

$$\Delta T = T_{\text{in}} - T_{\text{sat}}(P_o); \quad R_p = \frac{T_{\text{sat}}(T_0)}{P_o}$$

Here: $P_{\text{sat}}(T_0)$ is saturation point pressure at the nozzle inlet; $P_o$ is nozzle outlet pressure.

According to classical nucleating theory (CNT) the rate of nucleolus formation may be written [5] as follows:

$$J_{\text{CNT}} \sim \left(\frac{2\sigma}{\mu m}\right)^{1/2} \exp\left[-\frac{\Delta G}{k_b(\Delta \mu)^2}\right]$$

where $m$ is one molecule mass; $\Delta G$ is effective energy of critical cluster formation. Chemical potential, which represents the phase transformation moving force, may be written as:

$$\Delta \mu = k_b T \ln(R_p)$$

Here: $k_b$ is Boltzmann constant; $T$ is phase transition temperature. Dimensionless surface tension energy parameter proposed in [17]:

$$\Theta = \frac{a_0 \sigma}{k_b T_0}$$
σ is surface tension; $a_0$ is surface square conventionally referred to one liquid molecule:

$$a_0 = (36\pi)^{1/3} \left( \frac{M}{\rho_1 N_A} \right)^{2/3}$$  \hspace{1cm} (5)

Here: $M$ is mole mass; $\rho_1$ is liquid density; $N_A$ is Avogadro number. Combining equations (1-5) it may be written:

$$J_{CNT} = \left( \frac{2\sigma}{\pi m} \right)^{1/2} \exp \left[ -\frac{4\theta^2}{\ln(\rho_1)} \right]$$  \hspace{1cm} (6)

According to hypothesis under consideration, the energy nucleation barrier is a transition point to complete disintegration regime or so called «full flashing». It means that the value of the dimensionless parameter $\chi$ equals 1.

$$\chi = \frac{\theta^3}{\ln(\rho_1)}$$  \hspace{1cm} (7)

If $\chi$ is less than 1, or, in another words, the value of chemical potential is greater than surface tension energy the probability of full flashing regime is high. As it was found out in [5] for spirit and acetone, if $\chi$ is greater than 10, aerodynamic (mechanical) stream disintegration takes place for short constricting nozzles. Besides submicron mode the presence of considerable amount of micron size droplets is typical for such regime.

Speaking about “long” nozzles it should be marked, that according to experimental pressure distribution along the diverge zone there is a rarefied zone. Thus, the $\chi$ parameter may be modified and instead of $P_\infty$ there may be used minimal pressure along diffuser tract $P_{\text{min}}$. It may be found by calculations or by experiment. So the expression for parameter $\chi$ may be rewritten:

$$\chi_1 = \frac{16\pi \sigma^3}{3(\Delta \mu_{\text{max}})^2} \approx \frac{\theta^3}{\ln(\rho_1 \mu_{\text{max}}^2)} \cdot \frac{\Delta \mu_{\text{max}} \delta P}{P_{\text{sat}}(T_{\text{in}})} = \frac{P_{\text{sat}}(T_{\text{in}})}{P_{\text{min}}}$$  \hspace{1cm} (8)

The modified experimental data treatment is presented in figure 4.

![Figure 4](image-url)

**Figure 4.** Submicron droplets mass fraction in atomized superheated water plumes vs. $\chi$ parameter for nozzles with various geometries:
1 – “long” nozzles “Laval”-type $d_0=0.6$ mm.;
2 – short constricting nozzles;
3 – “long” nozzles “Laval”-type $d_0=1.6$ mm.

Note that parameter $\chi$ well describes the situation in “long” nozzles even for different geometry. After its value becomes less than 1 and within its subsequent decreasing the droplet size distribution becomes practically submicron mono-modal one. Another situation takes place for short constricting nozzles at the same inlet parameters. Even then $\chi$ value is less than 1 - the micron mass fraction remains great enough. The droplet size distribution remains bimodal. It is connected for different hydrodynamic conditions of flasing for short nozzles [15].

It should be once more noted, that “full flashing atomization” term does not fully coincide with the term, “full flashing” [5], which is determined only by diverge angle value for the short nozzles.
5. Conclusions
Application of nozzles with narrow throat and relatively long diverge part makes it possible to increase the submicron droplets mass fraction from ~50 to ~90%, initial temperature being 140-240°C. It is significantly greater than submicron mass fraction for short scattering nozzles under the same conditions.

Experimental results and numeral modeling reveal significant peculiarities of metastable superheated water flow in such nozzles in comparison with short ones in the throat zone and in diverge part of the “long” nozzle. These peculiarities are connected with “explosive boiling and subsequent defragmentation (“full flashing atomization”) and determine reaching practically submicron monomodal droplet size distribution in superheated water in atomization plumes.

The proposed dimensionless parameter $\chi$ reflects the situation of metastable superheated water atomization in “long” nozzles even with various geometry. When it becomes less than 1 practically submicron mono-modal droplet size distribution (“full flashing atomization”) may be reached.

6. References
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