Features of metastable superheated water atomization when being discharged through convergent-divergent nozzles at different superheat values

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Abstract. Experiments with the metastable superheated water atomization proved the significant increase of the submicron droplets mass fraction at the outlet of convergent-divergent nozzle from 0.45-0.55 to 0.75-0.9 with an increase of the inlet water temperature from 170 to 255°C. Two different approaches to dimensionless treatment of the atomization process data and determining the boundary of the zone of flashing predominance are compared. The analysis of two approaches to dimensionless treatment of experimental and calculating results concerning transition to predominating role of nucleation in the process of superheated liquid atomization in convergent-divergent nozzles is done.

1. Introduction.

Convergent-divergent nozzles with small diverge angles for highly disperse atomizing of superheated water are applied in different branches of industry. In particular, they are used in fire fighting [1], capturing harmful aerosols, etc. Such atomized sprays have two significant peculiarities. First is the high interface (this determines the intense heat transfer between the phases), second a notable increase of vapour concentration takes place while heating the highly dispersed phase. It provides displacement of oxidant from the fire zone. That is one of the reasons for investigating the conditions of formation of highly dispersed superheated water atomization plumes (SWAPs) containing mainly submicron droplets.

Such superheated water atomized plumes (SWAP) were studied experimentally in our previous works [2,3]. The nozzle geometry used made it possible to predict metastable superheated flows and water flashing in the nozzles. The experimental data on pressure and temperature distribution along the nozzle length obtained allowed determining the position of the flashing zone (in so doing different lengths of the nozzle diverging section were used). They confirmed the predicted estimates regarding the changes of the flow characteristics in the channel.

2. Experimental installation and results.

The main factor which determines intensity and a level of the metastable superheated water flow transformation into highly dispersed plume with submicron droplet mass fraction dominance is the initial level of water superheating. The modification of experimental installation (figure1) allowed to increase the initial temperature up to 260°C and the initial pressure to 6.0MPa. Simultaneously modification of the optical system was conducted. This system is used for scattering indicatrices measuring in optically dense plumes of atomized superheated water investigated, on the basis of which
the dispersion characteristics of plumes in submicron and micron diameter ranges are determined. The main aim of the measurement system modernization was decreasing the level of diagnostic and scattering laser rays attenuation in plumes.

![Figure 1a. Experimental installation](image1a)

1 – autoclave; 2 – valves; 3 – heaters; 4 - thermocouples; 5 – pressure sensors; 6 - compressed air cylinder; 7– test nozzle

![Figure 1b. Scheme of optical measurements using minitubes for optically dense superheated water plumes](image1b)

1 –test section; 2 –air inlet guide vane; 3 - nozzle; 4 – rotating plate; 5 – source of monochrome radiation; 6– limiting diaphragm; 7 – conemini-tubes; 8–detector of scattered radiation intensity; 9–sensor of direct radiation for loss registration; 10 – photo-camera

To decrease the diagnostic and scattered laser rays attenuation and to avoid multiple scattering in atomized superheated water plumes a special mini lightguides (the small diameter tubes) were introduced into the plume volume both for diagnostic ray and for scattered rays from outside the measuring volume. As a result, the attenuation coefficient for the plume of 30mm diameter (at 120mm from the nozzle outlet) was less than 4 (the distance was 5-6mm between mini-tubes) while at the absence of the lightguides the attenuation coefficient varied from 40 to 120 depending on the measurement angle. Besides in the modified system the attenuation coefficient did not depend upon the measurement angle.

The new data on distribution of droplet mass fractions as a function of droplet radius in the atomized superheated water plume are presented in figure2. for initial water temperature $T_1=260^\circ$C. The significant increase in submicron droplets mass fraction (from 0.6 to 0.8) as compared to the case of initial temperature $T_1=240^\circ$C. These results refer to the initial spray zone (less than 0.1m).

There are two mechanisms of superheated water atomization in convergent-divergent nozzles. Until certain level of superheating is reached mainly occurs liquid disintegration due to aeromechanic forces impact. In this case the atomization plume has an irregular structure and contains a lot of droplets which radius is more than $5\mu m$. When a certain level of superheating is reached some part of liquid is disintegrated by «flashing». As a result, a submicron droplet fraction appears, and droplet mass fraction distribution becomes bimodal. As the level of superheating increases the submicron droplet fraction increases as well. Finally, the “flashing” mechanism of superheated water atomization becomes predominant one.

One of the questions under consideration which concerns the atomization of the superheated water using the nozzles is the influence of the flow swirling on the level of dispersion and on the opening angle of the SWAP. This problem was discussed in [4]. As a result of investigations by various methods

![Figure 2](image2)
of the flow swirling and varying the level of the flow spin it was concluded that flow swirling do not significantly affect the above characteristics, however in some cases the influence is negative. It leads to unstable regimes. Our investigations confirm this conclusion, at least at the temperature of superheated water at the nozzle inlets 170-240°C.

3. Dimensionless treatment of experimental and predicted results

Analytical assessments show that in convergent nozzles and in a convergent section of convergent-divergent nozzles, as a rule, the saturation pressure that corresponds to initial inlet water temperature is not reached. It means that in the convergent-divergent nozzle atomizing process occurs downstream of the nozzle throat [3]. This atomization process is determined mainly by two following factors: aerodynamic (mechanical) disintegration of a jet and flashing inside liquid fragments. In convergent-divergent nozzles with a narrow throat and small opening angle flashing can play the more significant role than aerodynamic effects and at a certain level of the liquid superheat the flow fragmentation is fully determined by flashing inside the nozzle. The objective is to find dimensionless parameters that determine the zone of flashing process dominance. Below, we will consider two approaches to the problem.

For short converging nozzles the values of critical superheat were experimentally determined in [5] for acetone and ethanol. These data correspond to the case of jet disintegration out of the nozzle boundaries (so called external disintegration of a jet [5]). The main idea of the model proposed is as follows. Liquid atomization is determined by a bubble growth rate, which in turn is proportional to the value of Jacob number

\[ Ja = \frac{C_{pl} \cdot \Delta T \cdot \rho_l}{h_v \cdot \rho_v} \]  

(1)

where \( C_{pl}, \rho_l \) and \( \rho_v \) are specific heat, liquid and vapor velocities, respectively, while \( h_v \) is the enthalpy of evaporation. Figure 3 demonstrates the results obtained. The boundaries of mechanical (aerodynamic) jet disintegration (the lower line A) and the fully flashing atomization (the upper line C) are determined for nozzles with different aspect ratios (1.7 < \( L/D \) < 50). The slight additional effect of Weber number value (the proportion to \( We^{-1/7} \)) is also seen. Here

\[ We = \frac{D \cdot \rho_v \cdot u_0^2}{\sigma} \]  

(2)

where \( D \) is the nozzle diameter, \( u \) is the velocity at the nozzle outlet, and \( \sigma \) is the surface tension coefficient. In [6] such an approach was further developed in detail. The authors of the present paper
tried to apply such an approach while treating own experimental data for water atomizing in convergent-divergent nozzles. These data are shown in figure 3 as crosses, and they acceptably correlate with the data for acetone and ethanol. The experiments of JIHT confirmed the data of [5] regarding the change of the droplet-plume shape with the atomized liquid temperature increase. At the same time, under the conditions existed above line C in figure 3 (the zone of large Jacob number values) we always obtained the bimodal dispersion structure of the atomized plume [2, 3] with the submicron droplet fraction being up to 60-75%, while in [5] the “fully flashed” plume is treated as uniform and containing the droplets of several micrometers in diameter. Such a difference can be due different measurement techniques applied when determining droplet dimension in these two studies. Remind, that in [2, 3] light scattering method within large scattering angles was used.

Figure 3. The relationship of the transient point to “full flashing” regime from $Ja$ and $We$ numbers according [6]

In our dimensionless analysis on determining the boundary of the flashing dominance in the total liquid atomization process (just these conditions we treat as “fully flashing”) somewhat changed approach was applied. In our experiments with water fine atomization occurred at $R_p = p_{sat}/p_1$ values, which are more than 15-20, where $p_{sat}$ is the saturation pressure that corresponds to the inlet liquid temperature and $p_1$ is the pressure at the nozzle outlet. According to the assessments conducted it can be supposed that under these conditions an excess of the chemical potential existed due to the large water superheating relative to the saturation temperature at the nozzle exit (this excess is proportional to $\ln R_p$) almost fully transferred into the surface energy of small bubble clusters (the vapor bubbles of a critical radius $r = 2\sigma/(p_{sat}-p_1)$) formed. After certain transformation, the following transition parameter

$$K_s = \frac{3}{2} \frac{1 - 1/R_p}{\ln (R_p)}$$  \hspace{1cm} (3)$$

can be obtained that determines the degree of flashing effect.

Figure 4 shows the relationship between the transition parameter $R_s$ and the initial superheated liquid temperature $T_s$. The regions of different degree of flashing effect are also depicted in the Figure. Note
that during the above analysis a heterogeneity factor [8] was assumed being constant, otherwise, it must be included into the analysis also.

4. Conclusions
- The superheated water atomization experiments with convergent-divergent nozzles within initial superheated water temperature range of 170-255°C proved the significant change in submicron droplets mass fraction from ~0.5 to 0.75-0.85 near the nozzle outlet.
- Two approaches in dimensionless treating of experimental and predicted results concerning transition to predominating role of flashing in the process of metastable superheated liquid atomization in convergent-divergent nozzles has shown that flashing dominance starts at \( K_s = 0.8-0.6 \), which corresponds to \( Ja \) number values of 80-200.

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