Superheated metastable atomized water plume diagnostics peculiarities in confusor-diffuser nozzles; atomization process: dimensionless treatment

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Abstract. Micron mode mass fraction $\varepsilon$ determination method was tested for dense superheated water atomization plumes based on measurement attenuation coefficients of primary laser radiation. The initial water temperature in experiments was 200 and 240°C. The mass fraction of micron mode $\varepsilon$ was determined using Bugger-Lambert equation and Mi theory. The comparison with previous data, which were obtained by scattering indicatrix analysis, was done. In terms of development of dimensionless treatment of experimental data on superheated water spray, the parameter expression for the transition to predominating role of nucleation in superheated water atomization in confusor-diffuser nozzles was revised the base of critical bubble formation.

1. Introduction

Finely dispersed superheated water (or other liquids) may be applied and are already applied in power generation and in new techniques. Comparison of experimental and calculating data concerning thermo-physical and gas-hydrodynamic characteristics of atomized superheated metastable water flow and its disperse characteristics for various nozzle types shows that the optimal variant for most fine superheated water atomization at the initial temperature level of 240°C is spray by means of confusor-diffuser nozzles. The calculating estimation of the main processes, which determine the peculiarities of the atomized water plumes at initial temperatures more than 200°C has shown, that the main process leading to fine atomization is “explosive” boiling of superheated water [1]. It takes place in diffuser near the nozzle throat. Then subsequent quick transformation of foamed water into two-phase vapor-droplet flow occurs. This phenomenon leads to formation of significant submicron droplet fraction.

It should be noted, that total droplet mass fraction in such vapor-droplet flows significantly (1.5-2 orders) exceeds the mass fraction in atomized superheated water steam–air-droplet flows from short nozzles, which were studied earlier [2]. Both circumstances lead to rather high submicron droplet volume concentration in superheated water atomization plumes in confusor-diffuser nozzles. As a consequence, while crossing the plume, the diagnostic laser beam (as well as scattering radiation) significantly attenuates because of secondary scattering. This phenomenon reduces the scattering indicatrix measurement accuracy in plume diagnostic micro-volume (at the cross of diagnostic and scattering beams), and it needs to be studied and controlled. It is especially important for the nozzles under consideration.

At the first stage of the investigations in JIHT RAS the superheated water atomization through the short narrowing nozzles was studied [2]. As experiments have shown, rather wide initial diverge angle
(90° and more) is typical for such plumes. It is caused by two mechanisms of nozzle outflow jet disintegration: the first is aeromechanical one and the second is the mechanism of explosive boiling inside the liquid fragments of the disintegrated jet. Both mechanisms, which act successively (or practically simultaneously), in a comparatively short time ($10^{-5}$–$10^{-6}$s) lead to the jet disintegration with typical bimodal droplet size distribution [3]. At that the submicron droplet fraction is formed mainly due to explosive boiling mechanism. As initial superheated water temperature $T_0$ increases from 170 to 240°C the process of explosive superheated water boiling becomes predominating. And the submicron droplets mass fraction $\varepsilon$ in short narrowing nozzle plumes increases from approximately 0.35 to 0.6 [2]. Obviously the great droplet flying apart (and big initial plume angle: 90-110°) takes place due to explosive boiling process. Initial plume angle then decreases to about 12–14°.

By contrast to short narrowing nozzles, the superheated water atomization in confusor-diffuser nozzles with little expansion angles (about 12°) has essentially different behavior. Computational flow analysis and experiments with such nozzles show, that superheated water explosive boiling (at initial temperature levels of about 200-240°C) takes place in diffuser part near the throat of the nozzle, and subsequent quick foamed water flow transformation into steam-droplet flow occurs. The location of the superheated water boiling point was proved by a series of experiments using nozzles with various length of diffuser part [1]. In the mentioned range of $T_0$ (200 to 240°C) submicron fraction $\varepsilon$ increases more (in comparison with short nozzles) in confusor-diffuser nozzles, from 0.7 – 0.8 to 0.8 – 0.9.

2. Experimental investigation and analysis of laser radiation attenuation in atomized superheated water plumes for mass micron and submicron droplet fraction ratio determination

The aim of investigation was to independently confirm the previous results [1] (for estimation of secondary scattering influence). So the attenuation coefficients of primary laser radiation were measured in atomized superheated water plumes, as it was done in [2], for estimation of laser radiation attenuation at various angles. The initial water temperature in experiments was 200 and 240°C. The measurement zone of the experimental plant is shown at the figure 1. The experimental attenuation coefficients were $K_0=40$ at $\alpha=0°$ and $K=100-120$ at $\alpha=45°$. It is an order greater than in short narrowing nozzles, where (at the same overheating) the corresponding values were 2.8 – 3.0. These measurements were motivated by the fact, that according to Mi theory the scattering takes place mainly at relatively big droplets (1-10mkm), figure 2. As one can see in figure 2 the scattering at the droplets with radius $r=10mkm$ is several orders more than at $r<1mkm$ droplets. It confirms estimation of submicron mass fraction value in atomized superheated water plumes for nozzles with various geometry.

![Figure1. Experimental unit “Raspyl-M” – the active zone scheme](image-url)
3. The analysis of results

The value of micron fraction (1-10\,\text{mkm}) may be estimated using Buger-Lambert equation as follows:

\[
K_0 = \exp\{L \cdot \int_{1}^{10} [\Psi_0(r) \cdot n(r)] \, dr\} = \exp\{L \cdot \int_{1}^{10} [\Psi_0(r)/r^3 \cdot n(r) \cdot r^3] \, dr\} \tag{1}
\]

Here: \(K_0\) is the experimental attenuation laser radiation coefficient; \(L\) is the diagnostic laser beam length; \(r\) is the water droplet radius in micron range; \(n\) is the number of droplets and \(\Psi_0(r)\) is the scattering function, determined by calculation according to Mi theory for the droplet radius and laser wave length (532\,\text{nm}).

By the theorem on mean value:

\[
\ln(K_0)/L = \overline{\Psi_0(r)/r^3} \cdot \int_{1}^{10} [n(r) \cdot r^3] \, dr \quad \text{or} \quad \ln(K_0)/\left[\overline{\Psi_0(r) \cdot L/r^3}\right] = \int_{1}^{10} [n(r) \cdot r^3] \, dr \tag{2}
\]

Taking into account relatively uniform distribution of the function \(\Psi_0(r)/r^3\) in the range from 1 \,\text{mkm} to 10 \,\text{mkm}, we have:

\[
M_s = \int_{1}^{10} [n(r) \cdot r^3] \, dr \cdot \frac{4}{3} \pi \cdot \rho = \frac{4\pi \cdot \rho}{3L} \cdot \ln(K_0) / \overline{\Psi_0(r)/r^3} \tag{3}
\]

Here: \(\rho\) is the liquid density and \(M_s\) is the micron range droplet mass concentration in radiating volume.

On the other hand:

\[
M_{mk} = 4G_{mk}/(\pi \cdot D_f^2 \cdot U) = 4G \cdot \varepsilon / (\pi \cdot D_f^2 \cdot U) \quad \text{or} \quad \varepsilon = \pi \cdot D_f^2 \cdot U \cdot M_{mk}/4G \tag{4}
\]

Here: \(G\) is the droplet mass flow rate in atomized water plume; \(G_{mk}\) is the micron droplet mass flow rate in atomized water plume; \(D_f\) and \(U\) are the diameter and flow velocity in atomized water plume - experimental values and \(\varepsilon\) is the micron droplet mass fraction, scattering at which is significantly higher than at submicron droplets under experimental conditions.

Assuming \(M_{mk} = M_s\) and taking into account (3), the droplet mass fraction in 1-10 micron range is:
\[
e = \frac{\pi \cdot D_f^2 \cdot U}{4G} \cdot \ln(K_0) \cdot \frac{4}{3} \pi \cdot \rho
\]

And according [4]:
\[
\sum_{s}^{tr} = C \cdot \int_{1}^{10} Q_s \cdot (1 - \mu(r)) \cdot \pi \cdot r^2 \cdot F(r) \, dr
\]

Taking into account:
\[
C \cdot F(r) = n(r)
\]
\[
\Psi_0(r) = Q_s \cdot (1 - \bar{\mu}) \cdot \pi \cdot r^2
\]

And finally:
\[
e = \frac{\pi^2 \cdot U \cdot \ln(K_0)}{3 \Psi_0(r) / r^3 \cdot G \cdot L} = \frac{\pi \cdot U \cdot \ln(K_0) \cdot \rho \cdot D_f^2}{3 Q_s (1 - \bar{\mu}) / r \cdot G \cdot L}
\]

\(M_s = M_{mk}\) is the droplet mass concentration in spray plume; \(\Sigma u\) is the transport scattering coefficient; \(F(r)\) is the droplet radius distribution function; \(C\) is the droplet number per volume unit; \(\mu\) is the scattering asymmetry factor and \(Q_s\) is the scattering efficiency factor. Last two parameters are calculated according Mi theory being complicated functions of diffraction parameter: \(2\pi r / \lambda\). Parameters \(U, K_0, D_f, G\) and \(L\) are determined in experiment.

Then, the above relation was applied to experimental data, obtained at superheated water atomization through the short narrowing nozzles and through confusor-diffuser nozzles with laser beam crossing all plume or part of the plume, which was restricted by mini-tubes. According to these calculations for initial water temperature of 240°C the value of micron droplet mass fraction was \(\varepsilon \approx 0.35\) for short nozzles [2] and \(\varepsilon \approx 0.12\) for confusor-diffuser nozzles (both cases). This estimation conforms to previous results, which were obtained by means of laser scattering indicatrix analysis, according to which the submicron droplet fraction was \(\varepsilon \approx 70\%\) for short nozzles and 80-90\% for confusor-diffuser ones.

Thus independent new experiment analysis of laser radiation attenuation in atomized superheated water plumes confirms mass micron and submicron droplet fractions ratio which was obtained earlier by methodic [1,2].

4. The experimental and calculating data dimensionless treatment for explosive superheated water boiling in nozzles

Revision of the dimensionless treatment of calculated and experimental data on superheated water boiling in superheated water atomization process [5,1] was made on the base of critical cluster formation. Ratio of critical cluster formation work to chemical potential energy of phase transformation was considered. On this basis we can write the parameter, which determines transition to predominating role of explosive boiling in superheated water atomization process as follows:
\[
K_s = \frac{16 \sigma^3}{[3k_b \cdot T_s \cdot \ln(R_p) \cdot N_m \cdot (P_s - P_1)]}
\]

where: \(N_m\) is the molecules number in critical cluster, and \(R_p = P_2 / P_1\) and taking into account \(R_{cr} = 2\sigma / (P_s - P_1)\) we have:
\[
K_s = \frac{\sigma \cdot \pi \cdot M_l}{[k_b \cdot T_s \cdot \ln(R_p) \cdot \pi \cdot R_{cr} \cdot \rho_v \cdot Na]}
\]

Multiplying numerator and denominator by \(P_s\), and taking into account \(R \cdot T_s = k_b \cdot Na / M_l = P_2 / \rho_v\) we have:
\[
K_s = (1 - 1 / R_p) / 2 \ln(R_p)
\]

Within constant accuracy it coincides with criterion, which was derived in [1] from some other considerations.

Here: \(R_{cr}\) is the critical cluster radius; \(\rho_v\) is the vapor density at temperature \(T_s\); \(Na\) is the Avogadro number; \(M_l\) is the liquid molar mass; \(R\) is the vapor gas constant; \(k_b\) is the Bolzman constant; \(\sigma\) is the
surface tension; \( T_s \) is the liquid temperature at the nozzle inlet; \( P_s \) is the saturation pressure corresponding to \( T_s \); \( P_l \) is the pressure in liquid; \( \rho_l \) is the liquid density.

On the other hand our calculations and experiments [1] prove that explosive boiling begins at approximately two times lower pressure in comparison with equilibrium state, which corresponds to [6]. It means that the critical cluster radius will be two times greater, than in above parameter, so it can be rewritten as:

\[
K_s \approx 4\left(1 - \frac{1}{R_p}\right) / \ln(R_p)
\]  

(12)

Figure 3 shows the relationship between parameter \( K_s \), which characterizes the transition to predominating nucleation role in superheated liquid atomizing process, and liquid initial temperature. The parameter independence from surface tension connected with various critical cluster size for various liquids[1].

\[\text{Parameter } K_s \text{ via superheated liquid initial temperature } T_0.\]

Parameter \( K_s \) is correct until we assume heterogenous factor to be constant. Otherwise it should be considered as independent criterion. Besides, it should be noted, that the question about applicability of heterogeneous factor \( G \) [7] (in terms of classical homogenous nucleation theory) in connection with its rather grate values (more than \( 10^3 \)) remains open. Thus, actuality of adequate description of heterogenous nucleation remains high.

Conclusions
On the basis of experimentally measured attenuation coefficients of primary laser radiation \( (K_0) \) for scattering angle \( \alpha \equiv 0^\circ \) estimation of micron droplet mass fraction was investigated for various scattering volume geometry. Bugger-Lambert equation and data based on Mi theory were used for the new independent estimation of droplet mass fraction analysis. The comparison with previous results, which were obtained earlier using scattering indicatrix data analyses, confirms submicron droplet mass fraction increase in confusor-diffuser nozzles (80-90%) in comparison with short narrowing nozzles (60-70%) at initial superheated water temperature being more than 240°C.

In terms of development of dimensionless treatment of experimental data on superheated water spray, dimensionless parameter, based on the ratio of critical cluster formation work to chemical potential of phase transformation is derived. This parameter determines the transition to predominating role of explosive boiling in superheated meta stable water atomization process in confusor-diffuser nozzles.

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