Specific features of evolution of dense atomized superheated water plumes and peculiarities of its diagnostics

V I Zalkind, Yu A Zeigarnik, V L Nizovskiy, L V Nizovskiy and S S Schigel
Joint Institute for High Temperatures of RAS (JIHT), Moscow, 13/2 Izhorskaya Street, Russia
E-mail: levmobile@mail.ru

Abstract. Experimental study of evolution of plumes of atomized metastable superheated water during its discharge through convergent-divergent nozzles is conducted. Dispersion characteristics of dense plumes in micron and submicron droplet diameter ranges are obtained. Theoretical and prediction analyses of different coagulation mechanisms in the considered two-phase flow are performed. The negligible effect of Brown-type coagulation is shown. It is also demonstrated that turbulent coagulation can change the fraction of micron-diameter droplets within 9%. In addition, for the first time, an “inertial” mechanism of coagulation is considered for the studied plumes under the conditions of plume baking in a cocurrent flow or in the ambient air. It can lead to a considerable decrease in the submicron-droplet mass fraction, which is observed in experiments even at a small distance from the nozzle cut. The predicted data are compared with experimental ones obtained at the experimental setup.

1. Introduction
Convergent-divergent nozzles with small opening angles and high-density dispersed phase, which operate using superheated water atomization, are applied in different branches of industry and life. In particular, they are applied in fire-fighting [1], harmful aerosols capturing, etc. Here, two important specific features of such atomized media are used, i.e., large interface surface area between the phases, which provides intense heat transfer, and a considerable increase of steam concentration in the course of heating and evaporation of the highly dispersed phase. In this regard, it is especially important to study the conditions of fine atomization of liquid and evolution of the atomized flow at different distances from the nozzle (by optical and thermophysical measurements in the flow). In the paper the results of the first phase of experimental studies are presented. They include dispersion characteristics of the atomized water plume in different flow cross sections and a flow dynamic head that corresponds to different scattering indicatrices.

2. Experimental setup and results
The modernization of “Raspyl-2M” setup allowed increasing the water temperature $T_o$ at the nozzle inlet up to 260°C and the pressure up to 6.0MPa. Simultaneously, the test section was also modernized. This allowed conducting necessary optical and thermo physical measurements in the extended range of atomized plume length, from 50 to 220mm.

Intense attenuation of the diagnosing laser beam and its multiple scattering within the measurement section can introduce considerable errors in the results of scattering indicatrices treatment while
solving the inverse light scattering problem at large scattering angles using Mi’s theory [2]. Therefore, the existed optical scheme is reconstructed. Mini-tubes (light guides) are installed (see figure 1).

Figure 1. Experimental setup. Test section for measuring dispersion characteristics of the atomized water plume. 1 – test section; 2 – air duct; 3 – nozzle; 4 – rotating table; 5 – monochromatic light source; 6 – diaphragm; 7– conical tubes; 8 – scattering beam receiver; 9 – straight beam catcher for measuring light attenuation; 10 – photo-camera; 11 – dynamic head tap.

This considerably (by an order of the magnitude) shortened the diagnosing beam length within the plume volume and reduced the attenuation coefficient by more than an order of the magnitude, down to 4–5.

Figure 2. Distribution of the droplets by size at the plume axis and different plume lengths from the nozzle cut. $T_o = 240^\circ$C, pressure 4.2MPa. a – $L= 89$mm; b – $L= 118$mm; c – $L= 223$mm; curve – integral droplet volumetric fraction.

The conducted experiments using mini tubes confirmed the main trends revealed earlier, i.e., the existence of a bimodal droplet structure in the atomized plume, while using superheated water, and a high mass fraction of submicron droplets (from 65 to 85%) at $T_o = 240–260^\circ$C at a distance of 5–6 calibers from the nozzle cut.

They allow determining changes in the dispersion characteristics of the plume along its length and radius. Figure 2 presents changes in micron and submicron mass fractions depending on the distance from the nozzle outlet at the axis of the atomization plume. In the central part of the plume the radial
distribution appears to be uniform (figure 3). Typical distribution of the flow dynamic head at the
plume axis is measured as well. The data from the scattering indicatrices at \( L= 120 \text{mm} \) and different
distances along the plume radius show a small change in the submicron droplet fraction in the central
zone of the plume (figure. 3). Near the visible boundary of the plume this fraction decreases further,
1.5 – 2 times.

![Figure 3. Distribution of droplets of different size over the atomized plume cross section](image)

\[ \text{at } L=120 \text{mm, } T_s=240 ^\circ \text{C, pressure } 4.2 \text{MPa} \]

3. Discussion

One of the main objectives of the present study is the analysis of the atomized plume evolution as a
dependence of distance on the nozzle cut. The assessments show the importance of the droplet’s
coagulation in changing dispersion characteristics of dense atomized plumes.

Turbulent coagulation to a great extent is determined by the level of the considered flow
turbulence. In turn, this level depends on the gas-dynamic characteristics. Therefore, the assessments
are made assuming that the maximal level of turbulence in the plume is equal to that in a free turbulent
jet in an external air flow [3]. The level of turbulence at the nozzle cut is taken to be maximal – 0.15.
The predictions of Brown and turbulent coagulations are conducted according to [4] at the conditions
of experiments. The predictions show that the turbulent coagulation is by two orders of the magnitude
more intense than the Brown one; the mass of the micron-size droplets increases by up to 6% due to
turbulent coagulation at 120mm from the nozzle cut under the conditions of the experiment.
Assumingly, the rate of turbulent energy dissipation decreases in direct proportion with the flow
velocity at the plume axis as it usually happens in turbulent free jet predictions.

According to [4] the correlation between the turbulence level and dissipation rate is as follows:

\[ \varepsilon = C_\mu kT_L \]  

where \( C_\mu =0.09 \) is the Kolmogorov -Prandt constant; \( k \) is the turbulent energy of the carrying gas
flow; and \( T_L \) is the cross-section averaged Lagrange time scale.

According to [4] the turbulent coagulation core may be written as

\[ \beta_r \left( \frac{8\pi \varepsilon}{15k} \right)^{0.5} d^3 \]  

A decrease in a number of droplets due to coagulation is

\[ U = \frac{dN}{dx} = \frac{\beta_r N^2}{2}, \text{ where } Nd^3 = \frac{6\Phi_0}{\pi} \]
here $N_0$ is a number of droplets in the unit of volume and $\Phi$ is the initial volumetric concentration of droplets. With an account for (1) and (2) the equation (3) after integrating by $x$ with $N_0/N = (d/d_0)^3$ takes the following form:

$$\frac{d}{d_0} = \exp \left[ \frac{8e}{15\pi\nu} \Phi x \right] \frac{\Phi_0 x}{U}$$  \hspace{1cm} (4)$$

The assessments show that under the experimental conditions the turbulent coagulation provides the changes in the droplet dimensions, which are less than 12% at the maximum distance (220mm) investigated. In this context we consider the inertial mechanism of coagulation, which relates to the difference in slip velocities of droplets of different dimensions, in the course of plume braking in the cocurrent air flow. The calculation model is developed, and the corresponding predictions are made for droplets of 0.1 – 10\(\mu\text{m}\) in diameter and changes in relative fractions of submicron and micron droplets are assessed.

Droplet velocities at the nozzle cut are assumed to be equal. A velocity of droplet deceleration is written as $y_p = W_0 - W_p$, and a flow acceleration (deceleration) is taken to be constant and equal to $a_f = W_0 - W_f(t)/\tau$, where $\tau$ is the time of the flow displacement from the nozzle cut to the point of measurements. Then the particle deceleration (under Stokes’ flow) can be written as follows.

$$\frac{dy_p}{dt} = \beta \int_0^t \alpha f(t) dt - y_p$$ or $y' + f(t)y = g(t)$  \hspace{1cm} (5)

The solution to this differential equation for the integral curve passing through the point $(\eta, \xi)$ is as follows:

$$y = e^{-F} \left[ \eta + \int_\xi^t g(t) e^t dt \right]$$  \hspace{1cm} (6)

where

$$F(t) = \int_\xi^t f(t) dt$$

at the acceleration value within the initial section being constant

$$f(t) = \beta = \frac{9\mu}{2\rho r^2}; \eta = 0; \alpha f(t) = \alpha f = \text{const}$$  \hspace{1cm} (7)

and respectively

$$y = e^{-\beta t} \left[ \eta + \int_\xi^t \beta \alpha f(t) e^{t} dt \right] - \frac{\alpha (\beta t - 1)}{\beta}$$  \hspace{1cm} (8)

For the flow jet deceleration according to hyperbolic law, starting from a certain moment $t_1$ with the flow velocity $W_{f1}$ and the droplet velocity $W_{p1}$, ($W_{f1} = \eta W_{p1} = M$), the droplet deceleration velocity may be written as

$$\frac{dz_p}{dt} + \beta(t) z = \beta(t) \left( M + \frac{W_{f1}}{Kt} \right); \text{ with } \int_{t_1}^{t} \frac{dz_p}{dt} dt = z(t)$$  \hspace{1cm} (9)

and the solution of the equation for $z$ is

$$z = e^{-\beta t} \left[ M + \int_{t_1}^{t} \frac{W_{f1} \beta}{Kt} e^{\beta t} dt \right]$$  \hspace{1cm} (10)

or after integration
\[ z = e^{-\beta t_0} \left[ M + W_f / K \left( \ln t + \frac{\beta t}{1!} + \frac{(\beta t)^2}{2!} + \ldots + \frac{(\beta t)^n}{n!} \right) \right] t_1 / t_1 \] (11)

Now it is easy to find the relative velocity of two droplets of any dimension, which in turn allows constructing a model of inertial coagulation with an account for the coagulation efficiency coefficient [5], which depends on Stokes number \( \text{St} = \tau_0 U_r / R \), where \( \tau_0 \) is the relaxation time of the submicron droplet, \( U_r \) is the relative droplet velocity, and \( R \) is the radius of the large droplet.

**Figure 4.** Effect of coagulation on the relative diameter of the micron-mode droplet along the atomized superheated water plume. 1 – turbulent coagulation; 2 – inertial coagulation; 3 – the total effect. \( U_0 = 100 \text{ m/s}; \varepsilon_0 = 50\% \).

Figure 4 presents the dependence of the relative droplet diameter on the distance from the nozzle cut. The estimates for the turbulent coagulation effect are made for the turbulent energy dissipation rate at the nozzle exit \( \varepsilon_0 = 15\% \) (curve 1). It is supposed that \( \varepsilon \) decreases proportionally to the flow velocity at the jet axis. The same figure shows the change in the mean Sauter diameter of the micron-mode droplet due to inertial coagulation (curve 2). Note, that the ratio of mass fractions of submicron and micron droplets changes in proportion to the 3-rd degree of the value presented in the figure.

The relative decrease in the submicron mode fraction due to turbulent and inertial coagulation at the initial section of the plume is approximately two times less than that observed in the experiments. Apparently, simultaneously with the processes described above there is certain additional reason for such a decrease. Different rate of entrainment of the droplets with different diameters in radial direction can provide such an effect. It can occur due to mixing of the atomized water plume with the external air flow and an influence of the nozzle opening angle value (in the experiments conducted it was equal to 12°). Stokes number value for submicron droplets was about 0.01. These droplets are entrained with the gas flow and the entrainment velocity is significantly greater that for micron-size droplets with Stokes number values of about unity. On the whole, the evolution of the atomized superheated-water plume requires further investigations.
Conclusions
The evolution of dense atomized superheated-water plumes discharged through convergent-divergent nozzles has been studied experimentally. This included investigation of dispersion characteristics of such dense plumes in the micron and submicron size ranges of the droplet diameter, using the scattered monochromatic light indicatrices, and measuring flow dynamic head in different flow cross sections.

The theoretical and prediction analyses of the droplet coagulation in the considered two-phase plumes have been made. The Brown-type coagulation is shown to give a negligible effect. The turbulent coagulation can give a change in the micron-size droplets fraction within 9% at 120mm from the nozzle cut. The inertial-type coagulation mechanism has been studied for the first time for the specified flows. Such type of coagulation is caused by a difference in a slip velocity of droplets of different dimensions while the atomized water plume brakes in the concurrent flow or in the ambient atmosphere. The predictions have indicated a significant effect of inertial-type coagulation, which provides an increase in the micron-size droplets mass fraction up to 18%. Nevertheless, the total predicted effect of micron size droplets growth, which may be explained by various mechanisms of coagulation at the initial part of the jet, is approximately two times lower than the experimental one.

Acknowledgments
The work is supported by the Russian Foundation for Basic Research. Grant No 19-08-0050.

References
[1] Pryanichnikov A V, Roenko V V and Bondarev E B 2015 Fires and emergencies: prevention, elimination 4 7–12
[2] Zalkind V I, Zeigarnik Yu A, Nizovskiy V L, Nizovskiy L V and Schigel S S 2020 J. of Physics: Conference Series 1167501203
[3] Abramovich GN1969 Applied Gas Dynamics (Moscow: Nauka) 826
[4] Alipchenkov VM, Zaichick LI and Zeigarnik Yu A2001 Preprint JIHT RAS (Moscow) 53
[5] Varaksin AYu2008 Collisions In Gas Flows With Solid Particles (Moscow Physmathlit) 312