Superheated metastable water atomization: fine atomized water plumes diagnostics and disperse characteristics; summary of results, applications in power generation and new techniques.

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Abstract. Complex experimental investigation of superheated flow and dispersion characteristics of sprays in atomizing nozzles of various types is made. The comparative analysis of experimental and calculating investigations of thermo physic and hydro-gas-dynamic flow and disperse characteristics was carried out for various types of spray nozzles. It has shown that the main process, which determine peculiarities of superheated metastable water flow and phase transformation in spray nozzles, is quick (explosive) boiling up. And the optimal variant for superheated water atomization and achieving the most fine spray plumes, which contain mainly submicron droplet fraction, at initial temperature 240°C (and higher) is atomization by means of contracting-expanding nozzles. In such nozzles the explosive boiling is accomplished by quick transformation of foamed liquid into vapor-droplet flow. Diagnostic peculiarities are considered for these optically dense spray plumes; the auxiliary measurement methods were worked out for estimation superheated water high atomization level. The experimental and calculating data dimensionless treatment was made for achieving extremely fine (mainly submicron) superheated water spray. The dimensionless parameter, which determines necessary water (or some other liquids, for example – fuels) superheating level was derived. The possible technical applications of superheated water sprays are described, and up-to-date state of corresponding projects is given.

1. The superheated water spray comparative analysis for various nozzle types.

The comparative analysis of experimental and calculating investigations of thermo physic and hydro-gas-dynamic flow and disperse characteristics was made for superheated water atomization process. It was done for various nozzle types, and main processes which control the peculiarities of spray plumes were estimated. At the first stage of the investigations in JIHT the superheated water spray through the short narrowing nozzles was studied [1]. As experiment analysis had 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 connected with baro-capillary jet instability and the second is the mechanism of explosive boiling inside the liquid fragments of the disintegrated jet. Both mechanisms, which act consequently (or practically together) in a comparatively short time (10⁻⁵–10⁻⁶ sec) lead to the jet disintegration with typical bimodal droplet size distribution [2]. And 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. Submicron droplets mass fraction in short narrowing nozzles plumes increases from approximately 0.35 to 0.6. Obviously the great droplet flying apart (and large initial plume angle: 90-110°) takes place due to explosive boiling process. Initial plume angle then decreases till about 12–14°.

In contrast to short narrowing nozzles, the superheated water atomization in contracting-expanding nozzles with small diverge angles (about 12°) has significantly another behavior. Calculating flow analysis and experiments in such nozzles show, that superheated water explosive boiling up (at initial temperature levels about 200-240°C) takes place in diffuser part near the throat of the nozzle, and subsequent quick foamed water flow transformation into-vapor-droplet flow[3] occurs. It is possible, that this process of flow transformation in such type of nozzles takes place with some fluctuations. And these peculiarities may be the reason of submicron droplet mass fraction spread. The location of the superheated water explosive boiling point was proved by number of experiments using nozzles with various length of diffuser part. Superheated water atomization processes occurs in relatively long diffuser part near nozzle throat in more expressed and finished form. So it determines greater submicron droplet mass fractionin comparison with spray through short nozzles at the same overheating level. In above range $T_0$ (200-240°C) submicron fraction $ε$ increases more (in comparison with short nozzles) in contracting-expanding nozzles from 0.7–0.8 to 0.8–0.9.

2. Optically dense superheated water spray plumes diagnostic peculiarities in contracting-expanding nozzles.

Superheated water spray plumes, being investigated earlier, in short narrowing nozzles, had a large diverge angle. These plumes rather quickly were reaching relatively large diameter value (80-100 mm at the length 100 -120 mm from the nozzle) and were mixed with passing air flow. As for contracting-expanding nozzles, their spray plume diverge angles are small and constant – approximately 12°, and their diameter in the zone of optical measurements are about 30 mm at the noted length from the nozzle edge; besides these nozzles flow rates were an order and more greater than above short narrowing nozzles flow rates. Such nozzles were tested for possible application in GTU (gas turbine units) with wet compression. So above mentioned difference leads to rather high volume droplet concentration in superheated spray plumes in contracting-expanding nozzles with narrow throat, if compared with short ones. As a result, the laser ray crossing such plumes, as well as scattered radiation are significantly (an order and more) attenuated on their way to detector because of the secondary scattering. And after certain level of scattering is reached, the noticeable part of it is also multilaterally scattered. These phenomena significantly reduces indicatrix measuring accuracy from detected plume micro-volumes. Especially it is important for the small scattering angles. This fact requires special investigation and control, especially for optically dense spray plumes in contracting-expanding nozzles. That is why the initial laser radiation attenuation coefficients measurements were carried out according to rotating angle $α$. The value of this angle during scattering indicatrix measuring varied from -45° to +45°. In these experiments the superheated water initial temperature was 200 and 240°C. The typical experimental results and comparison with results for short narrowing nozzle spray plume are shown in figure 1.
As one can see at the figure 1, the experimental attenuation coefficients values (K) via $\alpha$ angle are about $K_0 = 40$ at $\alpha=0^\circ$ and till $K = 100-120$ at $\alpha=45^\circ$. It is more than order greater as for short narrowing nozzles, for which attenuation coefficients values $K_0$ were 2.8-3.0 at the abovementioned overheating temperatures [1]. It should be noted that $\ln K_0$ ratio for above nozzle types is 3.35 according above experimental data. This ratio may be calculated, using Bugger-Lambert equation according the following approximating function:

$$\ln(K_{02}/K_{01}) = \left[ G_2 \cdot (1 - \varepsilon_2)/(Dd_2 \cdot W_2) \right] / \left[ G_1 \cdot (1 - \varepsilon_1)/(Dd_1 \cdot W_1) \right]$$

where: $\ln K_{02}/\ln K_{01}$ – logarithmes ratio at $\alpha=0^\circ$ for contracting-expanding nozzles($\ln K_{02}$) and for short narrowing nozzles ($\ln K_{01}$) correspondingly; $G$ – corresponding experimental data on droplet flow rates in spray plumes; $Dd$ and $W$ – corresponding experimental data for diameter and flow speed in spray plumes; $(1-\varepsilon)$ – micron droplets mass, scattering at which at small angles (for considered conditions) is significantly greater according to Mi theory.

The second condition of validity of estimating equation (1) is sufficiently close similarity of micron droplet mass concentration relative distributions. It is really confirmed with necessary accuracy by comparison of relative micron droplets mass concentration disperse distributions, which were obtained (using Mi theory) from experimental indicatrixes. The calculating estimations of attenuation coefficients logarithm ratio according to equation (1) give rather close (to directly measured) value: from 3.25 to 3.5, which were obtained in the first experimental run with contracting-expanding nozzles at $\alpha = 0^\circ$. The second finding of the analysis being made is rather small value of micron droplets mass fraction (independently obtained) and consequently there is a great value of submicron droplets mass fraction in investigated superheated water spray plumes in such nozzles at initial temperature $T_0=240^\circ$C and higher. This is rather important for experiment validation.

Such complex technique for determining disperse characteristics of superheated water optically dense fine sprays should be recognized necessary one for obtained data validation. It should be noted, that in equation (1) the influence of probe monochrome radiation multilateral scattering is not included. And the scattering is rather noticeable in optically dense superheated water spray plumes in contracting-expanding nozzles. Analyses of direct laser beam attenuation coefficient as a function of rotating angle relatively to longitudinal plume axis perpendicular convincingly proves the
influence of multilateral scattering (figure 1). Really, taking into account exponential character of attenuation function from the beam way length in the plume volume, attenuation coefficient (at rotating angle 45°) should increase in 1.42 power. In another words, its value should be 190 instead of measured value 120-130. So above values differ 1.5 times, and it means, with high probability, that detector receives besides direct attenuated laser ray the multilateral scattered radiation.

As it was mentioned above, diagnostic beam attenuation and scattering rays from small diagnostic volume is rather great and it may lower primary scattering indicatrix accuracy significantly. Consequently the accuracy of water spray plumes dispersion characteristics values decreases also. That is why the second (and the main) aim of modifying indicatrix measurement technique for optically dense superheated water fine spray plumes investigations was diagnostic ray attenuation decreasing, as well as decreasing the radiation scattered in the plume. For the necessary scattering indicatrix measurement accuracy the measurement method was created, using tiny tubes, which are inserted into plume. These tubes conduct as diagnostic laser ray, so as scattered at various angles radiation from diagnostic volume on laser ray way (figure 2).

Figure 2. Scheme of optical measurements with mini-tubes for optically dense superheated water spray plumes:

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

The distance between tube edges, which are passed over by spray plume, was chosen 10mm, at the same time the laser ray diameter was 2 mm and inlet tube diameter was 2.5mm. It means that laser way length in the plume and the length of scattered rays had been decreased not less than three times in comparison with plume diameter. The measured laser ray attenuation (with corresponding mini-tubes disposition) is shown in figure 1 (3). This measurement technique allows to decrease an order and more the attenuation coefficient for scattered radiation up to 2.6-3.0 due to decreasing at 3-5 times its way length in plume volume. The second peculiarity of the developed methodic is rather week dependence radiation attenuation coefficient upon scattering angle due to the constant...
diagnostic laser way length in plume volume (figure 2). During above measuring technique development a number of complicating factors were fixed and special remedies for their elimination were worked out. Internal mini-tube surfaces were blacken in order to minimize hum radiation, which enters into the tubes at various angles. The origin of hum radiation may be as multilateral laser ray scattering, so as a part of initial laser ray; especially it is important at the little rotating angles. Also undesirable factor is droplet penetration into inlet tube holes. To prevent this factor the hole edges of both tube types were cut by 45° angles. Practically total elimination of above hum radiation is possible if solid flexible light conductors would be installed in mini-tubes with lens, which would focus received radiation parallel flux at their face surface. Let’s note that in [4] the similar technique is mentioned for spray plumes. But as for our case, special protecting methods are necessary to prevent droplet deposition at the lens surface. For example it may be certain air injection into mini-tubes, although it can make certain disturbances in investigated two-phase flow.

New technique using mini-tubes also allows to determine dispersion characteristic variety across plume cross-section. First experiments devoted to such spray plume optical characteristics investigation were carried out in the plume zone, which was located at the half - radius distance from the plume axis, at the initial superheated water temperature T_i=200 and 240°C. Measurements have shown a certain increase (20–40%) micron droplets mass fraction in comparison with central plume zone. As for calculating estimations according Mi theory monochrome radiation scattering takes place mainly at submicron droplets. As for small angles it takes place mainly at larger (micron size) droplets. That is why the mass ratio measurement accuracy of above modes greatly depends upon wideness of the measuring angles range. So the measurements in the angle range α from 0 to 45° are also more advantageous in modified scattering indicatrix determining technique in comparison with well-known instrument Malvern Tech, where angle α does not exceed 15°.

### 3. Dimensionless treatment and possible technical applications.

Dimensionless treatment of calculating and experimental results for superheated liquids boiling up and spray was done with reference to critical radius bubble. The ratio of critical cluster formation work to chemical phase transition potential was considered. The derived parameter, which determines the transition to predominated nucleation role in superheated liquid atomization, allows to estimate such transition for other liquids (for fuels, for example).

Superheated water fine sprays may be applied in various combined cycles with water injection in compressor and gas turbine units (GTU) combustion chamber. Such wet compression, when droplet evaporation increases an order and more, is especially promising for low-power GTU as it may increase the outlet GTU power for 12-20% and more according to the ratio of compression growth. In superheated water spray full-scale experiments at GTU compressor many tiny narrowing nozzles were applied; it provided quick and uniform mixing of droplet spray and compressed air[6]. Fine water spray injection also allows to avoid compressor blade erosion in GTU long-duration work.

Similar liquid fuel injections are investigated for ignition intensification. It is actual for some types of internal combustion engines and direct air jet engines.

Super fine superheated water sprays through contracting-expanding nozzles are also promising for new fire-fighting technique. It was demonstrated by technique developers from Academy Of The State Fire Service Of The Emercom Of Russia [7] with high dispersion of such sprays validation in JIHT RAS.

### Conclusions

1. A new optical diagnostic technique for optically dense superheated water spray plume disperse characteristics is developed.
2. The analysis of results and their dimensionless treatment allow to specify conditions for obtaining superheated water fine spray plumes.
3. The possible applications of obtained highly disperse (containing a significant submicron mass fraction) superheated water sprays are described.

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