Experimental study on steam plume and temperature distribution for sonic steam jet

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Abstract. The sonic steam jet in subcooled water was investigated experimentally over a wide range of steam mass flux and water temperature conditions. Four different steam plume shapes were observed in present test conditions, and the condensation form was mainly controlled by the steam mass flux and water temperature. Moreover, the unstable jet was observed on the condition of low steam mass flux and high water temperature. The transition criterion of unstable-stable jet was also given. The temperature fields in the steam plume and in the surrounding water were measured. Axial temperature distributions represented the four typical steam plumes, and the fluctuation of axial temperature confirmed the existence of expansion and compression waves. Additionally, the radial temperature distributions were independent of water temperature for small radial distance at nozzle exit, and further the axial location was apart from the nozzle exit, longer the radial distance affected by the momentum diffusion.

1. INTRODUCTION
The phenomenon of steam-water direct contact condensation has been investigated extensively, and used in engineering applications such as direct contact feed water heater, steam jet driven injector and nuclear reactor safety system, etc. When the steam was injected into the quiescent subcooled water, several condensation modes including chugging, bubbling and jet appeared according to the thermal hydraulic conditions (Chan et al., 1982; Liang et al., 1994).

The condensation of subsonic or sonic steam jet submerged in subcooled water has been studied by many researchers. The investigation about the jet mainly included condensation regime map, pressure and temperature distributions, and condensation heat transfer coefficient. At the high steam mass flux, the oscillatory cone jet and ellipsoidal jet were described (Chan et al., 1982). The three-dimensional condensation regime of steam injected into stagnant water was investigated (Petrovic et al., 2007), the nozzle diameter was also considered besides the steam mass flux and water temperature. The penetration length of sonic steam jet horizontally in quiescent subcooled water was experimentally and theoretically investigated (Kerney et al., 1972; Weimer et al., 1973), and the correlations to calculate the dimensionless penetration length was also given. The turbulent condensing vapor jets submerged in subcooled liquids was theoretically investigated (Chen et al., 1982), and they gave a model of this process for numerical simulation assuming an idealized plume shape and a homogeneous two phase flow. Giovanni et al. (1984) experimentally measured the pressure and temperature in the surrounding zone inside a steam jet condensing in a subcooled water pool and gave an adopted model to describe the phenomena. Chun et al. (1996) experimentally studied the direct contact condensation of steam injected into the subcooled water, two shapes of steam plume (conical and ellipsoidal) were observed,
and found divergent plume existed at relatively small subcooling. Eden et al. (1998) investigated the centerline pressure and cavity shape of horizontal plane under-expanded vapor jets with low condensation potential, the pressure measurements showed the existence of periodic expansion/compression cells associated with under-expanded non-condensing gas jets. Kim et al. (2001) observed conical and ellipsoidal shapes of steam jet in the experiment, established the empirical correlations for dimensionless steam jet length, and the axial and radial temperature distributions in the steam jet were measured. The supersonic steam jet in subcooled water was studied (Wu et al., 2007), six different steam plume shapes were observed besides conical and elliptical shapes, and the correlations to predict expansion ratio, penetration length and average heat transfer coefficient were given.

Almost all the research on the steam jet was for subsonic and sonic, and two typical conical and elliptical shapes were reported. In present work, four different steam plume shapes were observed in sonic steam jet, and the unstable jet was discussed. The axial and radial temperature distributions in the steam plume and surrounding subcooled water were investigated at various test conditions. Moreover, the effects of steam mass flux and subcooled water temperature on condensation form and temperature distributions were discussed.

2. EXPERIMENTAL APPARATUS AND METHODS

The experimental system for investigating the steam jet is schematically presented in Fig. 1. The apparatus mainly consists of an electric steam generator, a surge tank, a water vessel of 3000mm×1000mm×1200mm and some valves. The electric steam generator with electric heaters of 330 kW supplies continuously the steam. The steam was injected into the subcooled water through a sonic nozzle which was fixed on the wall of water vessel by a flange. In present work, the upper part of the water vessel is open to the ambient and two observation windows with the same size were designed for observation and taking pictures. The test conditions are shown in Table 1.

The steam flow rate was measured by a vortex type steam flowmeter (accuracy 0.5%FS). The temperature in the jet exit region was measured by a mobile test block which was equipped with 21 K-type thermocouples (diameter 1.0mm, accuracy 0.5%FS), as shown in Fig. 2. Actually, the test block was cuspidate and behind the thermocouple, which would not affect the upstream temperature fields. The water temperature in water vessel was measured by the same thermocouple. The inlet pressure in the nozzle was measured by high-temperature pressure transducer (MSI, accuracy 0.1%FS). A high-speed camera was used to take pictures of steam plume. All signals were processed by the data acquisition system consisting of PC and A/D converter.

![Fig. 1 Schematic diagram of experimental system](image-url)
Table 1. Test conditions in experiment

| Parameters                                      | Values      |
|-------------------------------------------------|-------------|
| Steam mass flux at nozzle exit \( G_s \), kg/m²s | 298-865     |
| Water temperature \( T_w \), K                  | 293-343     |
| Ambient pressure \( p_a \), MPa                | 0.102       |
| Exit diameter of nozzle \( d_e \), mm           | 6.0         |

![21 K-type thermocouples (diameter 1.0 mm)](image)

Fig. 2 Schematic diagram temperature test block

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Steam Plume Shape
In previous investigation on steam jet in subcooled water, the steam plume shape was observed mainly by high-speed camera, and the same method was used in present study. Almost only two typical steam plume shapes were reported for sonic jet by several researchers. The two steam plume shapes including conical and elliptical shapes, was also observed in present experiment, as shown in Fig. 3 (Shapes A and B). Additionally, another two steam plume shapes (Shapes C and D) were observed in sonic steam jet. The two shapes were reported in supersonic steam jet (Wu et al., 2007). Here, the four steam plumes (Shapes A, B, C and D in Fig. 3), were called constriction shape, expansion-constriction shape, double expansion-constriction shape, and double expansion-emanative shape, respectively.

According to the observation, the steam plume shape was influenced by steam mass flux and water temperature, actually. For low steam mass flux and low water temperature, the steam plume constricted directly. For the high steam mass flux and low water temperature, the steam plume expanded at the nozzle exit, then constricted due to the high condensation capability. With the increase of the water temperature, the steam plume expanded again, and the second expansion tended to emanative for the high water temperature (low condensation capability).
Additionally, the jet tended to be unstable with the increase of the water temperature for low steam mass flux (298 kg/m²s), as shown in Fig. 4. It is obvious that the transition of unstable-stable jet is between 318K and 323K. When the water temperature was below 318K, the steam plume was obvious. But as the water temperature was above 323K, the steam plume was emanative and unstable.

The criterion for bubbling-jetting transition was given (Liang et al. 1994). A criterion for the unstable-stable jet transition was developed based on the above method (Liang et al. 1994). The energy balance was used as follows:

\[
\frac{\rho v_i A_j h_{fg}}{h_j A \Delta T_{sub}} \geq 1.0
\]

where \( h_{fg} \) is latent heat of vaporization, \( \Delta T_{sub} \) is water subcooling. The area of the interface could be obtained by the photo, and the heat transfer coefficient could be expressed by interfacial transport due to turbulence intensity (Kim et al., 2004).

\[
h_i = St \left( \frac{1}{2n} \right)^{1/3} \left( \frac{\rho_f}{\rho_g} \right)^{2/3} c_r G_e
\]

where \( n \) is the ratio of the thermal boundary layer thickness to the eddy size, and it is recognized that the eddy size is about 1/5 of the thermal boundary layer thickness. \( G_e \) is the steam mass flux of nozzle exit. The Stanton number is the function of Nusselt number, Reynolds number and Prandtl number.
Here, the Jacob number, which was adopted to describe the ratio of the specific energy absorption capabilities of the liquid and the energy density of the steam, was defined as:

\[ Ja = \frac{\rho_f c_p \Delta T_{sat}}{\rho_v h_f} \]  

(3)

According to the experimental data, the final form of the criterion for unstable-stable jet transition is:

\[ 0.35 \left( \frac{\rho_f}{\rho_v} \right)^{1/3} Re_f^{1/4} Pr^2 Ja^{1.5} \geq 1.0 \]  

(4)

Fig. 5 gives the calculated transition criterion of unstable-stable jet for various test conditions in present study. It was actual that the stability was directly proportional to the value of \(0.35(\rho_f / \rho_v)^{1/3} Re_f^{1/4} Pr^2 Ja^{1.5}\). Although the steam mass flux was separated in other parameters, here, it was still used as the various test conditions, in order to compare the calculation with the experimental observation. As shown in Fig. 5, with the decrease of the water temperature and increase of the steam mass flux, the jet became more stable. When the water temperature was high and steam mass flux was small, the jet was unstable, which was in accordance with the observation of the experimental results, as shown in Figs. 3 and 4.

3.2 Axial Temperature Distributions

The temperature distributions along the steam jet axis and in the surrounding water were measured for various test conditions. Fig. 6 shows the axial temperature distributions for two different steam mass flux and water temperature in the range of 293K to 343K. For low mass flux, the axial temperature distributions decreased to the ambient water temperature directly, which represented the trend of the constriction steam plume shape. For high mass flux, near the nozzle exit inside the steam jet, the axial temperature variation was independent of the water temperature. When the water temperature was low, the axial temperature decreased first then increased, after a peak, the temperature decreased again to the ambient water temperature. Such a temperature distribution represented the expansion-constriction steam plume shape. For high water temperature, after the first peak, the axial temperature tended to
increase again, then decreased to the ambient water temperature due to condensation, which represented the double expansion-constriction steam plume shape. When the water temperature was above 343K, the second peak of axial temperature became smooth, which represented the double expansion-emanative steam plume shape.

In fact, the axial temperature distributions were affected by the expansion and compression waves for under-expanded jet (Kim et al., 2001; Wu et al., 2007). When the nozzle exit pressure is higher than surrounding water pressure, the expansion wave may occur at nozzle exit, which leaded to supersonic flow and steam flowing outward. When the supersonic flow was compressed by the ambient water, the compression wave occurred. The expansion and compression waves could reflect periodically for ideal condition. However, the reflection only occurred one or two times due to the condensation and viscosity. When the steam flow was expanded, the axial temperature would decrease, whereas the steam flow was compressed, the axial temperature would increase. Accordingly, the axial temperature distributions reflected the steam flowing characteristics. Fig. 7 shows the corresponding relation of axial temperature distributions and steam plume shapes. The peak and nadir of axial temperature were all in accord with the position of compression and expansion of steam plume, approximately.

![Fig. 6 Axial temperature distributions at various test conditions](image1)

![Fig. 7 Relations of axial temperature distributions and steam plumes](image2)
3.3 Radial Temperature Distributions

The temperature distributions in the radial direction have been obtained in the various test conditions. Radial temperature distributions at four different axial locations, for two steam mass flux and different water temperatures, are shown in Figs. 8 and 9. It can be seen that the radial temperatures were independent of water temperature for radial distance at axial location of 0, but for the far axial location, the radial temperatures were influenced by the water temperature significantly. Moreover, the influencing region was expansible with increasing the axial distance.

![Radial Temperature Distributions](image)

Fig. 8  Radial temperature distributions ($G_e=298 \text{ kg/m}^2\text{s}$)

In the case of the constriction steam plume shape, as shown in Fig. 8, the radial temperatures indicated the maximum values at the axial direction and then decrease toward the outer radial direction. But for the other cases of steam plume shapes, as shown in Fig. 9, the radial temperatures tended to increase first and then decreased toward the outer radial direction in this region, and this radial temperature characteristic was also reported for the case of elliptical steam plume shape (Kim et al., 2001). Based on the experimental data of expansion-constriction, double expansion-constriction and double expansion-emanative steam jet, a conclusion was drawn that the variation of the radial temperature was due to the expansion and compression waves of the under-expanded jet.
4. CONCLUSIONS

In present work, experimental study on sonic steam jet in subcooled water for wide ranges of steam mass flux and water temperature was carried out. The new characteristics of steam plume and temperature fields were obtained. The main results could be summarized as follows:

(1) Four different steam plume shapes were observed for various test conditions for sonic nozzle. Besides the constriction and expansion-constriction shape reported by previous investigation, the double expansion-constriction and double expansion-emanative shapes were also observed in sonic steam jet. And the condensation form was mainly controlled by the steam mass flux and water temperature. Moreover, the transition criterion of unstable-stable jet was given based on the present experimental data.

(2) The temperature distributions in the steam plume and in the surrounding water were measured for different test conditions. The influencing area was affected by steam mass flux and water temperature. The temperature fluctuation at axial direction and radial direction were evident due to expansion and compression wave, and the axial temperature distributions also represented the four typical steam plumes. Additionally, the radial temperatures were independent of water temperature for small radial distance at nozzle exit, and further the axial location was apart form the nozzle exit, longer the radial distance affected by the momentum diffusion.

ACKNOWLEDGEMENTS

This work was supported by National Natural Science Foundation of China (No. 50676078) and
National High-Tech Research and Development Program of China (863 Program) (No. 2006AA05Z230).

**NOMENCLATURE**

| Symbol | Description                                      | Unit          |
|--------|--------------------------------------------------|---------------|
| $A$    | heat transfer area                               | $m^2$         |
| $c_p$  | water specific heat                              | $J/(kgK)$     |
| $d$    | diameter of nozzle                               | $m$           |
| $G$    | steam mass flux                                  | $kg/(m^2s)$   |
| $h$    | heat transfer coefficient                        | $W/(m^2K)$    |
| $h_{fg}$ | latent heat of vaporization                    | $J/(kg)$      |
| $n$    | ratio of $\delta$ to $\lambda$                 |               |
| $T$    | temperature                                      | $K$           |
| $p$    | pressure                                         | $MPa$         |
| $Ja$   | Jacob number                                     |               |
| $Re_f'$ | steam-liquid Reynolds number, $\nu_s d_e / \nu_f$ |               |
| $Pr$   | Prandtl number                                   |               |
| $St$   | Stanton number                                   |               |
| $v$    | velocity                                         | $m/s$         |

**Greek Letters**

| Symbol | Description                                      | Unit          |
|--------|--------------------------------------------------|---------------|
| $\rho$ | density                                          | $kg/m^3$      |
| $\delta$ | thermal boundary layer thickness                | $m$           |
| $\lambda$ | eddy size                                    | $m$           |
| $\Delta T_{sub}$ | water subcooling                  | $K$           |

**Subscripts**

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| $a$    | ambient                                          |
| $axi$  | axial direction                                  |
| $e$    | nozzle exit                                      |
| $i$    | interface                                        |
| $f$    | liquid                                           |
| $rad$  | radial direction                                 |
| $s$    | steam                                            |

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