

Experimental study on the submerged steam jet through side hole nozzle

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Abstract: In this paper, the steam shape parameters and the condensation oscillation characteristics of the direct contact condensation of submerged steam jet into subcooled water were investigated through a side hole nozzle. Meanwhile, the dimensionless jet length and the expansion ratio versus pool water temperature and steam mass flux were obtained by measuring the photographs taken by a high speed camera. Both of them increased gradually with rise of pool water temperature and steam mass flux. A comparison of the shape parameters of three different style nozzles was also achieved. And a correlation of the dimensionless jet length was obtained, the predicted data agreed well with the experimental data, while the discrepancy was within $\pm 5\%$. For the pressure oscillation versus steam mass flux, the peaks and the root mean square value of pressure oscillation were almost consistent in the range of $150\text{--}400\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, while both of them increase in the range of $400\text{--}800\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The positive peak and negative peak were completely symmetrical.

1. Introduction

The direct contact condensation (DCC) has distinct advantages, such as high heat transfer coefficient, without heat transfer surface, and so on. It has been widely used in chemical industry, nuclear power, cryogenic refrigeration, utilization of waste heat, and other fields. The condensation of submerged steam jet is the most important issue of DCC. Many researchers were attracted to investigate this.

Because of the complication of mass and heat transfer and the widely application, many researchers have done large work about this from 1970s. Cho et al.[1] gave a relatively complete condensation regime map in a wide range of steam mass flux and subcool water temperature based on visual observation and acoustics. The condensation pattern was divided into six parts including chugging, transient region, condensation oscillation, bubbling condensation oscillation, stable

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condensation and interfacial oscillation condensation. Petrovic et al.[2] developed a three-dimensional condensation regime map of steam jet in water, which includes the effect of injector diameter. Wu et al.[3] suggested a three-dimensional condensation regime map of steam in water for supersonic and subsonic conditions, especially including the pressure ratio. Six shapes of the steam plume were observed, which were expansion-contraction, double expansion contraction, double expansion divergent, contraction, contraction expansion contraction and contraction expansion divergent. Kerney et al.[4] and Chun et al.[5] investigated the size of the steam plume and got the correlation of the dimensionless jet length in the similar pattern respectively. Kim et al.[6] found the relationship between the condensation heat transfer coefficient and the diameter of the nozzle outlet and the steam mass flow flux, and suggested three different models to calculate the condensation heat transfer coefficient. Cho et al.[7] corresponded the pressure oscillation characteristics of different flow patterns to the shape of the steam plume and achieved the effect of the steam mass flow flux on the pressure oscillation pulse. Qiu et al.[8] studied the pressure oscillation of the sonic nozzle including the pressure oscillation amplitude and the main frequency.

The side hole nozzle is a typical simplified model of the multiple holes nozzle. It is significant to study the single hole nozzle to state the mechanism of the multiple holes nozzle. Above all there were few reports to investigate the condensation of submerged steam jet for a side hole nozzle. In this paper, the steam shape and the condensation oscillation characteristics of the DCC of submerged steam jet into subcooled water were investigated for a side hole nozzle.

2. Experimental apparatus and measurement method

The experimental apparatus were schematically shown in figure 1. The experiment apparatus mainly consist of a steam boiler which can supply the saturated steam 0.3t/h continuously, a circular tank with diameter of 2000mm and height of 1500mm. Steam was generated from the boiler and flowed through the adiabatic pipes after being stabilized. Finally it jetted into the water tank through a nozzle and condensed in pool. The steam mass flux was controlled by an electric valve and measured by a vortex type steam flowmeter with accuracy of 0.5%FS. The steam pressure and temperature in the nozzle inlet was measured with a pressure transducer (0.1%FS) and a T-type thermocouple (0.1%FS), respectively. The temperature of pool water was measured by six uniform distributed T-type thermocouples. One fixed pressure sensor was installed on $X=80\text{ mm}$ and $R=50\text{ mm}$. The pressure sensor accuracy was 0.25% FS with the range of -100kPa–100kPa.

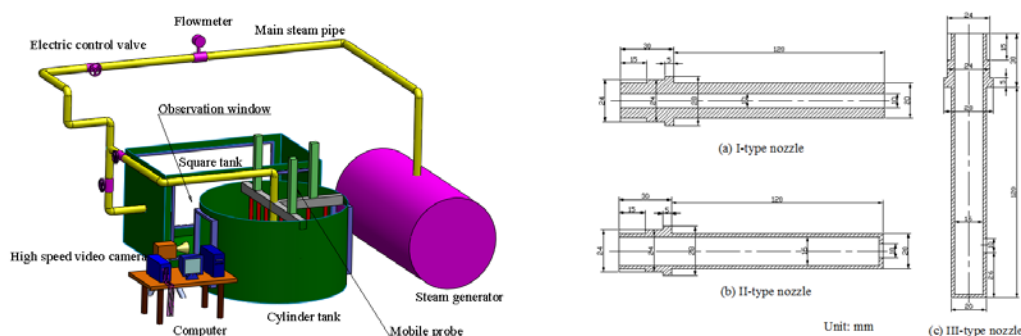


Figure 1. Schematic diagram of experimental system and the nozzle

In order to investigate whether the difference between the side hole nozzle and other kinds of nozzle exists, two different types of nozzle were used in this study as shown in Fig.1, and the side hole nozzle was the III-type nozzle. The test of these two kinds of nozzles were taken in the square. They are also widely used in industrial fields.

To obtain steam plume photographs with high quality, a high speed camera coupled with submerged lamps were applied for taking the photograph of plume. And the macroscopic parameters of steam shape (expansion ratio and dimensionless penetration length) versus pool water temperature and steam mass flux were obtained by measuring the photographs. The photograph of steam condensation was obtained with a high speed of 5000 fps. And the test conditions was chosen as table 1. The pressure sensor was arranged at the location in the same plane with the hole.

Table 1 Test conditions

parameters	value
Diameter of hole d_e (mm)	10
Pressure sensor radial distance R (mm)	50
Pressure sensor axial distance X (mm)	80
Pool water temperature t_w ($^{\circ}\text{C}$)	15-55
Range of steam mass flux G_e ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	150-800

3. Experimental result and discussions

In this article, the jet length was defined as the length of steam plume core which did not include the wake region. The corresponding dimensionless jet length L was the ratio of the jet length l and the hole width D . The jet width was defined as the width of steam plume core. The plume tail which was the steam clumps separated from the steam plume core was not taken into account. The corresponding expansion ratio R_{ex} was the ratio of the jet width d and the hole width D . The two phase mixture region was not measured as the steam jet length either, as shown in figure 2. It was a complete steam plume of the side hole nozzle, and the others had the same shape and measurement standard as this. The length and the width of the jet were obtained by measuring 10 continuous photos and taking an average. During measuring photos, a commercial software was used to obtain the coordinates of the four edge points of the steam plume and the two edge points of the hole. Then a mathematical operation was taken to get the length and the width of the jet.

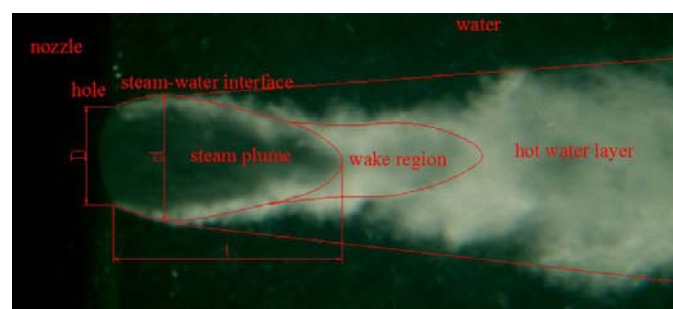


Figure 2 Schematic diagram of photo analysis

3.1 The macroscopic parameters of steam shape

The experiment results showed that the shape of steam jet plume was unstable when the steam flux was under $300 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and a relative stable steam plume was observed and measured at the steam flux larger than $400 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. According to Cho et al. [1], the change value from condensation oscillation to stable condensation in condensation regime was about $300\text{--}400 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. So, in the present paper, the stable shape size of the steam plume was measured when the steam mass flux was larger than $400 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$. Firstly, the dimensionless jet length and the expansion ratio of the side hole nozzle versus pool water temperature and steam mass flux were given. And then a comparison of three different nozzle was suggested.

3.1.1 Dimensionless steam jet length

The corresponding dimensionless jet length was in the range of 1.82 - 4.61 when the pool water temperature ranged from 10 to 55°C and the steam mass flux ranged from $400\text{--}800 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ as figure 3.

The jet lengths increased gradually with rise of pool water temperature and steam mass flux. There was no noticeable rise under the test condition. This was because the water test condition was in stable condensation region, and no divergent plume occurred.

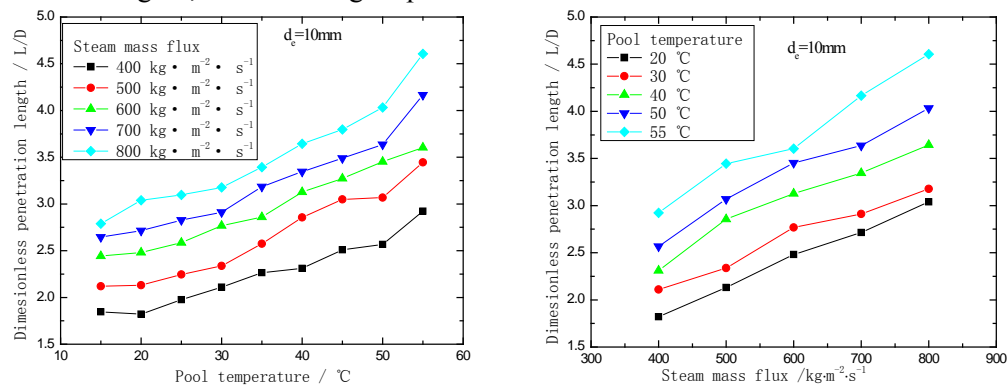


Figure 3 Dimensionless steam jet length versus pool water temperature and steam mass flux

Kerney et al.[4]proposed a theoretical model with the conversation of mass and energy to predict the steam jet length. According to the theoretical model, the jet length was closely related with the steam mass flux (G_0), dimensionless driving potential for the condensation process (B). Then a correlation of dimensionless jet length was obtained and expressed as $L/D=f(B, G_0/G_m)$. Later, the correlation form, treated as the basic form, was widely used by the later researchers.

Based on the experimental data and the previous work[4], an independent correlation was obtained as follow:

$$\frac{l}{D} = 0.374 B^{-0.739} (G_0 / G_m)^{0.628}$$

$$B = c_p (T_s - T_\infty) / h_{fg}, \quad G_m = 275 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$$

Here, G_0 is steam mass flux, $\text{kg}/\text{m}^2 \cdot \text{s}$, B is condensation driving potential, c_p is specific heat of pool, T_s is saturated temperature T_∞ is pool conditions, h_{fg} is latent heat at pool pressure.

And the predicted data and the experimental data agreed well and the discrepancy was within $\pm 5\%$

as figure 4.

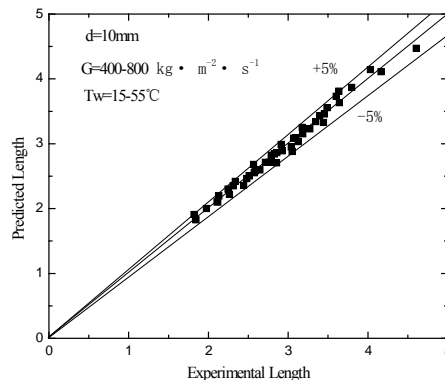


Figure 4 Comparison of predicted and experimental dimensionless jet length

3.1.2 Expansion ratio

The corresponding expansion ratio was in the range of 1.09 - 1.68 when the pool water temperature ranged from 10 to 55°C and the steam mass flux ranged from 500-800 kg·m⁻²·s⁻¹. The expansion ratio increased gradually with rise of pool water temperature and steam mass flux as figure 5.

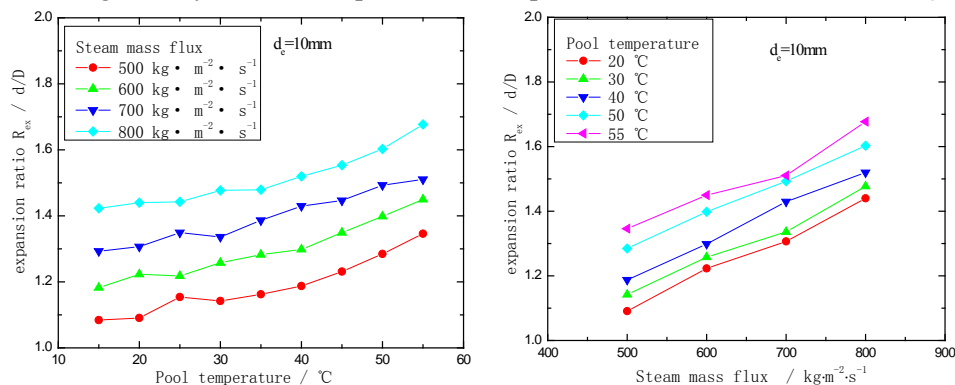


Figure 5 Expansion ratio versus pool water temperature and steam mass flux

It is easy to find that the expansion ratio and the jet lengths increased gradually with rise of pool water temperature and steam mass flux. It is because the capacity of heat transfer is closely related to the pool temperature and the flow flux. When the pool water temperature and steam mass flux increase, the capacity of heat transfer of the interface between steam and cool water decreases. So the larger heat transfer area is needed. Obviously it is efficient to prolong the length of steam plume and widen the width of steam plume.

3.1.3 The comparison of the expansion ratio and the jet lengths of the different style nozzle

The comparison of the jet lengths and expansion ratio of the three different style nozzles was shown as figure 6. In the figure, III-type nozzle was also the side hole nozzle. The steam mass flux was 600 kg·m⁻²·s⁻¹.

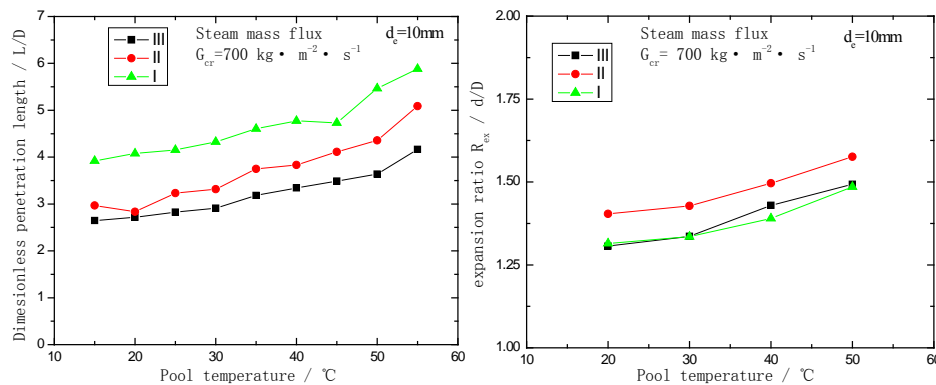


Figure 6 Comparison of the expansion ratio and the jet lengths of the three different style nozzle

From the Fig.6, the expansion ratio and the jet lengths of the side hole nozzle was quite different with the other two nozzles. The jet lengths of the side hole nozzle was smallest, and the expansion ratio was similar with that of I-type nozzle but smaller than that of II-type nozzle. The smaller jet length and expansion ratio are important parameter for the design of the size of the heat exchanger and have effect on the degree of the pressure oscillation of the whole equipment. So it was meaningful to investigate the pressure oscillation of the side hole nozzle.

3.2 Pressure oscillation

The results show that the condensation of side hole nozzle is really different with the other type nozzle. Pressure oscillation is another important side of the application of the direct contact condensation of submerged steam jet. It will affect the safety and the stability of the system. So it is necessary to study the pressure oscillation of the side hole nozzle.

3.2.1 Root mean square value of pressure oscillation

The pressure oscillation was got through arranging pressure transducer in the water tank. The experimental results show that the root mean square value of pressure oscillation increased gradually with rise of pool water temperature. And with the steam mass flux increasing, the root mean square value of pressure oscillation is almost consistent in the range of 150-400 $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$, and increases while in the range of 400-800 $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ as figure 7. This is because of the existence of the condensation transition region.

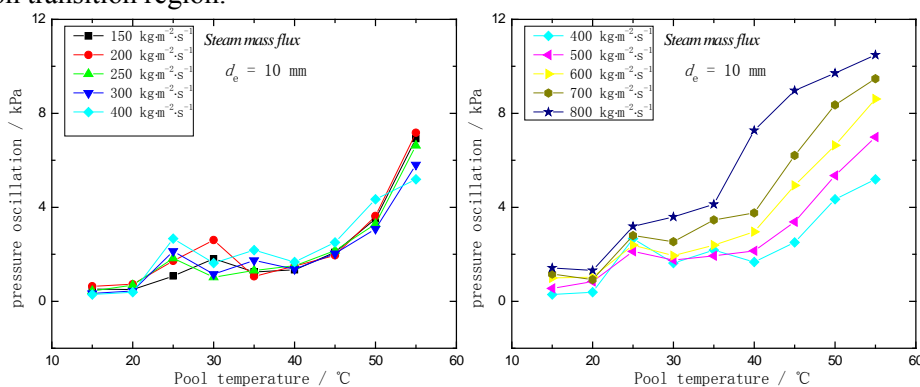


Figure 7 Root mean square value versus pool water temperature and steam mass flux

3.2.2 Positive peak and negative peak of pressure oscillation

The pressure oscillation is also got through arranging pressure transducer in the water tank. The experimental results show that the peaks of pressure oscillation increase gradually with rise of pool water temperature. And with the steam mass flux increasing, the peaks of pressure oscillation are almost consistent in the range of $150\text{--}400\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and increase while in the range of $400\text{--}800\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. This is because of the existence of the condensation transition region. And the Positive peak and negative peak are completely symmetrical as figure 8.

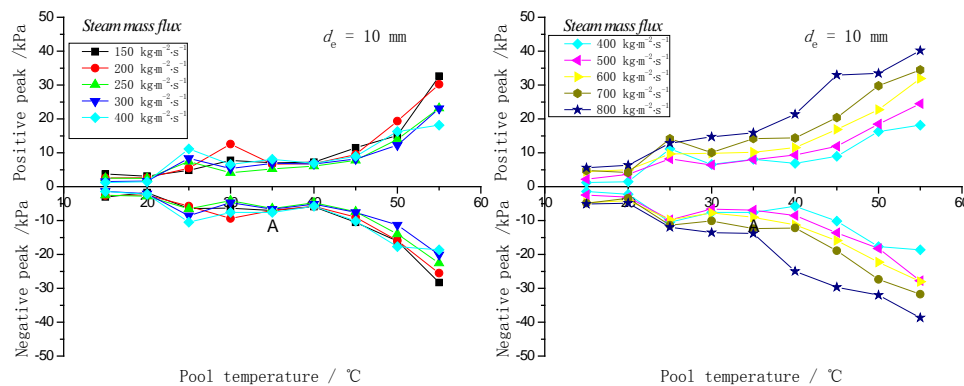


Figure 8 Positive peak and negative peak of the pressure oscillation versus pool water temperature

It is easy to find that with the steam mass flux increasing, the peaks and the root mean square value of pressure oscillation are almost consistent in the range of $150\text{--}400\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, while both of them increase in the range of $400\text{--}800\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. From the condensation regime map, there is a transient region between condensation oscillation region and stable condensation region. And in the transient region, the range of the steam mass flux was $200\text{--}400\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. With the steam mass flux increasing, the pressure oscillation should increase because that the more steam needs to be condensated, but it will also be close to the stable condensation region. So in these two sides, the pressure oscillation are almost consistent in this range of the steam mass.

The law of pressure oscillation suggested in this paper was quite useful to choose the relatively safe pool water temperature and steam mass flux to ensure the safety of the facility. And the conclusion of the study is very meaningful to the investigate of the multiple holes nozzle which is usually used in many industry fields.

4. Conclusions

In this paper, the steam condensation in quiescent subcooled water of the side hole nozzle was investigated experimentally under different steam mass fluxes and water temperatures. The steam shape parameters and the condensation oscillation characteristics were surveyed and studied. The results can be mainly summarized as follows:

- (1) The dimensionless jet length and the expansion ratio increased gradually with rise of pool water temperature and steam mass flux and were in different size with other two kinds of nozzles.
- (2) A correlation of the dimensionless jet length was obtained, and the predicted data and the experimental data agreed well and the discrepancy was within $\pm 5\%$.
- (3) In the range of $150\text{--}400\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ the peaks and the root mean square value of pressure oscillation are almost consistent, while in the range of $400\text{--}800\text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ both of them increase, and the positive peak and negative peak were completely symmetrical.

5. Reference

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