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Research on the steam jet length with different nozzle structures

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ABSTRACT

The effect of nozzle structure on the steam jet lengths of submerged condensation in quiescent water is investigated theoretically and experimentally. Two typical nozzles are analyzed and tested. Theoretical analysis shows that nozzle structure has a great influence on the steam jet length but was paid little attention before. Then a theoretical model for steam jet length with different nozzle structures is proposed based on the expansion and compression wave theory. Theoretical model indicates that steam jet length is greatly affected by nozzle structure. The steam jet length of straight pipe nozzle is longer than that of orifice nozzle under the same pool water temperature and steam mass flux, and the steam jet length is inverse proportion to the maximum expansion ratio, approximately. Then the theoretical model is verified by the experimental results. Finally, a universal semi-empirical correlation considering the nozzle structure is proposed. The prediction length corresponds to the experimental data very well and the discrepancy is within ±25% for different nozzle structures for the steam mass flux 400–800 $kg{\cdot}m^{-2}{\cdot}s^{-1}$ and water temperature 10–70 °C.

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1. Introduction

The phenomenon of direct contact condensation (DCC) occurs in nature and industry widely. The steam jet condensation is one typical process with DCC phenomenon, which is accompanied with exchange of mass, momentum and energy across the two-phase interface, and results in high efficiency of heat transfer. For this characteristic, the steam jet condensation has been applied for a series of industry operations, such as the In-containment Refueling Water Storage Tank (IRWST) and the Pressure Suppression Pool (PSP) in nuclear reactor safety system. The high heat transfer efficiency between the jet steam and subcooled water has great advantage in condensing the steam and controlling the reactor pressure. So the research on the steam jet condensation is significant to the industrial application.

When steam is discharged into subcooled water through a nozzle or a sparger, the direct contact condensation occurs between steam jet plume and subcooled water. The research on steam jet condensation mainly concludes the condensation regime [1–5], the steam jet pattern like the steam jet length [2,6–9], the coefficient of heat transfer [2,10–14] and the steam jet condensation load [15–18].

For the steam jet condensation, the steam jet length is a very important parameter which is closely related with steam plume shape [2,8,10], heat transfer [2,5,8,10,19] and condensation oscillation [20–22]. Firstly, the capacity of heat transfer is reflected from steam jet length directly. Generally, combining the steam jet length with the distribution of steam axial temperature [10,19,23,24], the coefficient of heat transfer can be obtained approximately. Usually, a negative correlation between steam jet length and heat transfer coefficient is shown in the previous work [10,12]. Secondly, according to Hong et al. [20], the condensation oscillation is generated along with the variation of steam jet length, and frequency of condensation oscillation is affected by the steam jet length greatly. So, accurate value of steam jet length is important to predict condensation oscillation frequency which has great significance to eliminate resonance. What's more, according to Shah et al. [25], the performance of steam jet pump is affected by the length of mixing section. The design of mixing section length closely relates to the steam jet length. Thus, the research on the steam jet length is very important for the industry.

Due to its importance, the dimensionless steam jet length (the ratio of the steam jet length to the hole/nozzle inner diameter) has been investigated in the past decades. Kerney et al. [6] proposed a theoretical model to predict the steam jet length based on the conversation of mass and energy. The steam plume was

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Nomenclature

L	steam jet length, m	G_0	steam mass flux, kg·m^{-2}·s^{-1}
D	diameter of nozzle outlet, m	G_m	mean steam mass flux, kg·m^{-2}·s^{-1}
R_{ex}	the maximum expansion diameter, m	B	condensation driving potential, Cp $(T_s - T_\infty)/h_{fg}$
r	radius of nozzle outlet, m	S_m	mean transport modulus, h/CpG_0
m	steam mass flux, kg·s^{-1}	Cp	liquid specific heat, J·kg^{-1}·K^{-1}
R	steam condensation rate, kg·m^{-2}·s^{-1}	T_s	saturation temperature, K
h	heat transfer coefficient, J·m^{-2}·K^{-1}·s^{-1}	T_∞	pool water temperature, K
h_{fg}	heat of condensation, J·kg^{-1}	V	velocity of steam flow, m·s^{-1}

assumed to be axial symmetry and the steam-water interface was in an equilibrium station. According to their theoretical model, the jet length is closely related with the steam mass flux (G_0), dimensionless driving potential for the condensation process (B) and transport modulus (S_m). Then a correlation of dimensionless jet length was obtained and expressed as $L/D = 0.5(BS_m)^{-1}\sqrt{G_0/G_m}$. But in this correlation, the transport modulus (S_m) was affected by many factors and it was hard to obtain directly. Research result showed that it was mainly affected by steam mass flux and condensation potential. So the basic form, $L/D = f(B, G_0/G_m)$, was applied and adopted widely by the later researchers, as shown in Table 1. Weimer et al. [7] also developed a model that treated the condensation jet as a two-phase, axial symmetry free jet with vapor bubbles and liquid dispersed throughout the jet. Then a semi-empirical correlation of jet length was obtained with the density ratio of water to saturated steam, the condensation driving potential and steam mass flux.

Comparing the correlations in Table 1, it indicates that the equation proposed by Kerney et al. [6] is applied widely. All the correlations conducted that the dimensionless steam plume length was reasonably well for their individual flow conditions. But the differences among them were obvious. The differences may mainly attribute to the nozzle structural differences in each study. For example, the straight-pipe nozzles were researched by Kerney et al. [6], while sonic and supersonic nozzles were adopted in the study of Wu et al. [8,12].

According to the previous investigations (Kerney et al. [6], Weimer et al. [7], Chun et al. [2], Kim et al. [10]), correlations predicted that the steam plume length was appropriate well for their individual nozzle structures. But very few papers have considered the effect of nozzle structure on the steam jet length. According to literature (Deckker and Chang [26], Liu et al. [27]), the flow parameters, such as the discharge coefficient, were affected by the structural parameter greatly. The discharge coefficient closely relates to the flow uniformity which affects the steam jet length greatly. So, the structural parameter also affects the steam jet length greatly. The structural parameter mainly includes the ratio of the orifice length to its diameter and the area ratio of orifice to nozzle inlet. According to Wu et al. [8,12], there was distinct difference for the steam jet length between sonic nozzle and supersonic nozzle. Also, the difference of steam jet length existed among the supersonic nozzles which were different in design pressure ratio. So, the structure parameter (design pressure ratio) was proposed to correct the basic steam jet length form by Wu et al. [8,12]. The difference in steam jet length with different nozzle structures indicated that the nozzle structure was another important influence factor, which was lack of attention by now. Thus, in this study, the effect of nozzle structure on the steam jet length in quiescent water was investigated theoretically by comparing two typical nozzles. Then, an experiment was conducted to further illustrate the influence of the structure on the steam jet length.

2. The analysis of steam flow with different nozzles

According to the above analysis, the nozzle structure has influence on the steam jet length. As shown in Table 1, the straight-pipe nozzles were applied by Kerney et al. [6] and Kim et al. [10], sonic nozzles were applied by Wu et al. [8,12]. However, the flow in sonic nozzle was very similar to that in straight-pipe and flow was well developed for both these two type nozzles when the steam leaves the nozzle. Thus, as a representative, the straight-pipe nozzle was applied in this study. Also, as a comparison, the nozzle reported by Song and Kim [28] was selected and named orifice nozzle, as shown in Fig. 1. Those two kinds of typical nozzle are distinctly different in structure. For the orifice nozzle, the length of orifice is considered as sharp edge. The ellipsoidal plume and the ideal gas were assumed, then according to Miller [29], the sonic line for those two kinds of nozzle was different. In Fig. 1, the line of AB and AA′BB′ (the red[1] line in Fig. 1) was the sonic lines of straight-pipe and orifice nozzles, respectively.

Based on the theory of expansion and compression wave [30], the ellipsoidal ideal gas plume can be mainly contribution to the expansion wave which has the role of transferring the ideal gas flow direction when the shape of wall or free surface changed. The flow deflection angle can be calculated with the Prandtl–Meyer equation:

$$\nu(M) = \sqrt{\frac{k+1}{k-1}}tg^{-1}\sqrt{\frac{k-1}{k+1}(M^2-1)} - tg^{-1}\sqrt{M^2-1} \tag{1}$$

Then the deflection angle can be expressed as Eq. (2) when ideal gas flows across the first expansion wave:

$$\alpha = \nu(M_{AE}) - \nu(1) \tag{2}$$

According to the theory of expansion and compression wave, ideal gas flow direction will keep parallel after flow across the second expansion wave, so the second deflection angle can be calculated as

$$\alpha_1 = \nu(M_{EC}) - \nu(M_{AE}) \tag{3}$$

where M_{AE} is the Mach number of Mach wave AE and M_{EC} is the Mach number of Mach wave EC.

With obtaining the Mach number of first Mach wave, the deflection angle and Mach number of second Mach wave is calculated easily. Based on the deflection angle and the Mach angle, μ_1 and μ_2, the maximum expansion ratio of ideal gas plume can be obtained based on the geometrical model.

$$\varepsilon = \frac{R_{ex}}{D} = \frac{\sin(\alpha+\mu_1)\sin(\alpha+\mu_2)}{\sin\mu_1 \sin\mu_2} \tag{4}$$

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.

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