Experimental Study on Steam Cavity Characteristics for Swirled Flow Nozzle Exhausting into Quiescent Water †

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Abstract: The steam–water direct contact condensation (DCC) process is commonly observed in various industries due to its fast heat and mass exchange characteristics. This study investigates steam plume characteristics by experimentally condensing the steam jet issuing from a swirled flow spray nozzle into stagnant subcooled water. On the basis of high-speed imaging, the effects of subcooled water temperatures on the cavity shape, its length, and maximum expansion ratio were explored. The existence of three distinct cavity shapes (ellipsoidal, double expansion–contraction and divergent) were identified. The dimensionless steam cavity penetration length and maximum expansion ratio were found to be in the range of 6.28–11.5 and 1.71–3.06, respectively. The results indicate that with the rise in water temperature, plume length and maximum expansion ratio increase.

Keywords: multiphase flow; plume cavity; swirl flow; direct contact condensation; fluid dynamics

1. Introduction

The phenomenon of steam-water DCC of steam has become of paramount interest in the industrial sector due to the high exchange rate of heat and mass at the interface [1]. Its typical applications in industry includes direct mixing heaters, thermal degasification systems, steam injectors, and nuclear reactor safety systems [2–4].

In the published literature, scholars mainly give stress to the study of steam jet characteristics including steam cavity shapes, cavity length, temperature profiles, heat exchange rate, and condensation oscillations [1,5,6]. Recently, researchers have considered the steam cavity shape as a key parameter during submerged jet condensing with water. It is also strongly linked with the above said research areas [4–8]. Additionally, it provides guidelines in the design and functionality of the DCC based systems [4,7]. Hence, the topic of the steam jet characteristics have become attractive in the field of DCC.

Previously published literature indicates that steam cavity characteristics depend upon the operating and geometric conditions [6–8]. Kerney’s study [8] was the first a predicting model for steam cavity axial size was formulated. Weimer et al. [9] modified Kerney’s model by including phasic densities effect.

Shah et al. [7] pointed out that the steam cavity shape is dependent on nozzle geometric parameters. Zhang and his group [10] studied the steam jet features for double hole nozzle under stable flow conditions. Quddus et al. [11,12] studied the steam jet features from the beveled steam spray nozzles. They also developed a predicting model for steam jet length by including the effects of nozzle exit bevel angle. In their study, they explored the physics of the jet shapes for various beveled nozzles.
The purpose of the present work is to investigate the characteristics of steam cavity shapes for swirled flow spray nozzles discharging into stagnant water. A high speed imaging technique was used for capturing the steam cavity shapes. The present findings are believed to be helpful for gaining more insight into steam-water DCC systems and understanding the associated problems.

2. Experimental Setup and Methodology

The details of the experimental facility and methodology are the same as presented in our previous work [11,12]. The only difference is the type of steam nozzle used. Here, as mentioned earlier, a steam swirled flow spray nozzle has been used which is shown in Figure 1.

![Figure 1](image)

Figure 1. (a) Section view of steam swirled flow spray nozzle. (b) Fabricated nozzle.

3. Results and Discussion

3.1. Effect on Steam Cavity Shape

This section presents the variation in cavity shapes under the action of the changing tank water temperature for steam issuing from a swirled flow spray nozzle exhausting into stagnant water at constant steam pressure, $P_s = 500$ KPa.

Figure 2a–e illustrates the steam cavity shape observed at various water temperatures i.e., $T_w = 30, 40, 50, 60$, and $70 \, ^\circ C$, respectively. From this figure, it can be seen that at $T_w = 30 \, ^\circ C$, the ellipsoidal cavity shape exists as shown in Figure 2a. The formation of such a cavity shape can be explained by the steam jet becoming under expanded at elevated steam pressures. From expansion-contraction theory, such cavities are expanded as the steam is ejected out from the nozzle at the exit location. When $T_w = 50$ and $60 \, ^\circ C$, condensation capabilities of cooling medium decrease. To dissipate the extra input of steam thermal energy, additional expansion of the plume occurs by increasing the surface area of the cavity. The cavity is again compressed by nearby water which is at relatively high pressure. The plume thus becomes inflexed which finally condenses to ambient water conditions. Consequently, the double expansion–contraction shaped cavity is formulated, as presented in Figure 2b,c. When $T_w = 60$ and $70 \, ^\circ C$, there is continuous expansion in the cavity which transforms the shape of the plume into a divergent jet as illustrated in Figure 2d,e. For such shapes, the losses for heat exchange capabilities become large due to escaping of steam bubbles which carry the heat with them.

![Figure 2](image)

Figure 2. Steam cavity shape observed at $P_s = 500$ kPa and at $T_w = (a) 30 \, ^\circ C$, (b) $40 \, ^\circ C$, (c) $50 \, ^\circ C$, (d) $60 \, ^\circ C$, and (e) $70 \, ^\circ C$. 
3.2. Effect on Steam Cavity Length

Figure 3a describes the effects of liquid phase temperature on steam cavity length at constant steam pressure, i.e., 500 kPa. The plume length was measured at five water temperatures, i.e., $T_w = 30, 40, 50, 60$ and 70°C. From the findings, it can be concluded that with the decrease in degree of subcooling of water, the steam cavity length prolongs in axial dimensions. This fact can be explained as follows: as the degree of subcooling of water decreases, its temperature rises, and its corresponding condensing capability is reduced. The heat transfer area of the cavity is increased to thermally balance the input heat. Consequently, the penetration length of the steam jet increases.

![Figure 3a](https://via.placeholder.com/150)

**Figure 3a.** Effect of tank water temperature on (a) cavity dimensionless length, and (b) maximum expansion ratio.

3.3. Effect on Steam Cavity Maximum Expansion Ratio

Figure 3b shows the variation of the steam jet maximum expansion ratio with water temperature at constant steam pressure $P_s = 500$ kPa. The maximum expansion ratio has been calculated at various degrees of subcooling of water by changing water temperature (i.e., $T_w = 30, 40, 50, 60$ and 70°C). It was observed that with the decrease in degree of subcooling, the steam jet maximum expansion ratio increases. This can be explained by the condensation capacity of the water reducing with increase in water temperature. Moreover, the area across which the jet exchanges its heat with the liquid phase is increased to thermally balance the heat. The increase in area is both from the axial and radial growth of the jet. Consequently, the radial growth of the cavity diameter increases the maximum expansion ratio.

4. Conclusions

In the current study, a steam jet from a swirled flow spray nozzle was condensed experimentally into stagnant subcooled water. A high speed imaging technique was utilized to explore the steam cavity characteristics. The effect of water temperature (range, 30–70°C) on cavity parameters at steam inlet pressure 500 kPa was studied. The following main conclusions were obtained.

1. A total of three different plume shapes exist for the above-described flow conditions: ellipsoidal, double expansion–contraction, and divergent.
2. At lower water temperature, an ellipsoidal plume shape was observed. At intermediate water temperature, the double expansion–contraction shape was recorded, while the divergent cavity presented at high water temperature.
3. The steam cavity length and maximum expansion ratio were found to be in the range of 6.28–11.5 and 1.71–3.06, respectively.
4. With the increase in the subcooled water temperature, both the steam cavity length and maximum expansion ratio increased.
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**References**


