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Study of Steam Jet Condensation for CD Spray Nozzle Exhausting into Quiescent Water †

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Abstract: Direct contact condensation (DCC) has achieved a well-known significance because of exceptional reasons such as efficient heat and mass transfer characteristics. The current experimental investigation involves considering the steam cavity shape characteristics with varying steam pressure, when the saturated steam is condensed into the one-phase water atmosphere using a converging-diverging (CD) nozzle. The results indicate the four different shapes of steam jet (oscillatory, conical, ellipsoidal and double expansion–contraction). It is observed that the penetration length and the maximum expansion ratio increase with the increase in steam saturated pressure and are found in the range of 1.8–2.8 and 1–1.13, respectively. Furthermore, the current results for jet length are compared with previously developed jet length predicting models which are found to be in good agreement.

Keywords: converging diverging nozzle; direct contact condensation; multiphase flows; steam cavity length; steam cavity shape

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1. Introduction

DCC occurs when the vapors are brought directly in contact with the cold liquid [1]. Kerney et al. [2] studied steam plume length whose correlation was developed as a function of subcooled water temperature, steam mass velocity and nozzle cavity diameter. Kerney's model was later modified by Weimer et al. [3] using turbulent entrainment and variable density theories. The calculations for chugging, oscillatory and stratified flows were executed by Aya et al. [4].

Later on, Chun et al. [5] presented the qualitative regime map of the saturated steam using both vertical and horizontal nozzles with the help of a total of 346 experiments. Kim et al. [6] attempted to measure the dimensionless length and expansion ratios of steam cavity for various steam conditions. Due to the unavailability of DCC involving supersonic steam jet, Wu et al. [7] presented the jet shape of the submerged supersonic nozzle. Shah et al. [8] examined the DCC of steam discharging into the liquid water atmosphere using the lab scale model of steam jet pump.

The current research aims to study steam plume parameters such as plume shape, dimensionless penetration length and maximum expansion ratio when the saturated steam is exhausted into the quiescent water tank via DCC. The outcomes would be significant in safe and economic design of DCC based equipment as well as in the validation of CFD results.

2. Materials and Methods

The experimental setup utilized in the current research is shown in Figure 1. This setup consists of electric boiler, surge tank, water tank, CD nozzle, instrumentation, valves, mobile measuring probe and high-speed camera. The steam generator, which is most crucial component of the setup, is used to supply saturated steam with the quality of ~99% having a peak value of operating pressure of 8 bar. The steam is injected horizontally via the CD nozzle. A rectangular water tank with dimensions of 1.2 m × 1 m × 1 m is used for the water storage. The captured images are processed using MATLAB to calculate the jet parameters. The operating and geometric conditions of the present experimental investigation are given in Table 1.

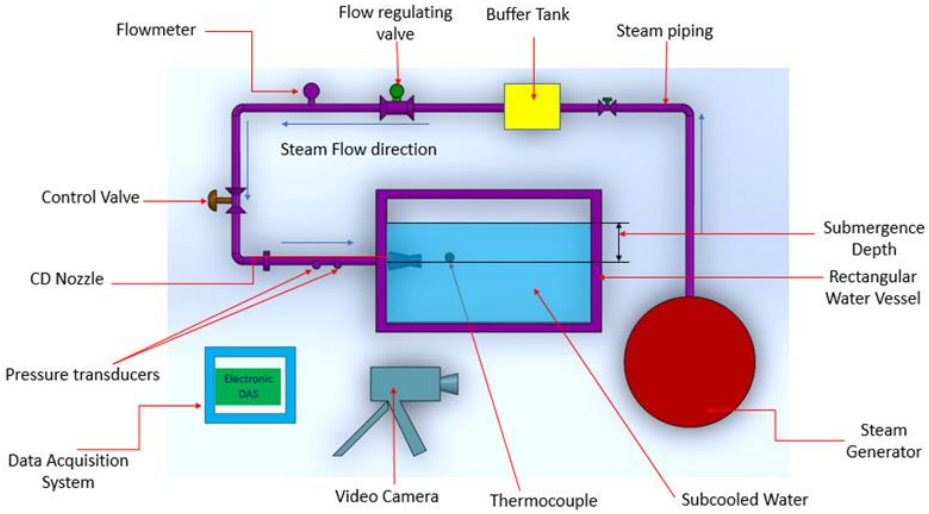

Figure 1. DCC experimental facility.

Table 1. Operating conditions.

Parameters	Value/Range
Steam pressure (Absolute)	1.5–4.5 bar
Water temperature, Tw	35 °C
Nozzle inlet diameter	10 mm
Throat diameter of nozzle	5 mm
Nozzle submergence depth	200 mm

3. Results and Discussion

3.1. Influence of Steam Saturated Pressure on the Jet Shapes

The alteration of steam cavity shapes with the steam saturated pressure at the constant temperature of 35 °C is shown in Figure 2. At the low pressures of 1.5 bar and 2 bar, (a) and (b) show the unstable steam jet shapes and oscillations take place at the steam water interface. This phenomenon is called condensation oscillations. At the pressures of 2.5 bar and 3 bar, the shape of steam plume is found to be conical as shown in (c) and (d). This type of shape is formed if the pressure at the exit of the nozzle is kept below the atmospheric pressure, hence resulting in the compression of plume.

However, as the pressure is further increased, an ellipsoidal shape was observed as shown in (e) and (f). The formation of this type of shape is associated with the theory of expansion and contraction. If the pressure is increased further to 4.5 bar, the plume manifests a double expansion–contraction shape which is shown in (g). The formation of this shape is associated with the fact that as the pressure elevates further at the constant temperature, momentum is imparted along with the transfer of thermal energy to the water.

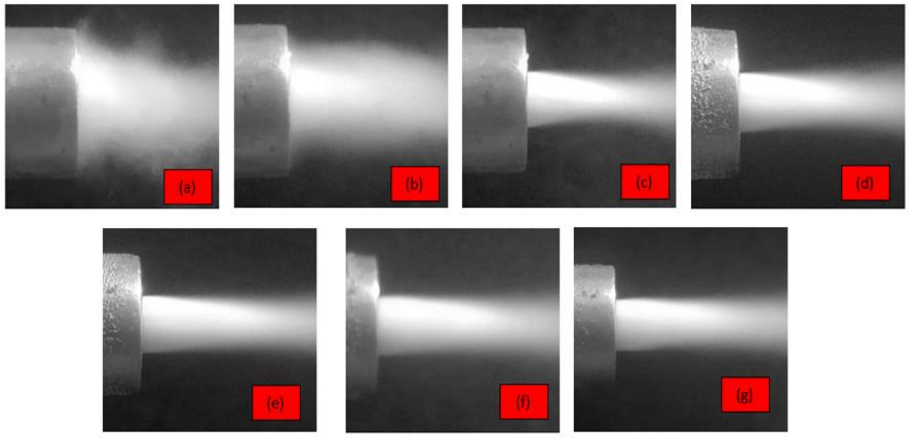

Figure 2. Steam pressure effect on jet shapes at 35 °C: (**a**) 1.5, (**b**) 2, (**c**) 2.5, (**d**) 3, (**e**) 3.5, (**f**) 4, (**g**) 4.5.

3.2. Influence of Steam Saturated Pressure on the Dimensionless Penetration Length

The variation of penetration length with the steam pressure at a temperature of 35 °C is shown as the black line in Figure 3. The parameter is taken in the dimensionless form by dividing the penetration length over the nozzle exit diameter. It is clear from the trend that as the steam pressure is increased, the dimensionless penetration length goes on increasing. This variation is obvious because at higher steam pressure, higher momentum is imparted, and the input content of heat energy also rises. The values of dimensionless penetration were found in the range of 1.8–2.8 which is in well accordance with the range of previous researchers at the low temperatures.

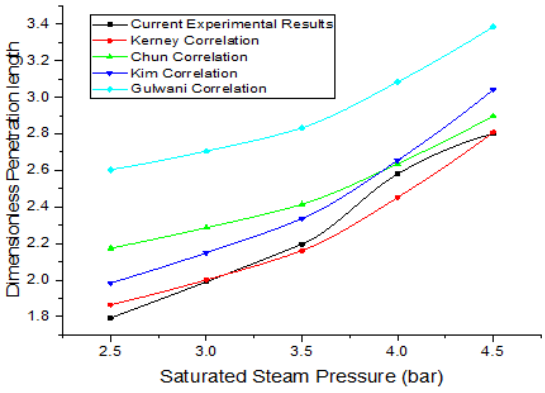

Figure 3. Comparison of Current Experimental Results with the Predicted Data.

The dimensionless penetration length is also predicted using the various correlations given in the literature for the comparison purposes. Overall, all the correlations determined the much reasonable agreement lying within the −30% and +5% as a whole with the absolute average deviation of 10.2%. The inflection point is observed in the current data because of the variation of shape from ellipsoidal to double-expansion contraction.

3.3. Influence of Steam Saturated Pressure on the Expansion Ratio

It has been found that as the saturated steam pressure increases, the maximum expansion ratio also increases. The reason behind the increasing trend of maximum expansion ratio with the steam pressure can be explained on the basis of higher momentum transfer which expands the steam in the radial direction. At the low pressures, the maximum expansion ratio was simply 1 because of the convergent shape; however, it increases as the plume becomes ellipsoidal at higher pressures. It was found to be maximum at the maximum pressure of 4.5 bar where the double expansion–contraction shape was found. The maximum expansion ratio was obtained in the range of 1–1.133 which is in accordance with the previous studies at lower temperatures.

4. Conclusions

The following are some of the major conclusions obtained after the current investigation:

1. A total of four different steam plume shapes were observed including oscillatory, conical, ellipsoidal and double contraction–expansion shape at the relatively lower temperature of 35 °C within a pressure range of 1.5–4.5 bar.
2. The dimensionless penetration length increases with the increase in steam pressure and was found in the range of 1.8–2.8.
3. Among the four correlations employed for the prediction of penetration length, Kerney's correlation agreed the most with the experimental data while the maximum discrepancy found throughout was between the data and Gulwani's correlation.
4. The maximum expansion ratio also increases with the increase in steam pressure and was found in the range of 1–1.13.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wu, X.-Z.; Yan, J.-J.; Pan, D.-D.; Liu, G.-Y.; Li, W.-J. Condensation Regime Diagram for Supersonic/Sonic Steam Jet in Subcooled Water. *Nucl. Eng. Des.* **2009**, *239*, 3142–3150. [CrossRef]
2. Kerney, P.J.; Faeth, G.M.; Olson, D.R. Penetration Characteristics of a Submerged Steam Jet. *AIChE J.* **1972**, *18*, 548–553. [CrossRef]
3. Weimer, J.C.; Faeth, G.M.; Olson, D.R. Penetration of Vapor Jets Submerged in Subcooled Liquids. *AIChE J.* **1973**, *19*, 552–558. [CrossRef]
4. Aya, I.; Nariai, H. Evaluation of Heat-Transfer Coefficient at Direct-Contact Condensation of Cold Water and Steam. *Nucl. Eng. Des.* **1991**, *131*, 17–24. [CrossRef]
5. Chun, M.-H.; Kim, Y.-S.; Park, J.-W. An Investigation of Direct Condensation of Steam Jet in Subcooled Water. *Int. Commun. Heat Mass Transf.* **1996**, *23*, 947–958. [CrossRef]
6. Kim, H.Y.; Bae, Y.Y.; Song, C.H.; Park, J.K.; Choi, S.M. Experimental Study on Stable Steam Condensation in a Quenching Tank. *Int. J. Energy Res.* **2001**, *25*, 239–252. [CrossRef]
7. Wu, X.-Z.; Yan, J.-J.; Shao, S.-F.; Cao, Y.; Liu, J.-P. Experimental Study on the Condensation of Supersonic Steam Jet Submerged in Quiescent Subcooled Water: Steam Plume Shape and Heat Transfer. *Int. J. Multiph. Flow* **2007**, *33*, 1296–1307. [CrossRef]
8. Shah, A.; Chughtai, I.R.; Inayat, M.H. Experimental and Numerical Analysis of Steam Jet Pump. *Int. J. Multiph. Flow* **2011**, *37*, 1305–1314. [CrossRef]