Review of the Characteristics of Steam Plume Jet in Water

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1. Introduction

When steam is introduced into the pool of water by means of a pipe, DCC of steam in water occurs. In general, DCC consists of four different regions. The first region in the process of condensation is the steam plume. This region occurs at the steam pipe (or nozzle) exit through which the steam is introduced into the pool of water. The outer surface of the steam plume is the steam-water interface. The hot water layer is also named bulk water. And the pool water us a single-phase area of water at certain temperature. When the steam jet is condensed in a pool, the plume modes due to DCC can be classified into three main patters: chugging; jetting; and bubbling. These modes can be shown in condensation regime map. In the view point of the engineering, the pool mixing analysis related to DCC is also very important. In this paper, the characteristics of the steam plume jet in water will be reviewed more detail in the following sections.

2. Review and Results

Del Tin et al. [1,2] measured the axial temperature and static pressure profiles for various operating conditions. A micrometric device was used for the displacements of the thermocouple and pressure probe with accuracy better than 0.05mm. Among their test results, data referring to 6 mm nozzle diameter, for three different water temperatures, are shown in figure 12. As it can be observed, at the nozzle exit, were the jet diameter tends to increase, the steam temperature rapidly falls, then it increases again in a manner practically not dependent on the pool water temperature. Subsequently the temperature decreases with a trend which is clearly dependent on the pool water temperature. The sharp decrease of the temperature inside the vapour jet can be due to the subcooled liquid entrainment. Kim et al. [3] also measured similar results of the temperature profiles for different test conditions. Like as the temperature profiles, similar trends were found in the static pressure profiles as shown in figure 1. Figure 1 shows both the total and static axial pressure profiles; the so called static pressure is that measured by pressure taps normal to the flow direction.

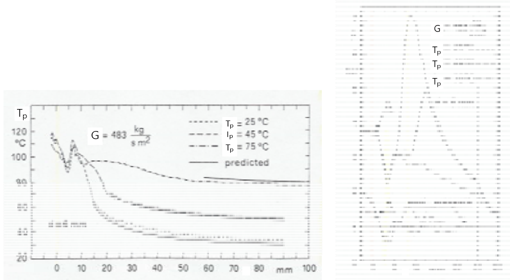

Fig. 1. Center Line Axial Plume Temperature and Total and Static Pressure Profiles [2]

Wu et al. [4] also measured the temperature distributions along the steam jet axis and in the surrounding water. Figure 2 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, e.g. shape (1) in the figure. 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-contraction steam plume shape, e.g. shape (2). For high water temperature, after the first peak, the axial temperature tended to increase slightly again, then decreased to the ambient water temperature due to condensation, which represented the double expansion-contraction steam plume shape, e.g. shape (3). When the water temperature was above 343K, the second peak of axial temperature became smooth, which represented the double expansion-divergent steam plume shape, e.g. shape (4).

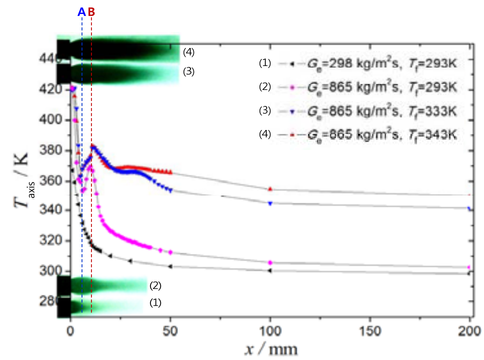

Fig. 2. Relations of Axial Temperature Distributions and Steam Plumes [4]

The axial temperature distributions were affected by the expansion and compression waves for under-expanded jet [3,5]. When the nozzle exit pressure is higher than the 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. Figure 13 shows the corresponding relation of axial temperature distributions and steam plume shapes. The nadir and peak of axial temperature were all in accord with the position of expansion (dotted line A) and compression (dotted line B) of steam plume, approximately. Although the authors showed no data on static pressure in the steam plume, the trends of static pressure might tend to follow that of the temperature profile, which was confirmed by Del Tin et al. [2].

When the steam plume shape was review, the application of the theory of expansion and compression waves was compared with DCC conditions, e.g. works of Baek [19]. The author showed pitot impact pressure profile along the centreline of moist air jet as shown in figure 3. From the figure, the lowest pressure was occurred near the Mach disk and after then pressure gradually and periodically increased like an oscillating pattern. This trend is an ideal pattern of pressure profile for under-expanded jet in the atmospheric condition. From figure 3, the lowest pressure was occurred at the external expansion (dotted line A in the figure 2) of the ellipsoidal shape, where the Mach disk existed.

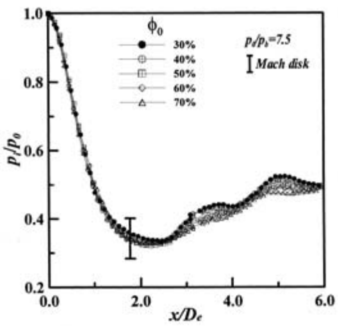

Fig. 3. Pitot Impact Pressure Distributions of Moist Air Jet [6]

Now it would be noteworthy that an interesting finding by Baek [6] should be discussed here. The author tested the effect of wall which is located at the downstream of the free jet. In that case, the test result showed that the wall of the downstream affects the patterns of jet, e.g. the shapes of jet boundary, barrel shock and the Mach disk location. If the downstream wall comes to closer to the nozzle, the overall jet shape becomes to be shrunk axially. The figure 4 shows this kind of trends, where z_n is the wall distance from the nozzle exit and d_e, nozzle diameter. The author showed the dimensionless axial location of the Mach disk is about 1.8 for free jet without downstream wall, which seems to be reasonable compared with the predictions of Kim et al. [3]. If there was a downstream wall at about $2d_e$ distance from the nozzle for a free jet, the dimensionless location of the Mach disk became to be about 1.0. For the steam jet injected into water, the water might be a kind of downstream wall although quite a large condensation between steam jet and water. This trend can be found from the test data measured by Kim et al. [3]. The authors showed that the location of external expansion (EE) of the ellipsoidal plume becomes half of the no condensation value.

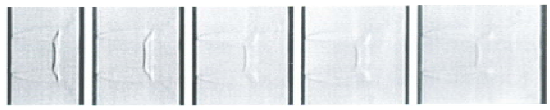

Fig. 4. Visualization Pictures of Impinging Moist Air Jet (Φ_0=30%; p_0/p_b = 7.5) [6]

3. Conclusions

The characteristics of the steam plume jet in water was reviewed more detail especially on the plume temperature and pressure distribution. It found that the steam jet in water was related to the characteristics of the jet flow in the ambient physically. Due to the condensation, the location and diameter of EE gets closer to the nozzle exit and smaller, respectively. In addition to this aspect, pool water seemed to be a kind of wall to the injected steam, so the point of EE became even more close to nozzle.

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