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Development of an Empirical Correlation for the Velocity and Temperature at the Centerline of a Turbulent Jet by a Steam Jet Condensation

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1. Introduction

The experimental and CFD (Computational Fluid Dynamics) research for an unstable steam condensation in a DCC (Direct Contact Condensation) which may happen in the IRWST (In-containment Refueling Water Storage Tank) of APR1400 were performed [1,2]. One of the main reasons for the unstable steam condensation was found to be the increased temperature of a turbulent water jet entraining on the steam jet [2]. Thus, it may be very useful for the evaluation of an unstable condensation and a thermal mixing of the IRWST pool if an empirical correlation to predict the velocity and temperature of a turbulent water jet induced by the condensation of a steam jet is developed. Therefore, a fundamental test for a turbulent jet due to a steam jet condensation was performed to develop correlations [3].

2. Experiment of the Turbulent Water Jet

2.1 Experimental Facility

In order to measure the velocity and the temperature distribution of a turbulent jet, the GIRLS facility [1] with a single-hole sparger submerged in a subcooled water tank was used. The velocity and temperature distribution of the turbulent jet was simultaneously measured by a pitot tube/thermocouple which can be moved in the axial and radial direction by a transport device (Fig. 1).

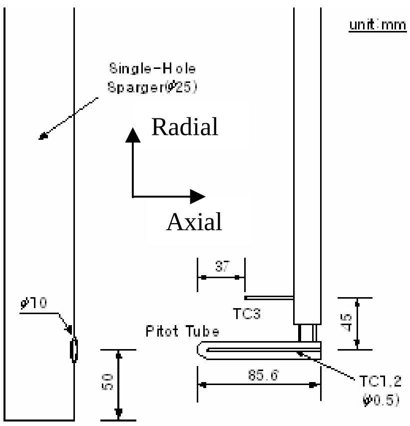

Figure 1. Single-hole sparger and pitot tube/TC

2.2 Experimental Matrix

The experimental matrix (Table. 1) was designed to maintain a quasi steady state of the steam jet discharge under various temperatures of the tank water. The pitot tube/TC was continually moved to measure the velocity and the temperature inside the turbulent jet at the same test case. While moving the pitot tube/TC, the temperature of the tank water was slightly increased by the heat of the steam condensation. The distance range of the pitot tube/TC in the radial direction was about 1~3cm.

Table 1. Experimental matrix

	Temp. of water (T_w)	Discharged steam	Axial Measure't location
Case 1	15~22℃	G ≈ 1,000 kg/m^2s T_{sat} ≈ 166℃	8, 12, 16cm
Case 2	27~35℃		
Case 3	31~36℃		
Case 4	36~41℃		
Case 5	39~48℃		8, 12, 16, 20cm

3.4 Discussion on the Experimental Results

According to the test results, a typical jet behavior of a single phase like that the velocity at the centerline was decayed and the width of the jet was increased as the jet flowed along the axial direction (Fig. 2).

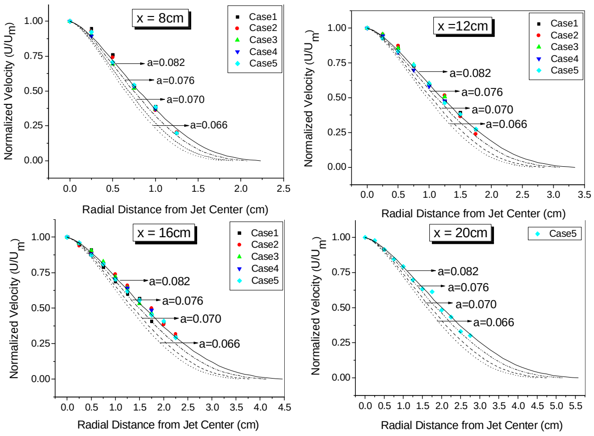

Figure 2. Velocity distribution of turbulent jet

To quantify the spreading value of the jet width, a jet theory from Tollmien's axially symmetric turbulent source [4] was introduced and compared with the test data. The used value of the coefficient (a) concerning the spread of the jet width in Tollmien's solution is 0.082 [3,4]. When using these solutions and coefficient, the radial distribution of the velocity and the temperature of the turbulent jet at a certain axial location can be obtained easily. The correlation to predict velocity at the centerline of the turbulent jet was proposed like as Eq. (1) with the help of both the previous one and the test data [3,5]. In Eq. (1), "d" is the diameter of the discharge hole of the steam jet, "U_o" is the steam velocity at the exit of the discharge hole and "y_c" is the radial distance from the centerline to 50% of U_m at a certain location along the propagation of the turbulent jet.

$$U_m = 0.95 \frac{dU_o}{y_c} \sqrt{\frac{\rho_v}{\rho_l}} \qquad (1)$$

And also, the correlation of the temperature like as Eq. (2) with an error of $\pm 20\%$ based only on the test data (Fig. 3) was developed.

$$\frac{T(x-L)}{T_w} = e^{-y_c}\left[0.36(x-L)+1.8d\right] \qquad (2)$$

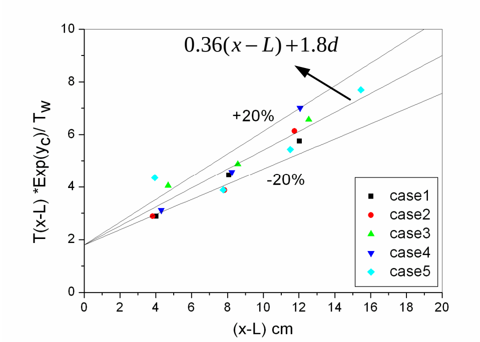

Figure 3. Garph of T(x-L)*exp(y_c)/T_w vs (x-L)

In the Eq. (2), a new variable of "x-L" which physically means the distance from the end of the steam jet penetration (L, Eq. 3) to an axially measured location was introduced to account for a variation of the mass flux of the steam jet and the temperature of the tank water.

$$\frac{L}{d} = 0.51\left[\frac{(h_f - h_w)}{(h_s - h_f)}\right]^{-0.7}\left(\frac{G}{G_m}\right)^{0.47} \qquad (3)$$

It may be very useful to use Eq. (1) and Eq. (2) when the variable of a half width of a turbulent jet (y_c) is also empirically predicted with the information of the mass flux of the steam jet and the water temperature. Generally, "y_c" is known to be mainly proportional to the axial distance in a single phase [4]. Thus, a correlation of "y_c" was developed with an error of $\pm 10\%$ such as Eq. (4) using the variable of "x-L" (Fig. 4) [3].

$$y_c = 0.11(x-L) + 0.3d \qquad (4)$$

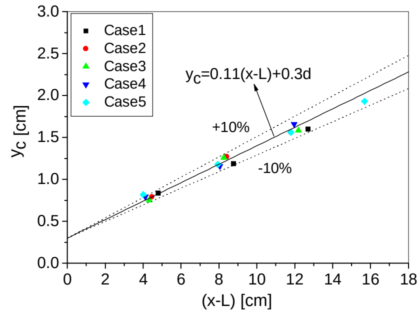

Figure 4. Garph of y_c vs (x-L)

4. Conclusion and Further Work

The empirical correlations for the velocity, the temperature at the centerline and the half width of a turbulent jet induced by a steam jet condensation were developed based on the experimental results of the discharge of the steam jet into a subcooled water through a single-hole sparger. These correlations may be used to evaluate the thermal mixing and the thermal hydraulic load of the IRWST. However, the developed correlations should be validated with other test results to enhance their accuracy.

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