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On the Steam Jet Condensation Oscillation in Sonic Flow

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1. Introduction

Advanced Power Reactor 1400MW (APR1400), an advanced type of Pressurized Water Reactor (PWR) adopts an In-containment Refueling Water Storage Tank (IRWST) and spargers in it, which increases the quenching efficiency of steam and alleviates probable pressure surge induced by the sudden discharge of the high pressure steam. For the design and operation it is essential to understand the phenomena of submerged steam jet condensation. Especially, the pressure oscillation during steam jet condensation may directly damage the structures or resonate with the structures. Eventually, the structure may be directly damaged or the fatigue can cumulate in them.

Steam jet condensation has been investigated as a function of steam mass flux, pool subcooling (pool temperature) and nozzle diameter, and the phenomena related largely depends on the condensation map[1].

The objective of this study is to investigate the dominant frequency of pressure oscillation in submerged horizontal steam jet condensation. The range of steam mass flux was 200~900 kg/m^{2}s, and that of pool temperature was 35~95℃. In particular, the high steam mass flux region (>300 kg/m^{2}s,) was intensively investigated. For such a range the study has not been intensively performed.

2. Experiment

GIRLS (General Investigation Rig for Liquid/Steam Jet Direct Contact Condensation) was constructed, whose diameter is 1.8m, height 1.5m, water level 1.3m. Sparger was a pipe of 1 inch and schedule 40. Near the end of the sparger, the steam was horizontally discharged into subcooled water through a single hole of diameter 10mm. In order to measure pressure oscillation when steam jet condenses in subcooled water, pressure transducers of piezoelectric type were used. For the data analysis Fourier transform (or Fast Fourier Transform (FFT)) was utilized. Based on this FFT, averaging method was adopted. And these processes were coded with C++ computer language, and named as GAPF (GIRLS Analysis Program based on FFT). The GAPF greatly decreases the randomness. The GAPF makes the curves smooth and makes it easy to find the dominant frequency [2].

The measured and analyzed results are shown in figure 1. Under the steam mass flux around 300 kg/m^{2}s the frequency is proportional to steam mass flux increase. However, over the steam mass flux around 300 kg/m^{2}s the frequency decreases as the steam mass flux increases. In the contras, the frequency is inversely proportional to pool temperature regardless of pool temperature.

3. Analytic Model

The governing equation is based on the balance of kinetic energy that the steam jet gives and the ambient water receives when the steam jet grows. On this basic idea, the fundamental theory of submerged turbulent jet was adopted. Through the observation of steam jet, figure 2 was suggested as a simplified structure of submerged steam jet. It is mainly composed of vapor dominant region (VR) and liquid dominant region (LR). Followings are principal assumptions for the derivation of balance equation.

The derivation processes for the governing equation are very similar to that for Rayleigh bubble equation. Through the complicated processes the final equation is obtained as following;

$$X\frac{d^2X}{dt^2}+\frac{3}{2}\left(\frac{dX}{dt}\right)^2-\frac{1}{\rho_l}\left(\frac{k_2}{k_1}\right)^2\left(P_s-P_\infty\right)=0 \qquad (1)$$

This equation is named as 'jet equation', and is the form of second order one dimensional non-linear ordinary differential equation.

In order to solve the jet equation, perturbation solution method was used with following initial conditions;

$$t=0,\quad X=X_E\left(1+\varepsilon\right),\quad \frac{dX}{dt}=0 \qquad (2)$$

Only the 0th order set and 1st order set were considered, and the final solutions are as follows;

$$X_1\left(t\right)=X_E\cos\left(\frac{1}{X_E}\frac{k_2}{k_1}\sqrt{\frac{3nP_\infty}{\rho_l}}t\right) \qquad (3)$$

Frequency, the target of this analysis, is given by

$$f=\frac{\sqrt{3n}}{2\pi}\frac{k_2}{k_1}\frac{1}{X_E}\sqrt{\frac{P_\infty}{\rho_l}} \qquad (4)$$

This solution shows that the frequency is inversely proportional to steam jet length.

In order to get substantial frequency, all of the terms in Eq. (4) have to be specified. At first, for the equilibrium jet length, X_E experimental correlations of Kerney's type (including Kim, Y.S. and Kim H.Y), which considers both steam and pool conditions, were used [4,5,6]. The ambient pressure or water pressure P_∞ was assumed to be atmospheric pressure, 101325 Pa, and the density of water was obtained from steam table. Adiabatic process was assumed, and $n = \gamma = 1.32$. The ratio of jet expansion coefficients for VR and LR is assumed to be $k_2 / k_1 = 3.2592$ from trial and error. This ratio of coefficients means that the expansion ration in LR is larger than that in VR by 3.2592 times.

The calculated results are shown in figure 3, which shows very good agreement with experimental data.

4. Conclusion

Above the steam mass flux around 300 kg/m^{2}s, the experiment was conducted, and shows the different frequency trend from the trend under steam mass flux around 300 kg/m^{2}s. The frequency in high steam mass flux is inversely proportional to steam mass flux. However, the frequency is consistently inversely proportional to pool temperature regardless of pool temperature. Analytic model based on the theory of turbulent jet also shows excellent agreement with experimental data.

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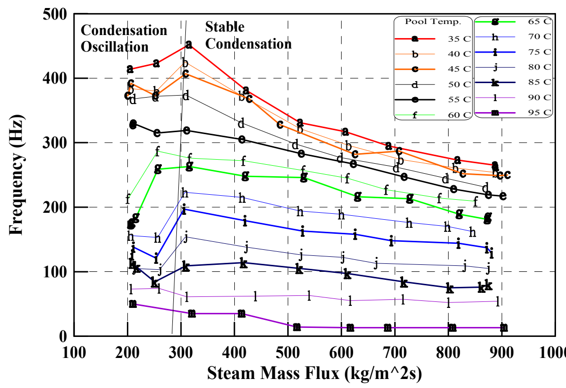

Figure 1. Test Results : Frequency according to steam mass flux and pool temperature

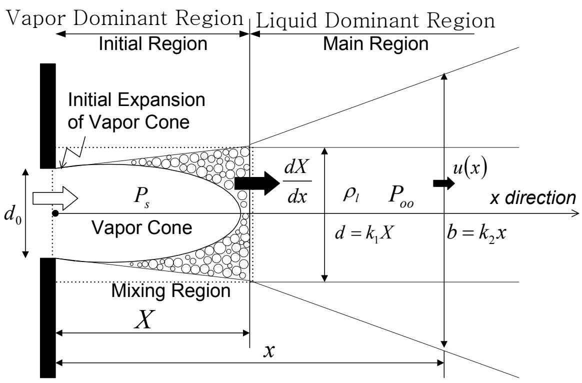

Figure 2. Structure of submerged steam jet for modeling

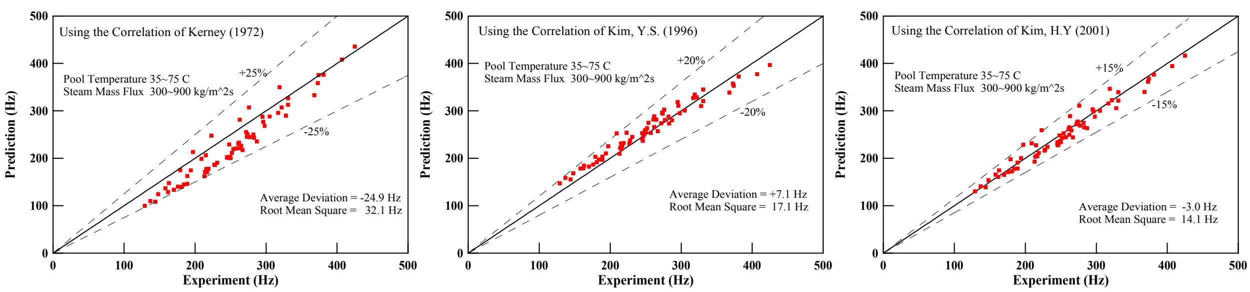

Figure 3 Error bound of prediction for pool temperature 35~75℃ and steam mass flux 300~900 kg/m^{2}s