Proceedings of the 3rd IASME/WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT, Corfu, Greece, August 20-22, 2005 (pp332-337)

Modeling of Pressure Oscillation for Submerged Condensing Steam Jet in Choked Condition

SOON-JOON HONG
FNC Technology Co.
Seoul National University Research Innovation Center 516, San 4-2, Bongchun 7-Dong, Kwanak-Gu, Seoul, 151-818
S. KOREA
sjhong90@fnctech.com   http://www.fnctech.com

Abstract: - This study is a fundamental analysis for the prediction of single submerged steam jet condensation. Based on turbulence jet theory and energy conservation, a prediction model was derived, and compared to experimental data. For choked steam flow condition and pool temperature under 75 ℃, the proposed model shows good agreement with experimental data within 10% error. It is expected that the model presented in this study will be very useful in structural design of submerged steam jet condensation oscillating system.

Key-Words: - submerged steam jet, condensation, pressure oscillation, frequency, steam mass flux, pool temperature, choked condition

1 Introduction

Korean nuclear industry has pursued a development of a revolutionary pressurized water reactor (PWR), called APR1400 (Advanced Power Reactor 1400 MWe) since 1992, and now reaches engineering design step for a specific power plant. APR1400 incorporates a lot of new advanced safety features including in-containment refueling water storage tank (IRWST).

The IRWST system performs water collection, delivery, storage and heat sink functions inside the containment during normal plant operation and accident conditions. An type I sparger containing multi-hole is adopted in the IRWST in order to increase the quenching efficiency of steam, and to alleviate probable pressure surge induced by the sudden discharge of the high pressure steam from Reactor Coolant System (RCS) during postulated accident. Conceptual configurations are shown in Fig. 1. When the Pilot Operated Safety Relief Valve (POSRV) opens in Safety Depressurization and Vent System (SDVS), the steam is discharged into the subcooled water in IRWST, following water clearing and air clearing, and the steam undergoes violent direct contact condensation in the form of oscillatory jet or chugging. Such a violent transient issues several design or regulatory concerns, and one of them is an effect of pressure oscillation on structure [1].

This study aims to model such an oscillatory motion of single jet in choked condition as a fundamental analysis, even though the sparger in APR1400 is multi-hole system. The oscillatory motion of single jet is directly related with steam jet volume or the steam jet length by the equation of state.

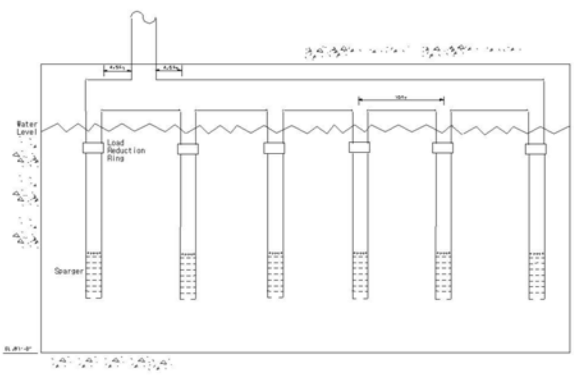

Fig. 1 Conceptual configurations of IRWST and sparger in APR1400

2 Review of Submerged Steam Jet Condensation

Steam jet condensation shows very different phenomenon according to mass flux of discharged steam and the temperature of pool water, which results in regime map like as Fig.2[2]. Operating condition of IRWST system is expected to fall mainly on SC (stable condensation) region of choked steam flow condition. In this region the steam condensation shows the most stable behavior, and steam-water interfaces are also very stable. Only the entire jet length moves back and forth accompanying pressure oscillation.

Proceedings of the 3rd IASME/WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT, Corfu, Greece, August 20-22, 2005 (pp332-337)

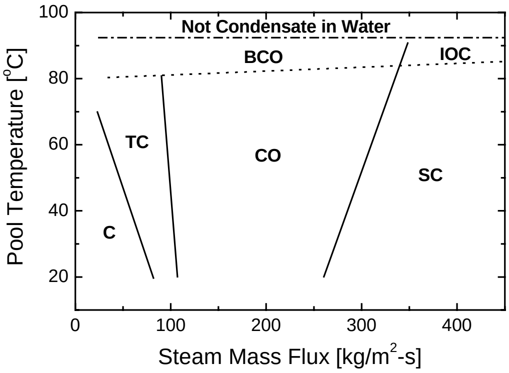

Fig. 2 Condensation regime map by Cho et al. [2]

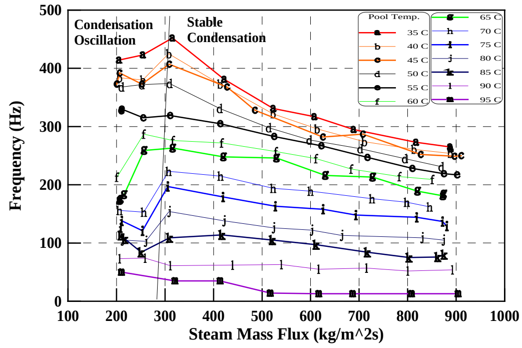

Fig. 3 Pressure oscillation by Hong, S.J. [5]

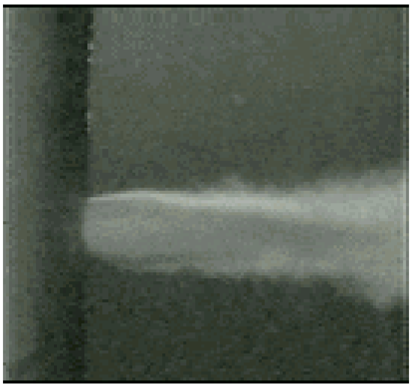

Fig. 4 Steam jet ejected through single hole at steam mass flux 625 kg/m^{2}s pool temperature 47℃ [5]

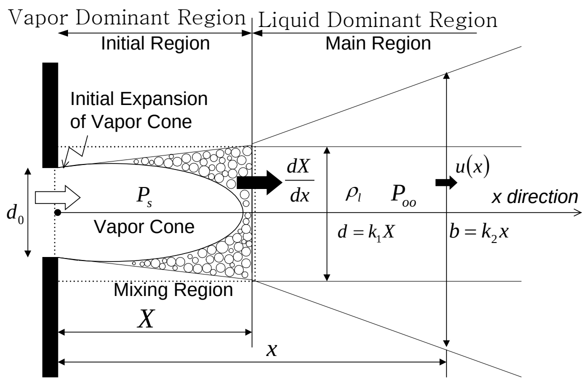

Fig. 5 Structure of submerged steam jet for modeling

Continuous steam ejection increases the pool temperature, and the regime transits into IOC (interfacial oscillation condensation) region. Steam jet in this region shows similar behavior to that in SC, however, the steam jet is extreamly elongated, and the steam-water interfaces are more unstable with larger pressure oscillation compared to SC. Whe the steam mass flux decreases and the steam velocity becomes subsonic, the regime transits into CO (condensation oscillation) or BCO (bubbling condensation oscillation), which shows more violent condensation than SC or IOC. The regimes mentioned above is some times called as jetting, however, at the lower steam mass flux the steam cannot form a jet shape, and eventually the steam forms chugging, an extremely violent condensation phenomena. More details are attributed to reference 2.

Pressure oscillation was intensively studied by Damasio et al. [3]. They suggested an experimental frequency correlation using Strouhal number for frequency (St), Reynolds number (Re) for steam, Jacob number (Ja) for pool, and Weber number (We) up to maximum steam mass flux 250 kg/m^{2}s. The frequency is proportional to steam mass flux and pool subcooling, but inversely proportional to nozzle diameter. Nariai et al. analytically studied on the pressure oscillation, and well predicted experimental data[4]. However, they were all limited to steam mass flux up to 300 kg/ m^{2}s, that is, CO or BOC region in Fig.2. Hong, S.J. experimentally identified pressure oscillation for higher steam mass flux with 10mm diameter hole, as shown in Fig.3[5].

3 Modeling of Oscillatory Jet Motion

3.1 Derivation of Governing Equation

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 in Fig. 4, Fig. 5 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.

(1) The effective width of LR is proportional to the distance from the exit of hole, and the conceptual diameter is $k_2 x$. Such an assumption is based on the theory of submerged turbulent jet. With similar reason, the effective width of VR at X is proportional to the distance from the exit of hole, and the conceptual diameter is $k_1 X$.
(2) Its mean velocity can represent the liquid velocity in LR.
(3) The entrained water does not affect the total kinetic energy in VR and LR. This assumption is based on that the entrainment is also caused by the kinetic energy transfer from VR and LR to ambient liquid.

The mass conservation of liquid at the point X and x gives

$$\frac{\pi}{4}(k_1 X)^2 \frac{dX}{dt} = \frac{\pi}{4}(k_2 x)^2 u(x) \tag{1}$$

, where $u(x)$ is an area-averaged velocity at x, and can be arranged into;

$$u(x) = \left(\frac{k_1 X}{k_2 x}\right)^2 \frac{dX}{dt} \tag{2}$$

Throughout the LR, $X < x < \infty$, the liquid gains the kinetic energy from the motion of the VR. Using Eq. (2) and the relation $dV = \frac{\pi}{4}(k_2 x)^2 dx$, following kinetic energy can be obtained;

$$\begin{aligned} KE &= \int_X^\infty \frac{1}{2}\rho_l u^2(x)\,dV \\ &= \frac{\pi}{8}\rho_l \left(\frac{dX}{dt}\right)^2 \left(\frac{k_1^4}{k_2^2}\right) X^3 \end{aligned} \tag{3}$$

The net work W_l done against the LR as the VR grows from $x = 0$ to X is given by

$$\begin{aligned} W_l &= \int_0^X P_s \frac{\pi}{4}(k_1 x)^2 dx - P_\infty \frac{1}{3}\frac{\pi}{4}(k_1 X)^2 X \\ &= \frac{\pi}{12} k_1^2 X^3 (P_s - P_\infty) \end{aligned} \tag{4}$$

In the first line of this equation, the second term subtracts work done against the LR to accommodate the volume change of the VR. Equating the Eq. (3) and Eq. (4), arranging, and differentiating with respect to X gives

$$X\frac{d^2X}{dt^2} + \frac{3}{2}\left(\frac{dX}{dt}\right)^2 - \frac{1}{\rho_l}\left(\frac{k_2}{k_1}\right)^2 (P_s - P_\infty) = 0 \tag{5}$$

This equation is named as 'jet equation', and is the form of second order one dimensional non-linear ordinary differential equation. The form of Eq. (5) is very similar to Rayleigh bubble equation.

3.2 Solution of Jet Equation

In order to solve the jet equation, perturbation solution method was used. For the Eq. (5), following initial conditions were considered.

$$t = 0, \quad X = X_E(1+\varepsilon), \quad \frac{dX}{dt} = 0 \tag{6}$$

The equilibrium jet length is disturbed by the amount εX_E in Eq. (6). A series expansion of $X(t)$ is assumed in the form

$$X(t) = X_0(t) + \varepsilon X_1(t) + \cdots \tag{7}$$

It was assumed that the pressure of VR undergoes the polytropic process, and given by

$$\begin{aligned} P_s &= P_\infty\left(\frac{V_E}{V}\right)^n = P_\infty\left(\frac{X_E}{X}\right)^{3n} \\ &= P_\infty\left[\frac{X_E}{X_0(1+\varepsilon X_1/X_0 +_0 \cdots)}\right]^{3n} \\ &= P_\infty\left(\frac{X_E}{X_0}\right)^{3n}\left[1 - 3n\varepsilon\frac{X_1}{X_0} + \cdots\right] \end{aligned} \tag{8}$$

where n is a coefficient of polytropic process. The other terms in jet equation and initial condition also can be expanded in the similar manners. If only terms up to the first order of ε are kept, the problem will be linearized.

Now, the expanded terms in jet equation can be rearranged according to the order of ε. The 0th order of governing equation (GE) and initial conditions (ICs) are as followings;

$$\begin{aligned} GE: \quad & X_0\frac{d^2X_0}{dt^2} + \frac{3}{2}\left(\frac{dX_0}{dt}\right)^2 \\ & -\frac{1}{\rho_l}\left(\frac{k_2}{k_1}\right)^2 P_\infty\left[\left(\frac{X_E}{X_0}\right)^{3n} - 1\right] = 0 \end{aligned} \tag{9}$$

$$ICs: \quad X_0(0) = X_E, \quad \dot{X}_0(0) = 0$$

The solution of Eq.(9) is self-evident: the non-perturbed equilibrium state.

$$X_0(t) = X_E \tag{10}$$

The 1st order of equation and initial condition are as followings

$$GE: \quad \frac{d^2 X_1}{dt^2} + \frac{1}{\rho_l}\left(\frac{k_2}{k_1}\right)^2 P_\infty(3n)\frac{X_1}{X_0^2} = 0 \tag{11}$$

$$ICs: \quad X_1(0) = X_E, \quad \dot{X}_1(0) = 0$$

The solution is easily obtained: second order ordinary differential equation.

$$X_1(t) = X_E \cos\left(\frac{1}{X_E}\frac{k_2}{k_1}\sqrt{\frac{3nP_\infty}{\rho_l}}t\right) \tag{12}$$

Frequency, the target of this analysis, is given by

$$f = \frac{\sqrt{3n}}{2\pi}\frac{k_2}{k_1}\frac{1}{X_E}\sqrt{\frac{P_\infty}{\rho_l}} \tag{13}$$

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

4 Comparison with Experimental Data

The experimental data for comparison of this modelling are those in Fig.3 by Hong[5]. And in order to get substantial frequency, all of the terms in Eq. (13) have to be specified. At first, for the equilibrium jet length, X_E, experimental correlations of Kerney's type, which considers both steam and pool conditions, were used.

$$\frac{X}{d_0} = c_1 B^{c_2}\left(G_0/G_m\right)^{c_3} \tag{14}$$

$$B = c_p\left(T_s - T_\infty\right)/h_{fg} \quad G_m = 275kg/m^2s$$

Three correlations have been suggested and summarized in Table 1 [6,7,8]. It was revealed that the Kerney et al.'s length is the longest, Kim, Y. S.'s is the shortest, and the Kim, H. Y.'s lies between the two. 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 3.2592times.

The predicted frequencies are compared to experimentally measured one's in Fig. 6. Fig. 7. shows good agreement between experiment and prediction except for over 80℃ pool temperature and under 300 kg/m^{2}s steam mass flux. In particular, the prediction using Kim, H.Y. was bounded within 15% error for steam mass flux 300~900kg/m^{2}s and pool temperature 35~75℃. In Fig. 7 the average and the root mean square (RMS) are defined as follows.

Table 1 Correlations for steam jet length

Author	Correlation
Kerney [6]	$X/d_0 = 0.3583B^{-8311}\left(G_0/G_m\right)^{0.6446}$
Kim, Y. S.[7]	$X/d_0 = 0.5923B^{-0.66}\left(G_0/G_m\right)^{0.3444}$
Kim, H.Y.[8]	$X/d_0 = 0.51B^{-0.70}\left(G_0/G_m\right)^{0.47}$

$$Average\ Deviation = \frac{1}{N}\sum_i^N\left(f_{pred} - f_{exp}\right)_i \tag{15}$$

$$RMS = \sqrt{\frac{1}{N}\sum_i^N\left(f_{pred} - f_{exp}\right)_i^2} \tag{16}$$

However, it should be noted that from the condensation regime map in Fig. 2 the pool temperature 80℃ and the steam mass flux 300 kg/m^{2}s are transition boundaries. Thus, it is necessary to analyze only the data in SC region. This analysis shows more accurate prediction, only 10% error, as shown in Fig.8. For IOC region, using modified ratio of jet expansion coefficients, (k_2/k_1), for each pool temperature gave an improved prediction. However, consistent coefficient ratio regardless of pool temperature was not obtained for improved predictions.

5 Conclusion

This study suggests analytic model for prediction of pressure oscillation frequency for SC region (choked steam flow condition and pool temperature under 80 ℃). Except for transition region of SC, the proposed model shows good agreement with experimental data within 10% error. The result of this study supports the experimental results of reference 5, that is, the oscillation mechanisms of SC and CO are different each other. It is expected that the model presented in this study will be very usful in structural design of submerged steam jet condensation oscillating system.

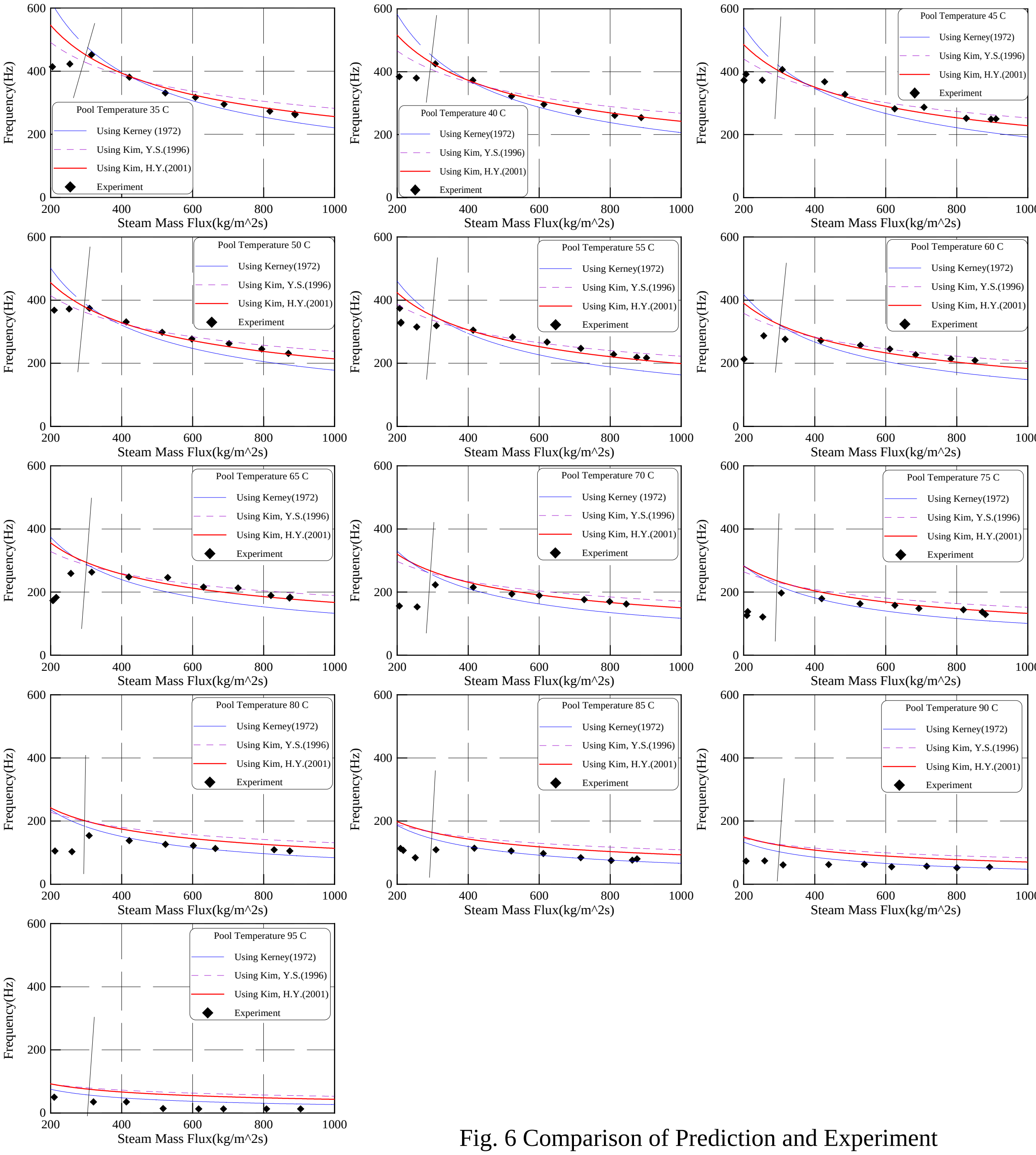

Fig. 6 Comparison of Prediction and Experiment

Nomenclature:

c_p	specific heat of water (J/kgK)
d	diameter of jet or VR (m)
d_0	hole diameter (m)
f	frequency (Hz)
G_0	steam mass flux at the exit of hole (kg/m^{2}s)
k_1, k_2	expansion coefficient of VR and LR
n	coefficient of polytropic process
P_s	pressure of VR (Pa)
T_∞	pressure of LR (Pa)
T_s	temperature of VR (Pa)
P_∞	temperature of LR (Pa)

Proceedings of the 3rd IASME/WSEAS Int. Conf. on HEAT TRANSFER, THERMAL ENGINEERING AND ENVIRONMENT, Corfu, Greece, August 20-22, 2005 (pp332-337)

t time (s)
u velocity (m/s)
V volume (m^3)
W_l net work done against the LR (J)
X steam jet penetration length (m)
X_E equilibrium length of steam jet (m)

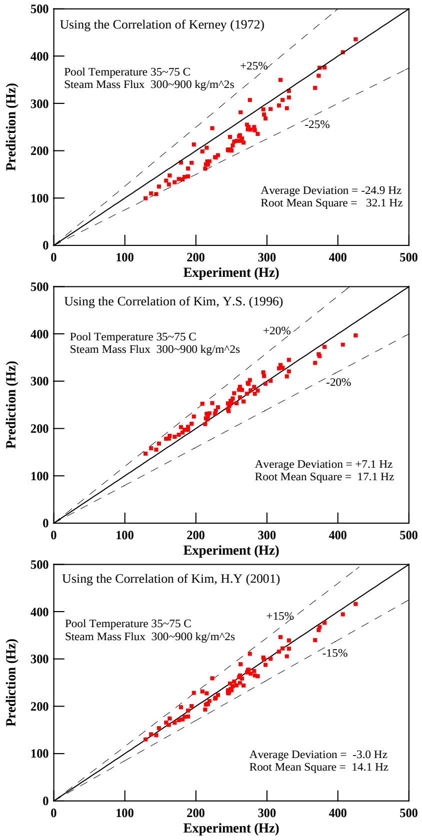

Fig.7 Error bound of prediction for pool temperature 35~75℃ and steam mass flux 300~900 kg/m^2s

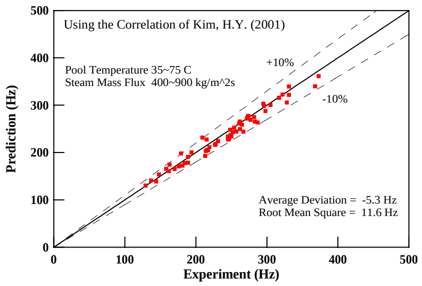

Fig.8 Comparison of prediction and experiment - steam mass flux over 400kg/m2s and pool temperature 35~75℃

x distance in the direction of jet axis (m)
ε perturbation
γ ratio of specific heat
ρ_l density of LR (kg/m^3)

References:

[1] Choi, Y.S., et al., Research & Development on Korean Next Generation Reactor (Phase II), Ministry of Commerce, 1999, Industry, and Energy and Ministry of Science and Technology

[2] Cho, S., Song, C. H., Park, C. K., Yang, S. K., and Chung, M. K., Experimental Study on Dynamic Pressure Pulse in Direct Contact Condensation of Steam Discharging into Subcooled Water, *First Korea-Japan Symposium on Nuclear Thermal Hydraulics and Safety, NTHAS98*, Pusan, Korea, , 1998

[3] Damasio, C., Del Tin, G., Fiegna, G. and Malandrone, M., Experimental Study on the Unstable Direct Contact Condensation Regimes, *Proc. of the 3rd Int. Topical Meeting on Reactor Thermal Hydraulics*, , 1985, pp. 6.C-1～6.C-8

[4] Nariai, H. and Aya, I., "Fluid and Pressure Oscillations occurring at Direct Contact Condensation of Steam Flow with Cold Water", *Nuclear Engineering and Design*, Vol. 95, 1986, pp. 435-45

[5] Hong, S.J., Lim, B.K., Cho, S., Chun, S.Y., and Park, G.C., Dynamic Characteristics of Horizontal Submerged Steam Jet Condensation, *Twelfth International Heat Transfer Conference (IHTC12)*, August 18-23, 2002, Grenoble, France

[6] Kerney, P. J., Faeth, G. M., and Olson, D. R., Penetration Characteristics of Submerged Jet, *AIChE J., Vol. 18, No. 3*, 1972, pp. 548-553

[7] Kim, Y. S., An Investigation of Direct Condensation of Steam Jet in Subcooled Water, *PhD. Dissertation*, 1996, Korea Advanced Institute of Science and Technology (KAIST)

[8] Kim, H. Y, A Study on the Characteristics of Direct Contact Condensation of a Steam Jet Discharging into a Quenching Tank through a Single Horizontal Pipe, *PhD. Dissertation*., 2001, Korea Advanced Institute of Science and Technology (KAIST)