Proceedings of Korean Nuclear Society Spring Meeting
Cheju, Korea, May 1996

Applicability of One-Dimensional Mechanistic Post-Dryout Prediction Model

Hae Yong Jeong and Hee Cheon No
Korea Advanced Institute of Science and Technology

Abstract

Through the analysis of many experimental post-dryout data, it is shown that the most probable flow regime near dryout or quench front is not annular flow but churn-turbulent flow when the mass flux is low. A correlation describing the initial droplet size just after the CHF position at low mass flux is suggested through regression analysis. In the post-dryout region at low pressure and low flow, it is found that the suggested one-dimensional mechanistic model is not applicable when the vapor superficial velocity is very low, i.e., when the flow is bubbly or slug flow regime. This is explained by the change of main entrainment mechanism with the change of flow regime. Therefore, the suggested correlation is valid only in the churn-turbulent flow regime ($j_g^* = 0.5 \sim 4.5$).

1. Introduction

Liquid droplets, existing in reactor core at uncovery or reflood state after a large loss of coolant accident, enhance the heat transfer above the dryout or quench front by the absorption of heat from wall and vapor. This effect restrains the wall temperature from an abrupt increase and the failure of the cladding wall is prevented or lessened.

To describe the heat transfer in the post-dryout region, empirical correlations are frequently used. However, the empirical correlations do not describe the real heat transfer process properly. Therefore, many mechanistic models for post-dryout heat transfer are developed. In the mechanistic post-dryout model, it is very important to evaluate the initial hydrodynamic parameters correctly. The droplet diameter near the dryout location is one of the main parameters. To evaluate the initial droplet size after dryout, the Weber number criterion is frequently used (Varone and Rohsenow,1986).

One-dimensional safety analysis code, such as RELAP5/MOD3, also adopts Weber number criterion to calculate the droplet size at the CHF location. However, the Weber number criterion is useful only when the entrainment mechanism primarily depends on the shear force from a fast moving vapor stream to the slow moving liquid surface. If such a condition is questionable, this kind of mechanism can not be applied. Actually, the analysis of reflooding core by RELAP5/MOD3 (Analytis, 1995) results in a large error due to the inappropriateness of the initial droplets size. To avoid this erroneous result, it is recommendable to determine the droplet size based on the droplet generation mechanism. For this, it is needed to distinguish the entrainment mechanism with given flow conditions such as flow regime or void fraction, *et cetera.*

The entrainment mechanism and the generated droplet size are believed to be most closely related to the flow regime. However, there exist no reliable correlations for the estimation of droplet sizes depending on the flow regimes. In a liquid pool or slow-reflood channel, the entrainment is achieved by bubble-bursting or splashing from the turbulent surface. Especially, the splashing in a low flow channel mainly comes from the liquid slug burst due to the wall impact of the liquid slug.

Some experiments in rod bundle geometry were performed to study the heat transfer and hydrodynamic aspects in the reflooding reactor core; the ACHILLES tests and the FLECHT SEASET tests. The droplet sizes obtained from these experiments showed strong pressure dependence. Kocamustafaogullari et al.(1983) analyzed the data generated in the PWR FLECHT SEASET experiments and concluded that the majority of droplets observed were generated through entrainment at the quench front, and not during the subsequent flight of droplets in the gas stream. Therefore, the flow regimes at the quench front should be important in determining the mechanisms of droplet entrainment. They showed that at lower gas fluxes where churn-turbulent flow occurs before the quench front, the stable droplet size was estimated by considering the relative velocity for churn-turbulent flow and assuming that rising particles were stable only if they were in wake particle flow regime:

$$D_s = 4\left(\frac{2\sigma}{g\Delta\rho}\right)^{1/2} N_{\mu g}^{1/3}. \tag{1}$$

M.Andreani (1992) analyzed many reflooding experimental data with the 2-D Eulerian vapour field model. He concluded that it was not clear whether large droplets could exist above the quench front and then broke further up, or whether only small droplets existed from the generation point up under low gas flux conditions.

To describe the break-up of the large liquid slugs by vapor generation due to wall-slug collisions, which is active at low pressure, Bartak et al.(1994) suggested the following expression for the Sauter mean diameter due to slug break-up:

$$D_{32} = 1.05 \times 10^{-3}\left(\frac{\sigma}{g\Delta\rho}\right)\left(\frac{\rho_f + \rho_g}{\rho_g}\right). \tag{2}$$

I.Kataoka and M.Ishii (1984) proposed a mechanistic modeling of pool entrainment phenomenon. Through the comparison of the derived entrainment equation with the data of Rosen et al., they suggested a correlation which describes the maximum droplet diameter in pool entrainment. Assuming the distribution of upper limit log-normal, the mean diameter can be described as follows:

$$D_{32,pool} = 0.254 \times 7.24\frac{\sigma^{3/4}}{j_g(g\Delta\rho)^{1/4}\rho_g^{1/2}}. \tag{3}$$

It is not well clarified which parameters strongly affect the entrained droplet sizes at low mass flux. Up to now, it is found that the droplet size is dependent on the vapor mass flux as well as pressure. The demerit of the correlations describing the droplet sizes from the churn-turbulent surface is that they are derived from the data of limited pressure ranges. Therefore, it should be checked whether the effects of pressure and vapor velocity can be well described by these correlations.

2. Mechanistic Post-Dryout Model

Since 1960's, a significant number of post-dryout heat transfer prediction models are suggested on the basis of experimental results or analytical methods. In empirical correlations, it is assumed that the liquid is in thermal equilibrium with the vapor. However, some experimenters reported the evidence of vapor superheating in the post-dryout region. The fact that there exists thermal nonequilibrium makes the pure empirical correlations erroneous. Therefore, it is needed to develop new methods predicting post-CHF heat transfer characteristics which can deal with vapor nonequilibrium. These efforts resulted in the step-by-step calculation method. In these type of models, the hydrodynamic and thermal parameters are initially evaluated at the dryout location. And the downstream conditions are obtained on the basis of upstream conditions.

Among these models, the following model suggested by Varone and Rohsenow includes the main heat transfer mechanisms governing post-dryout:

$$\frac{dV_f}{dz} = -\frac{g}{V_f}\left(1-\frac{\rho_g}{\rho_f}\right) + \frac{3}{4}C_D\frac{\rho_g}{\rho_f}V_f(S-1)^2\frac{1}{D} \tag{4}$$

$$\frac{dD}{dz} = -2\left[\frac{h_{vd}(T_g-T_s)}{V_f\rho_f h_{fg}} + \frac{2}{3}\frac{D}{D_T}\frac{V_p}{V_f}\epsilon\right] \tag{5}$$

$$\frac{dx_a}{dz} = -3\frac{(1-x_a)}{D}\frac{dD}{dz} \tag{6}$$

$$\frac{dT_g}{dz} = \frac{4q_w''}{D_T G x_a C_{pv}} - \left[(T_g-T_s)+\frac{h_{fg}}{c_{pv}}\right]\frac{1}{x_a}\frac{dx_a}{dz} \tag{7}$$

The above model results in fairly good predictions at the flow conditions where dryout occurs in annular flow regime. However, the predictions by this model become poor at low mass flux at which flow regime before dryout is churn-turbulent or slug. An example of the temperature predictions at low mass flux by the model is presented in Fig. 1.

The poor prediction of the model at low mass flux is mainly due to the inappropriateness of some constitutive relations at this flow condition. Especially, the wall-vapor heat transfer model of Hadaller used in the original model is found to be invalid at low mass flux. In addition, the initial droplet diameters evaluated from the original model become unrealistically large. In the post-dryout region at low flow, it is recommendable to use the following wall-vapor heat transfer model of Webb and Chen (1984) derived from the data of low flow instead of the Hadaller one for the Varone and Rohsenow history-dependent post-dryout model:

$$h_{Webb-Chen} = h_{mod-CSO}(1+F_s)\left[1+0.8(z/D_T)^{-1}\right]. \tag{8}$$

As for the initial droplet diameter, there is no well verified correlation that can be used at low flow. This is a main obstacle to expand the availability of the mechanistic post-dryout model to the low flow regime.

3. Regression Analysis

In a bubbling pool or a low flow boiling channel, the bubbly flow regime is limited to a very small gas velocity. The transition criterion from slug to churn-turbulent flow regime is postulated to occur when the mean void fraction over the entire region exceeds that over the slug-bubble section. The transition criterion between churn-turbulent flow and annular flow had been developed by Ishii postulating two different mechanisms. The flow regime before dryout is believed to be annular when the mass flux is rather high and the dryout quality is moderate or high. However, the situation will be different if the mass flux is decreased. In Fig. 2, many experimental dryout conditions near 400 kPa are plotted on the flow regime map. It can be seen that most experimental dryout conditions are in churn-turbulent flow regime.

The experimental data showing the droplet size due to slug break-up in tube geometry are very scarce. In addition, the validity of existing correlations is very limited. In the present study, the droplet size after dryout is determined through computer simulation. The history-dependent post-dryout model of Varone and Rohsenow replaced by the Webb-Chen model for wall-vapor heat transfer is selected as a reference model. The simulation is done changing the initial droplet size and the droplet size which results in the best predictions of wall temperatures and vapor temperatures is selected. Through the present study, it is expected that the applicable range of the selected reference model is extended to the lower mass flux condition where the flow regime is churn-turbulent if the model is proved to be valid just modifying some constitutive relations in this flow condition.

62 cases of the Lehigh University experiment (Evans et al., 1983) and 34 cases of the INEL experiment (Gottula et al., 1985) are simulated. The simulated results are catagorized into 4 groups; very good prediction, fairly good prediction, not-bad prediction and bad prediction.

Among the analyzed cases, 34 cases of the Lehigh University experiment and 19 cases of the INEL experiment show good or reasonable temperature predictions for the selected initial droplet diameter. The prediction results for Lehigh University data near 400 kPa are given in Fig. 3. The predictions with the 1-D model become poor as the superficial vapor velocity approaches the slug-churn transition. Therefore, the one-dimensional post-dryout model is not applicable when the vapor superficial velocity is very low. This is due to the change of the main entrainment mechanism when the flow regime near the quench front changes from churn-turbulent to slug flow. In other words, the radial motion of droplet is not negligible and becomes important in the region of very low vapor superficial velocity.

The initial droplet sizes determined through the simulation are non-dimensionalized and plotted against non-dimensional superficial vapor velocities in Fig. 4. The experimental data of Lopes and Dukler (1986), which were obtained in the region of churn-annular boundary, are introduced for the smooth fitting. It can be noticed that the dimensionless Sauter mean diameters derived by the regression analysis are smoothly fitted into the Lopes and Dukler ones. The simulated results can be best-fitted by the following third-order polynomial:

$$D_{32}^{*} = 0.003087 - 0.00205 j_g^{*} + 5.2685 \times 10^{-4} \left(j_g^{*}\right)^2 - 4.5137 \times 10^{-5} \left(j_g^{*}\right)^3 . \tag{9}$$

4. Results and Discussions

To check the appropriateness and applicability of the above equation, it is compared with the existing correlations described previously. In the proposed correlation and the Kataoka correlation, the SMD of entrained droplets is dependent on superficial vapor velocity, j_g as well as pressure, while there exists only the pressure effect in the correlations suggested by Kocamustafaogullari and by Bartak.

The comparison results are shown in Fig. 5 for atmospheric pressure. The present correlation gives a very similar trend with the Kataoka correlation which is derived from atmospheric pressure data. At 200 kPa where the Bartak correlation is derived, the results from the present correlation remain around those from the Bartak correlation.

The correlation obtained through the regression analysis is included in the post-dryout heat transfer model and the effects of the correlation in the temperature prediction are analyzed.

The prediction results of wall and vapor temperatures for Lehigh University experimental data are shown in Fig. 6. Though there exist some deviations, the wall and vapor temperatures in the post-dryout channel at low mass flux can be reasonably predicted by the one-dimensional mechanistic post-dryout model when the initial droplet size is evaluated appropriately.

5. Conclusions

The flow regime just before the CHF point at core-uncovery or reflooding at low mass flux is churn-turbulent flow. Through the analysis, it is also suggested that the size of droplet generated from the churn-turbulent surface is dependent not only on the pressure but also on the vapor superficial velocity.

The applicability of 1-D mechanistic post-dryout model, which is originally valid at high mass flux conditions, is extended to the churn-turbulent region. This is achieved by showing that the model is applicable at low mass flux when the initial hydrodynamic parameters are evaluated appropriately. However, if the flow condition is in slug or bubbly flow, the prediction of 1-D model becomes poor. Therefore, it is presumed that a one-dimensional safety analysis code, such as RELAP5/MOD3, have limitation to describe the post-dryout flow at low mass flux because the radial motion of droplets plays an important role in that situation.

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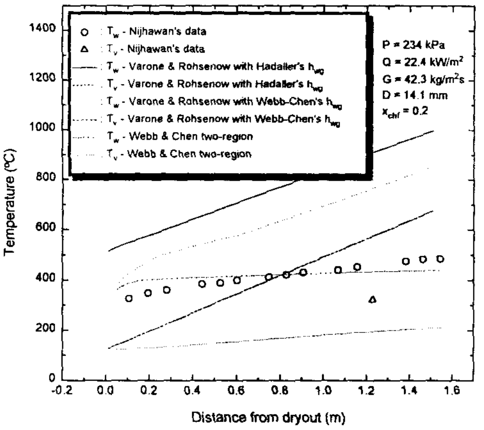

Fig. 1 Prediction results of post-dryout models for low mass flux

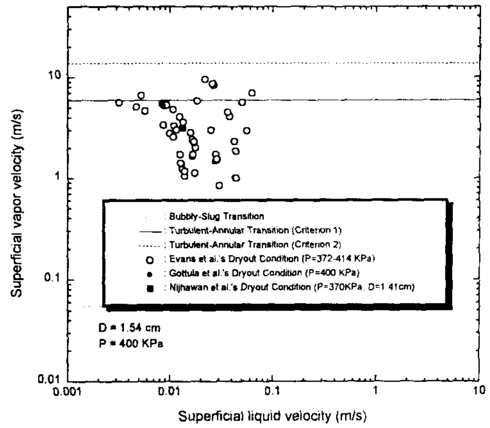

Fig. 2 Flow regime near dryout location at low flow (D = 1.54 cm, P = 400 KPa)

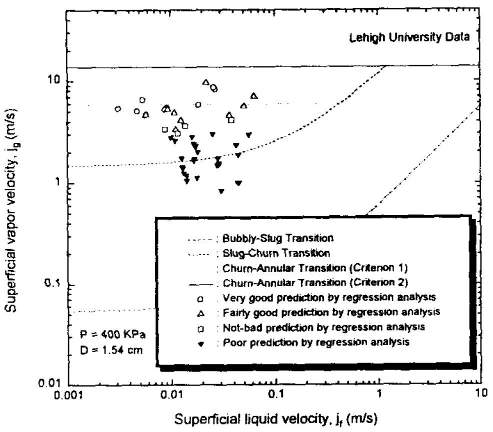

Fig. 3 Flow regime and applicability of the modified Varone and Rohsenow model (Lehigh University data)

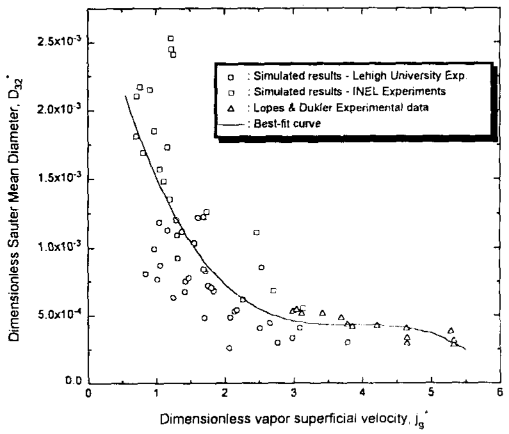

Fig. 4 Variation of Sauter mean diameter with vapor superficial velocity for various conditions

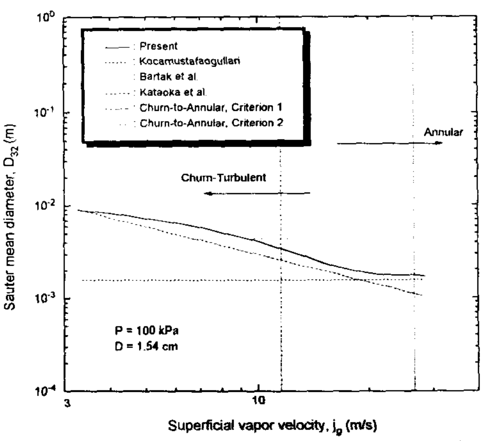

Fig. 5 Comparison of present correlation with other existing correlations at 100 kPa

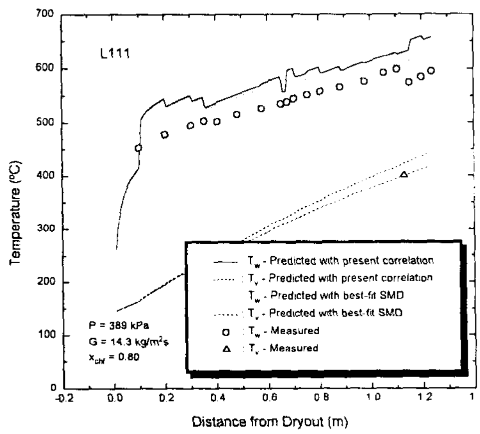

Fig. 6 Temperature predictions from present droplet size correlation for Lehigh Test No. 111