

DNB PREDICTION USING LOCAL VOID DISTRIBUTION IN HIGH QUALITY FLOW

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Abstract

A coupled code between a sub-channel analysis code and a computational multi-fluid dynamics code was developed for predicting departure from nucleate boiling (DNB). Local void fraction near the wall was used to define the onset of DNB. The local void fraction distribution in a sub-channel was determined by a bubble diffusion equation. To cover the flow regime at the high quality condition, a new source term was introduced. The present method was applied to the analysis of DNB test data including high quality condition. The result showed remarkable improvement of predictability by introducing the new source term.

1. Introduction

The departure from nucleate boiling (DNB) is an important phenomenon in designing the fuel assembly for the pressurized water reactor (PWR). One of the characteristic aspects of DNB is the variety of unsteady flow regimes in which DNB occurs [1]. Because of this variety of flow regimes, it is not realistic to model all of the mechanism involved in the phenomena. So is the reason why empirical correlations have been widely used to evaluate the DNB heat flux. These empirical methods however are not applicable to a new grid development, because they always require database obtained for existing grid designs. To predict the DNB performance of a new grid design, simulating a physical mechanism of DNB is important. Such a mechanistic model is useful for effective development of new grid design.

Various mechanistic models [2,3] have been proposed so far. Some of them successfully predict the DNB in rod bundle, however the physical basis of these models still remains uncertain. Weisman and Pei [3] proposed a DNB model, which illustrated the DNB as the bubble congestion to reach over a constant critical void fraction in a bubbly layer close to the heated wall. In this model, the local void fraction was evaluated by a simple two-layer model, and the model could not provide reasonable void fraction at thermal non-equilibrium condition in a non-uniform power distribution [4].

The purpose of this study is to use the local void fraction as only parameter for predicting the DNB heat flux. The coupling method was to use the new technology of computational multi-fluid dynamics (CMFD) together with abundant experience and models developed for sub-channel analysis codes. Average void fraction calculated in the sub-channel analysis code was responsible for representing boiling phenomena like wall boiling and sub-cooled boiling using

existing reliable correlations. The local parameters like liquid velocity, turbulence energy and void fraction in a sub-channel was calculated in a CMFD code.

The present method was applied to DNB test analyses. In Section 2 and Section 3, analysis methodology and analysis result are shown respectively. The conclusion is given in the Section 4.

2. Analysis methodology

2.1 Sub-channel analysis

Sub-channel analysis is conducted by use of VIPRE-01 [5]. This code was developed by Battelle Pacific Northwest Laboratories under the sponsorship of EPRI. The basic equations are the conservation laws for mass, energy and momentum based on homogeneous flow model.

The sub-channel analysis code also consists of several two-phase constitutive models. A sub-cooled boiling model and a void / quality relation model are used to calculate the void fraction, and a two-phase friction multiplier model is used to calculate the friction loss reflecting the two-phase modification. Some options are available for these two-phase constitutive models in Vipre-01. The default models are selected for all of them in the following analysis.

2.2 CMFD code for void distribution calculation

A CMFD code is developed to predict the void distribution in a rod bundle[6]. This code calculates two dimensional distributions of liquid velocity, turbulence energy and void fraction in sub-channel. The basic equations are the conservation laws for turbulence energy, axial momentum and the diffusion of bubble. The equation for turbulence energy of liquid phase is based on a one-equation mixing length model[7].

The diffusion equation of bubble[8,9] is

$$\frac{\partial}{\partial z} \{ \alpha w_g \} = \frac{\partial}{\partial x} \left(D_B \frac{\partial \alpha}{\partial y} \right) + \frac{\partial}{\partial y} \left(D_B \frac{\partial \alpha}{\partial x} \right) \quad (1)$$

where

$$D_B = \frac{1}{3} d_B w_l' = d_B \sqrt{\frac{2}{27} k_l} \quad (2)$$

The computational domain and the coordinate are shown in Figure 1. The computational domain covers an octa-symmetric region of sub-channel ($0 \leq \theta \leq 45$ degrees).

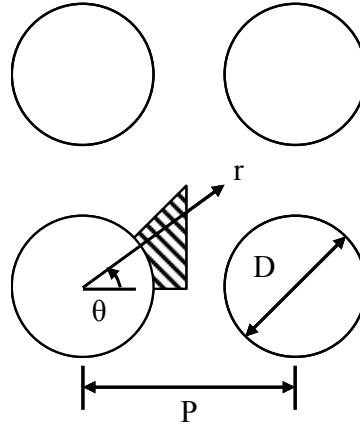


Figure 1 Computational domain in sub-channel

2.3 Codes coupling method

Channel averaged parameters calculated by the sub-channel analysis code are used in the CMFD code to predict two dimensional distribution of local void fraction in sub-channel. The calculation result of VIPRE-01 is used for the enthalpy in the basic equations of CMFD. Regarding void fraction, $\bar{\alpha}$ calculated by VIPRE-01 is inputted as the initial boundary condition of CMFD, that is α at the wall. To integrate CMFD with sub-channel analysis, CMFD calculation is iterated with modifying α at the wall, until $\bar{\alpha}$ in CMFD code agrees with that of VIPRE-01 within 1%. As for velocity, $\bar{w}$ of VIPRE-01 is used to calculate the pressure drop in CMFD, however $\bar{w}$ in CMFD code does not consistent with VIPRE-01. This mismatch is caused because CMFD code assumes idealized distribution of w by use of the wall function. Thus, the sub-channel analysis code and CMFD code are coupled to communicate global and local parameters. Typical result of the analysis is shown in Figure 2

2.4 DNB Prediction method

The DNB heat flux is predicted by the procedure shown in Figure 3. The test condition is inputted into VIPRE-01 coupled with the CMFD code, and three dimensional development of local void fraction in sub-channel is calculated.

Then, the void fraction near heated wall α_{BL} is compared with critical void fraction α_{crit} . The occurrence of DNB is defined as the condition in which α_{BL} agrees with α_{crit} within 0.5%. The calculation is iterated with modifying heat flux until the occurrence of DNB is recognized. Here, α_{BL} is defined as the averaged void fraction in the bubbly layer, whose thickness is estimated as $5.5d_B$ [3]. In typical case of this study, the thickness is approximately 0.05-0.2mm based on Levy's model. To locate a number of meshes within the bubbly layer, the grid number is set as $N_x \times N_y = 16 \times 16$. The value of α_{crit} is discussed in the following section.

The applicability of the DNB model using local void fraction to different working fluid was already confirmed through the analysis of DNB test using water and Freon[4], where the result showed the model could successfully predict the DNB independently from fluids.

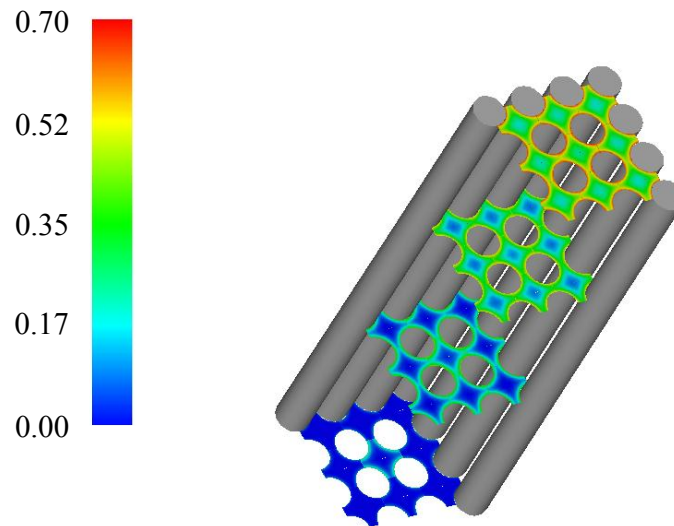


Figure 2 calculation result of void distribution

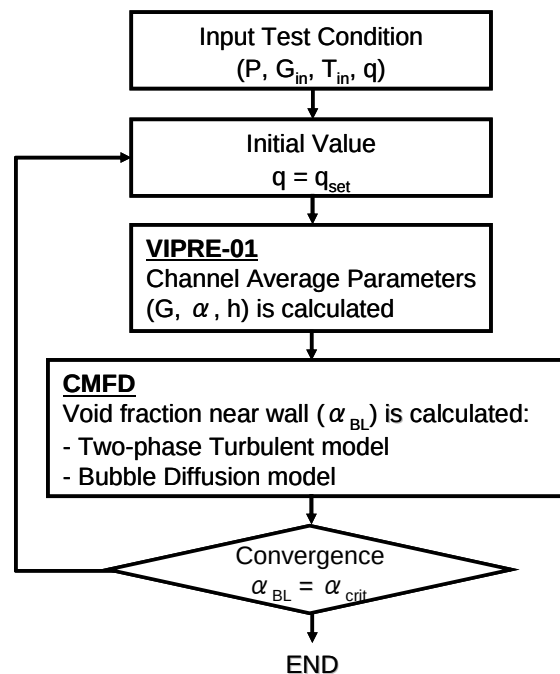


Figure 3 DNB prediction scheme

3. Analysis result

3.1 Analysis by the existing model

A set of Freon DNB test data using 5×5 rod bundle [10] are picked up for the validation of the present method because the test condition covers a variety of flow regimes. The main parameter of this test is shown in Table. 1.

Figure 4 and Figure 5 show the analysis result, where 0.82 is used for α_{crit} according to the model proposed by Weisman and Pei [3]. The predictability is reasonable when the channel averaged void fraction at DNB position $\bar{\alpha}_{DNB}$ is close to 0.2. However, the ratio of the measurements to the predictions (M/P) significantly deviates from 1.0 when the void fraction is very low or high. The reason for the overestimation in low quality condition is unreasonably high α_{crit} . The value 0.82 for α_{crit} was originally derived from the maximum void fraction at which bubbles exist separately from each other in bubbly layer. However DNB shows wide variety of flow regimes, and the experimental observation of DNB in low quality shows no bubble crowding near heated wall [1]. This suggests that using a single α_{crit} value through whole flow regimes is not valid, and lower value should be used for low void fraction. The underestimation in high void fraction is attributed to the applicability of the bubble diffusion equation for high quality flow. The flow is supposed to be churn turbulent flow or annular turbulent flow in high quality condition, while Eq.(1) assumes the simple wall peak distribution in bubbly flow. The basic equation for void distribution should be revised to handle flow regimes in high quality condition.

3.2 Gas volume flux of bubble diffusion

The analysis result shown in Figure 4 and Figure 5 suggests that a new arrangement of the critical void fraction and bubble diffusion equation depending on the flow regime is required to improve the predictability. From this point of view, classifying flow regimes is important to take into account different two-phase flow behavior. In this study, the flow regime of the Freon DNB test is categorized as Figure 6 by using Weber number and equilibrium quality. The boundary between isolated bubble nucleation type DNB and vapor clots type DNB is based on flow regime map reported by Le Corre [1]. Another boundary at $x_e=0.2$ represents a new category to classify the churn turbulent flow at high quality, where the dependence of the DNB heat flux on the quality is sharply changed [11]. Based on this flow regime map, the improvement of the predictability is attempted by modifying model as described below.

Regarding isolated bubble nucleation type DNB, α_{crit} is revised to take into account the mismatch between the assumption for original value 0.82 and the experimental observation. To converge M/P into 1.0, the value of α_{crit} is reduced to 0.4.

As for churn turbulent flow type DNB, α_{crit} remains 0.82, while the bubble diffusion equation is modified to handle high quality flow by introducing new source term. Kataoka [12] proposed a void transport model for churn flow in round tube, and the analysis result using this model well reproduced experimental data of radial void distribution. This model takes into account the gas volume flux caused by the wake of large bubble in churn flow as schematically shown in Figure 7. The gas volume flux is assumed to be proportional to the channel averaged void fraction and the distance from the center of pipe,

$$J_c = K_c \frac{r}{R} \{0.35\sqrt{gD}\} \bar{\alpha} \quad (3)$$

By introducing the gas volume flux represented by Eq. (3), the bubble diffusion equation in round tube can be written as,

$$\frac{\partial}{\partial z} \{\alpha w_g\} = \frac{1}{r} \frac{\partial}{\partial r} \left(r D_B \frac{\partial \alpha}{\partial r} \right) + K_c \frac{0.35\sqrt{gD}}{R} \bar{\alpha} \quad (4)$$

As shown in Eq. (4), the effect due to the wake of churn flow appears as a source term in bubble diffusion equation. In this analysis, similar source term to Eq. (4) is introduced into the bubble diffusion Eq. (1) with small modification,

$$\frac{\partial}{\partial z} \{\alpha w_g\} = \frac{\partial}{\partial x} \left(D_B \frac{\partial \alpha}{\partial y} \right) + \frac{\partial}{\partial x} \left(D_B \frac{\partial \alpha}{\partial y} \right) + A \bar{\alpha} + B \quad (5)$$

The values for A and B are determined to reproduce reasonable void distribution in churn turbulent flow. The value of the source term is evaluated for each test case by iterating calculation with changing the source term until M/P converges to 1. Figure 8 shows the relation between the calculation result of the optimum source term and $\bar{\alpha}_{DNB}$. As shown in Figure 8, the optimum source term is well correlated with $\bar{\alpha}_{DNB}$, and the larger source term is obtained for the higher void fraction. Based on the fitted line for the source term shown in Figure 8, the values for A and B are set at 305.5 and 164.1 respectively.

Table. 1 DNB test parameters

Rod bundle configuration	5×5
Rod diameter (mm)	9.5
Heated length (m)	2.0
Power distribution	uniform
Pressure (MPa)	1.6 - 3.2
Mass flux(kg/m ² s)	800 - 3600

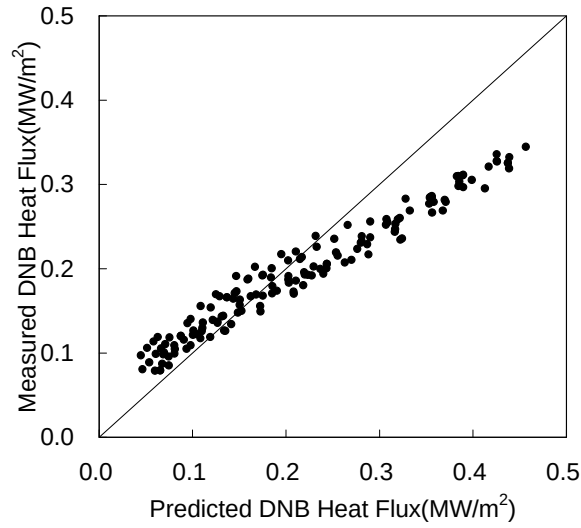


Figure 4 DNB heat flux ($\alpha_{crit} = 0.82$)

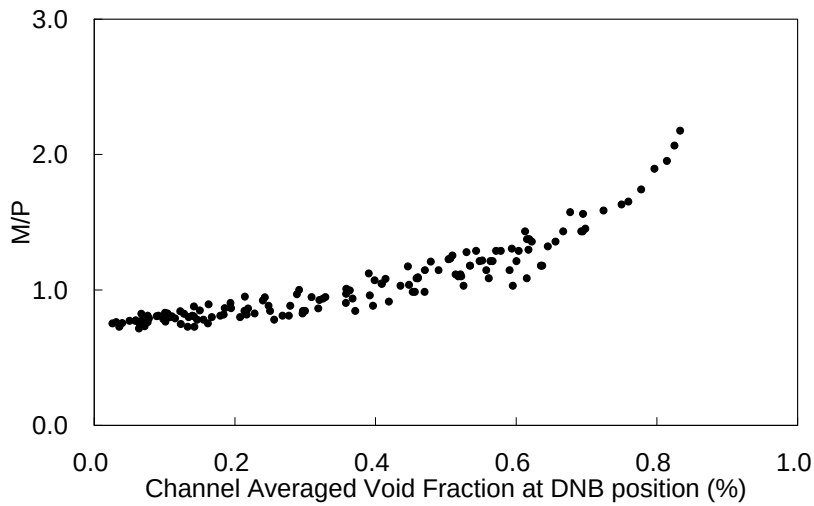


Figure 5 M/P of DNB heat flux and $\bar{\alpha}_{DNB}$ ($\alpha_{crit} = 0.82$)

3.3 Analysis by the new model

Finally, the analysis is performed again with revised α_{crit} and bubble diffusion equation. The results are shown in Figure 9 and Figure 10. The trend of M/P is improved in isolated bubble nucleation type DNB and churn turbulent flow type DNB. As a result, the DNB heat flux is reasonably predicted through the whole range of void fraction. However the predictability degrades around the boundary between each flow regime, for example at low and high void fraction in vapor clot type DNB. This degradation is considered to be caused by rough classification of flow regimes. Especially the mismatched categorization seems to occur at the

boundary ($x_e=0.2$), because a dependence on We is neglected here and the quality may not be enough parameter to separate the vapor clots type DNB and the churn turbulent flow type DNB. Another issue is large deviation of M/P in churn turbulent flow type DNB. Since the physical basis of new source term in the present bubble diffusion equation is not clear quantitatively, further development of the bubble diffusion equation is required to improve the predictability.

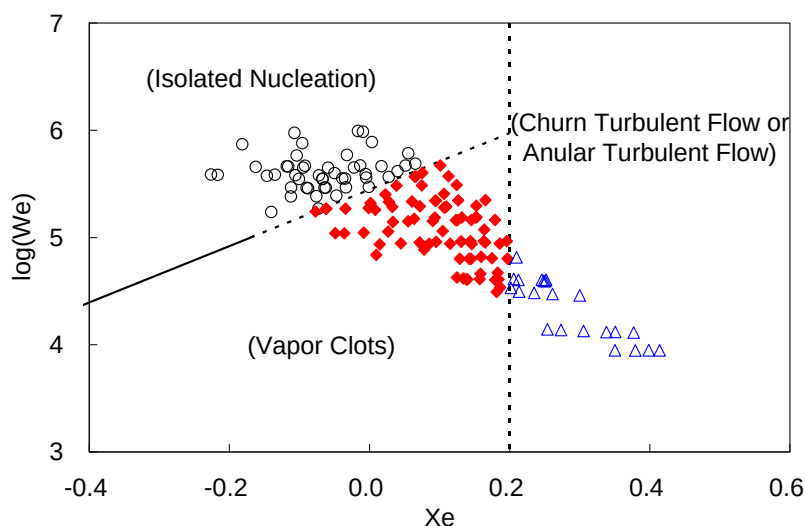


Figure 6 Freon DNB test data with flow regime

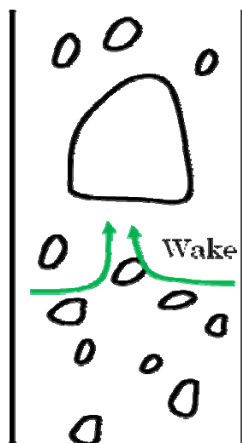


Figure 7 Wake in churn flow regime

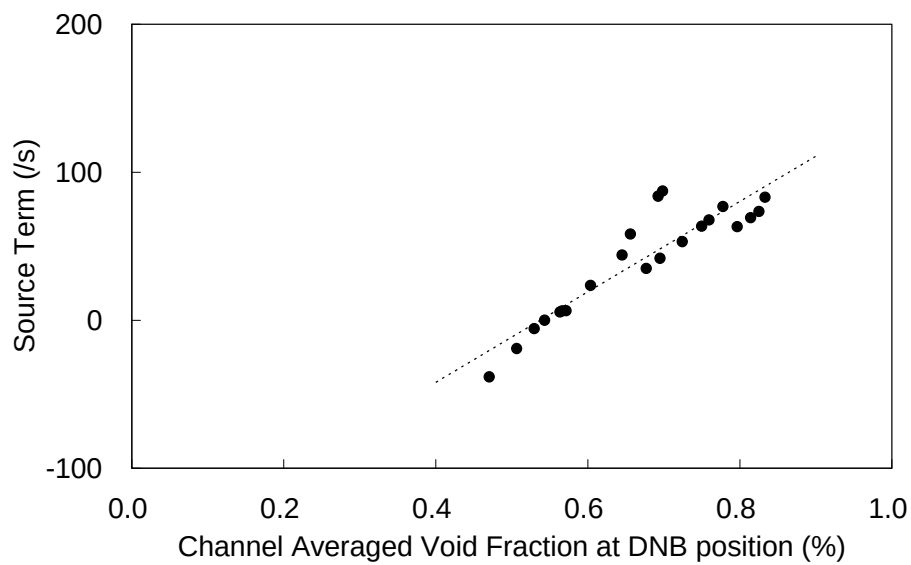


Figure 8 Relation between optimum source term and $\bar{\alpha}_{DNB}$

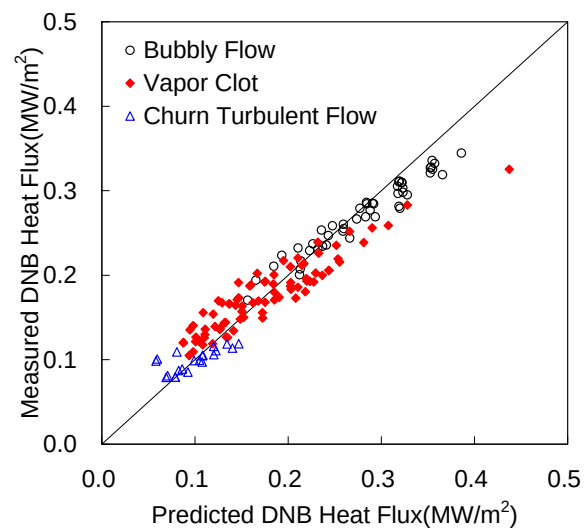


Figure 9 DNB heat flux (modified model)

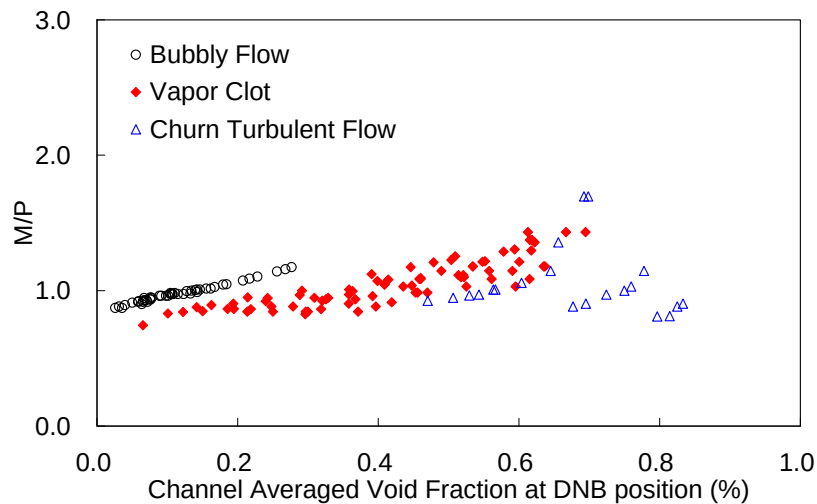


Figure 10 M/P of DNB heat flux and $\bar{\alpha}_{DNB}$ (modified model)

4. Conclusion

A DNB prediction model using the local void fraction was proposed. To implement this model, a coupled code between a sub-channel analysis code and a CMFD code was developed.

The present method was applied to the analysis of DNB test data including high quality condition. The first analysis without classification of flow regimes showed necessity to revise the critical condition and bubble diffusion equation depending on corresponding flow regime.

The model was modified to use reduced critical void fraction for isolated bubble nucleation type DNB and revised bubble diffusion equation for churn turbulent flow type DNB. The analysis performed again using modified model showed improvement of the predictability. However, the following items still remain as the future issue.

- The development of the source term with physical basis in the bubble diffusion equation is required to improve the predictability for churn turbulent flow DNB type.
- Detailed DNB flow regime map is needed to improve the predictability at the boundary between flow regimes, especially for the boundary between the vapor clots type DNB and the churn turbulent flow type DNB.

5. Nomenclature

A, B	constants	T	Temperature
d_B	average bubble diameter	w	velocity in z-coordinate
D	pipe diameter	We	Weber number
g	gravity	x_e	equilibrium quality
G	mass flux	(Greek symbols)	
h	enthalpy	α	void fraction
J_C	gass volume flux	(Subscripts)	
k	turbulence energy	g	gas phase
K_C	constant (0.015)	l	liquid phase
P	pressure	(Superscripts)	
q	heat flux	$\bar{\phi}$	spatially averaged value of ϕ
R	pipe radius		

6. References

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