ASSESSMENT OF FLUID-TO-FLUID MODELLING OF CRITICAL HEAT FLUX IN HORIZONTAL 37-ELEMENT BUNDLE FLOWS

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ABSTRACT

Fluid-to-fluid modelling laws of critical heat flux (CHF) available in the literature were reviewed. The applicability of the fluid-to-fluid modelling laws was assessed using available data ranging from low to high mass fluxes in horizontal 37-element bundles simulating a CANDU® fuel string. Correlations consisting of dimensionless similarity groups were derived using modelling fluid data (Freon-12) to predict water CHF data in horizontal 37-element bundles with uniform and non-uniform axial-heat flux distribution (AFD). The results showed that at mass fluxes higher than ~4,000 kg/m^{2}s (water equivalent value), the vertical fluid-to-fluid modelling laws of Ahmad (1973) and Katto (1979) predict water CHF in horizontal 37-element bundles with non-uniform AFD with average errors of 1.4% and 3.0% and RMS errors of 5.9% and 6.1%, respectively. The Francois and Berthoud (2003) fluid-to-fluid modelling law predicts CHF in non-uniformly heated 37-element bundles in the horizontal orientation with an average error of 0.6% and an RMS error of 10.4% over the available range of 2,000 to 6,200 kg/m^{2}s.

Key Words: Fluid-to-Fluid Modelling, Critical Heat Flux (CHF), Horizontal Flow, Correlations, 37-Element Bundles

1. INTRODUCTION

Critical heat flux (CHF) is of importance in nuclear reactor design and thermalhydraulic analysis. However, experiments to measure CHF in water flow at high temperature and high pressure, simulating water-cooled reactor operation conditions, are complex and costly. Fluid-to-fluid modelling is therefore of practical significance in reducing the high cost of CHF testing applicable to water-cooled reactors. Water at high temperature and pressure is replaced by a modelling fluid having a lower latent heat of vaporization with lower saturation temperature and pressure.

Ahmad (1973) developed a generalized technique for vertical fluid-to-fluid modelling of CHF in vertical tubes. The model was tested for various Freon compounds, water, potassium, and carbon dioxide, over a large range of flow conditions. Katto (1979) suggested a mass-scaling factor in a generalized correlation for CHF in vertical tubes, and examined the validity of the model using different fluids.

The horizontal configuration of CANDU-reactor channels requires horizontal fluid-to-fluid modelling that adequately accounts for the flow orientation effect on CHF. While the fluid-to-fluid modelling for CHF in vertical tubes has been well established, horizontal fluid-to-fluid modelling is still in the development stage.

Merilo (1979) suggested a fluid-to-fluid model for CHF in horizontal tubes. The model was derived by adding a term representing the effect of gravity to the vertical fluid-to-fluid law. Ahmad *et al*. (1982) attempted to establish a horizontal CHF modelling criterion for 37-element bundles with uniform AFD. Leung and Groeneveld (2000) examined the applicability of vertical fluid-to-fluid modelling laws for CHF in 37-element bundles, and observed that at high-pressure and high-flow conditions of interest, the water-equivalent values of the Freon-test data closely represent the water-test data of uniformly and non-uniformly heated bundle strings for vertical and horizontal flows.

The objectives of this study are to review and assess fluid-to-fluid scaling laws that are available in the literature, and to quantify the applicability of fluid-to-fluid modelling for available data ranging from low to high mass fluxes in horizontal 37-element bundles with uniform and non-uniform AFD.

2. FLUID-TO-FLUID MODELLING REVIEW

Similarities of fluid-to-fluid modelling in vertical or horizontal flows are described as below:

2.1 Geometric Similarity

The geometric similarity for the modelling fluid (M) and working fluid (W) can be achieved using the same L/D ratio, *i.e.*,

$$\left(\frac{L}{D}\right)_M = \left(\frac{L}{D}\right)_W \tag{1}$$

2.2 Pressure Similarity

The same density ratio of liquid to vapour, ρ_f / ρ_g, is required for pressure similarity.

$$\left(\frac{\rho_f}{\rho_g}\right)_M = \left(\frac{\rho_f}{\rho_g}\right)_W \tag{2}$$

2.3 Thermodynamic Similarity

For thermodynamic similarity, the subcooling number ($\Delta H_i/H_{fg}$) is fixed at the inlet location in both systems.

$$\left(\frac{\Delta H_i}{H_{fg}}\right)_M = \left(\frac{\Delta H_i}{H_{fg}}\right)_W \tag{3}$$

The thermodynamic similarity can also be established in terms of the thermodynamic quality

(x_{do}) at the axial dryout location in both systems by employing the heat balance equation.

$$x_{do}(z)_M = x_{do}(z)_W \tag{4}$$

2.4 Critical Heat Flux

The Boiling number (Bo) similarity for the modelling fluid and working fluid is given as

$$Bo = \left(\frac{q_c}{GH_{fg}}\right)_M = \left(\frac{q_c}{GH_{fg}}\right)_W \tag{5}$$

2.5 Mass Flux

(1) Vertical Orientation
Ahmad (1973) suggested a compensated distortion technique to develop a generalized model for fluid-to-fluid modelling for CHF in vertical flows. Ahmad identified the distorted dimensionless variables due to fixing the controllable parameters in Equations (1), (2) and (3). Using experimental CHF data in various fluids, Ahmad (1973) proposed the following modelling parameter to determine the scaling of mass flux:

$$\Psi_{Model\ para} = \left[\left(\frac{GD}{\mu_f}\right)\left(\frac{\mu_f^{\ 2}}{\sigma D\rho_f}\right)^{2/3}\left(\frac{\mu_f}{\mu_g}\right)^{-1/5}\right]_M = \left[\left(\frac{GD}{\mu_f}\right)\left(\frac{\mu_f^{\ 2}}{\sigma D\rho_f}\right)^{2/3}\left(\frac{\mu_f}{\mu_g}\right)^{-1/5}\right]_W \tag{6}$$

Katto (1978, 1979) and Katto and Ohno (1984) developed generalized correlations for CHF in vertical, uniformly heated tubes. In particular, Katto (1979) proposed a dimensionless parameter that determines the mass-flux scaling:

$$\left(\frac{\sigma\rho_f}{G^2 D}\right)_M = \left(\frac{\sigma\rho_f}{G^2 D}\right)_W \tag{7}$$

The above dimensionless parameter can be replaced with $GD^{1/2}/\left(\sigma^{1/2}\rho_f^{\ 1/2}\right)$, which is defined as the Weber number. Thus the Katto modelling parameter is given as:

$$\Psi_{Model\ para} = \left(\frac{GD^{1/2}}{\sigma^{1/2}\rho_f^{\ 1/2}}\right)_M = \left(\frac{GD^{1/2}}{\sigma^{1/2}\rho_f^{\ 1/2}}\right)_W \tag{8}$$

(2) Horizontal Orientation
Merilo (1979) suggested a modelling parameter for the fluid-to-fluid modelling for CHF in a horizontal tube using the Ahmad (1973) method of compensated distortion. The fluids used

were water and Freon-12. The Bond number (B_d) was introduced to account for gravity effects in horizontal flows, which is defined as:

$$B_d = \left(\rho_f - \rho_g\right) g D^2 / \sigma \tag{9}$$

Merilo (1979) derived a dimensionless correlation for CHF in horizontal tubes using available data (water and Freon-12), and suggested a horizontal modelling parameter given as:

$$\Psi_{Model\ para} = \left[\frac{GD}{\mu_f}\left(Z^3 B_d\right)^{-1.05}\left(\frac{\mu_f}{\mu_g}\right)^{6.41}\right]_M = \left[\frac{GD}{\mu_f}\left(Z^3 B_d\right)^{-1.05}\left(\frac{\mu_f}{\mu_g}\right)^{6.41}\right]_W \tag{10}$$

where

$$Z = \frac{\mu_f}{(\sigma\ D\rho_f)^{1/2}}$$

Ahmad *et al*. (1982) made an attempt to establish a horizontal CHF fluid-to-fluid modelling criterion for long complex geometries using bundle data. They stated that modelling of CHF in horizontal long multi-rod bundles was feasible for the case where full-scale geometries were used. They suggested a modelling parameter with a modified Boiling number ($Bo*$) for horizontal flows as:

$$\Psi_{Model\ para} = \left[\frac{GD}{\mu_f}\left(\frac{gD^{0.5}\mu_f^{\ 3}}{\rho_f^{\ 0.5}\sigma^{2.5}}\right)^{0.542}\left(\frac{\mu_f}{\mu_g}\right)^{-1.55}\right]_M = \left[\frac{GD}{\mu_f}\left(\frac{gD^{0.5}\mu_f^{\ 3}}{\rho_f^{\ 0.5}\sigma^{2.5}}\right)^{0.542}\left(\frac{\mu_f}{\mu_g}\right)^{-1.55}\right]_W \tag{11}$$

$$Bo* = \left(\frac{q_c D}{H_{fg}\mu_g}\right)_M = \left(\frac{q_c D}{H_{fg}\mu_g}\right)_W \tag{12}$$

where $Bo*$ is the modified Boiling number.

(3) Inclined Orientation

Francois and Berthood (2003) proposed a parameter for CHF modelling in inclined rectangular channels. Freon-12 was used as the modelling fluid. They derived a dimensionless correlation for CHF and deduced the following modelling parameter:

$$\Psi_{Model\ para} = \left[\mathrm{Re}_m\left(\frac{\mu_f^{\ 2}}{\sigma D\rho_f}\right)^{-0.476}\left(\frac{\mu_f}{\mu_g}\right)^{1.765}\right]_M = \left[\mathrm{Re}_m\left(\frac{\mu_f^{\ 2}}{\sigma D\rho_f}\right)^{-0.476}\left(\frac{\mu_f}{\mu_g}\right)^{1.765}\right]_W \tag{13}$$

where

$$\mathrm{Re}_m = \frac{GD}{\mu_f - \frac{L_w^3 g \sin\theta}{GD}\left[\rho_f(\rho_f - \rho_g) - x(\rho_f - \rho_g)^2\right]} \tag{14}$$

here, θ is an angle from the vertical axis, and L_w is a weighting factor having a unit of length that is determined by optimising the prediction using experimental data.

The dimensionless groups applicable to fluid-to-fluid modelling for critical heat flux in different flow orientations, which are described above, are listed in Table 1. The models were tested for flows in horizontal 37-element bundles. Note that the Ahmad (1973), Katto (1979) and Merilo (1979) models were derived based on tube data, the Ahmad *et al*. (1982) model is based on bundle data, and the Francois and Berthoud (2003) model is based on rectangular channel data.

Table 1 Dimensionless Groups Used for Fluid-to-Fluid Modelling of Critical Heat Flux

Reference	Pressure	Modelling Parameter, $\Psi_{Model\ para}$	Geometry	Inlet Sub-Cooling	CHF	Flow Orientation
Ahmad (1973)	$\frac{\rho_f}{\rho_g}$	$\left(\frac{GD}{\mu_f}\right)\left(\frac{\mu_f^2}{\sigma D \rho_f}\right)^{2/3}\left(\frac{\mu_f}{\mu_g}\right)^{-1/5}$	$\frac{L}{D}$	$\frac{\Delta H_i}{H_{fg}}$	$\frac{q_c}{GH_{fg}}$	Vertical (Tube)
Katto (1979)	$\frac{\rho_f}{\rho_g}$	$\frac{GD^{1/2}}{\sigma^{1/2}\rho_f^{1/2}}$	$\frac{L}{D}$	$\frac{\Delta H_i}{H_{fg}}$	$\frac{q_c}{GH_{fg}}$	Vertical (Tube)
Merilo (1979)	$\frac{\rho_f}{\rho_g}$	$\frac{GD}{\mu_f}\left(Z^3 B_d\right)^{-1.05}\left(\frac{\mu_f}{\mu_g}\right)^{6.41}$ where $B_d = \frac{(\rho_f - \rho_g) g D^2}{\sigma}$, and $Z = \frac{\mu_f}{(\sigma D \rho_f)^{1/2}}$	$\frac{L}{D}$	$\frac{\Delta H_i}{H_{fg}}$	$\frac{q_c}{GH_{fg}}$	Horizontal (Tube)
Ahmad *et al*. (1982)	$\frac{\rho_f}{\rho_g}$	$\frac{GD}{\mu_f}\left(\frac{gD^{0.5}\mu_f^3}{\rho_f^{0.5}\sigma^{2.5}}\right)^{0.542}\left(\frac{\mu_f}{\mu_g}\right)^{-1.55}$	$\frac{L}{D}$	$\frac{\Delta H_i}{H_{fg}}$	$\frac{q_c D}{H_{fg}\mu_g}$	Horizontal (Bundle)
Francois and Berthoud (2003)	$\frac{\rho_f}{\rho_g}$	$\mathrm{Re}_m\left(\frac{\mu_f^2}{\sigma D \rho_f}\right)^{-0.476}\left(\frac{\mu_f}{\mu_g}\right)^{1.765}$ where $\mathrm{Re}_m = \frac{GD}{\mu_f - \frac{L_w^3 g \sin\theta}{GD}\left[\rho_f(\rho_f-\rho_g) - x(\rho_f-\rho_g)^2\right]}$ where L_w is weighting length θ : Inclination to the vertical [°]	$\frac{L}{D}$	$\frac{\Delta H_i}{H_{fg}}$	$\frac{q_c}{GH_{fg}}$	Inclined (Rectangular channel)

3. ASSESSMENT METHOD

Experimental data for the working fluid and modelling fluid at equivalent flow conditions are essential to assess fluid-to-fluid modelling laws. Point-by-point comparison is ideal but it is not usually possible to find perfectly matching data sets for both fluids, depending on fluid-to-fluid modelling laws. But comparison of multiple data points (modelling fluid vs. working fluid) can be made using CHF correlations derived from experimental data. Experimental data for CHF correlations can be based on the modelling fluid (Ahmad *et al*. 1982), the working fluid (Francois and Berthoud 2003) or both fluids (Merilo 1979). In this study, CHF correlations were derived using modelling fluid data and subsequently used to assess the fluid-to-fluid modelling laws. CHF correlations were derived based on local conditions (P, G and $x_{do}(z)$). The correlations can be expressed in terms of dimensionless variables by:

$$Bo = A + B \cdot x_{do}(z) \tag{15}$$

where

$$A = a_1 \left(\frac{\rho_f}{\rho_g}\right)^{a_2} \left(\Psi_{Model\ para}\right)^{a_3} \tag{16}$$

$$B = b_1 \left(\frac{\rho_f}{\rho_g}\right)^{b_2} \left(\Psi_{Model\ para}\right)^{b_3} \tag{17}$$

A linear relationship has been assumed between boiling number and dryout quality since both water and Freon data exhibit a linear relation between these parameters. This approach is different from that used in previous studies (Ahmad 1973, Merilo 1979, Ahmad *et al*. 1982, and Francois and Berthoud 2003) where the inlet subcooling number was used instead of the local quality at the dryout location ($x_{do}(z)$). Boiling number correlations having the forms given by Eqs. (15) – (17) were derived using modelling fluid data (*e.g.*, Freon), and subsequently used to predict Boiling numbers for water data.

4. ASSESSMENT OF FLUID-TO-FLUID MODELLING IN HORIZONTAL BUNDLE FLOWS

4.1 37-Element Bundles with Uniform AFD

The vertical models (Ahmad 1973, Katto 1979) were applied to predict the Boiling number of water in horizontal 37-element bundles with a uniform AFD (Ahmad *et al*. 1982): mass-flux ranged from 2,100 to 4,700 kg/m^{2}s. The results showed that at mass fluxes higher than ~4,000 kg/m^{2}s, the correlations of Ahmad and Katto models predict Boiling numbers of water with average errors of 5.2% and 2.3% and RMS errors of 8.4% and 7.2%, respectively. At mass fluxes below 4,000 kg/m^{2}s, the prediction errors become larger and can be up to 100% at the lowest mass fluxes. Predictions errors for mass fluxes greater than 4,000 kg/m^{2}s are listed in

Table 2. It was found that the Merilo (1979) horizontal fluid-to-fluid modelling was not satisfactory for bundle flows, which was noted by Ahmad *et al.* (1982).

Table 2 Prediction Errors Using Freon-Based Correlations to Predict Boiling Number in Water Flows

Model	ADF	Prediction Errors	
		Average Error (%)	RMS error (%)
Ahmad (1973)*	Uniform	5.2	8.4
	Non-uniform	1.4	5.9
Katto (1979)*	Uniform	2.3	7.2
	Non-uniform	3.0	6.1
Ahmad *et al*. (1982)	Uniform	3.8	12.3
	Non-uniform	-13.3	15.9
Francois and Berthoud (2003)**	Uniform	4.7	13.3
	Non-uniform	0.6	10.4

* Mass flux range greater than 4,000 kg/m^2s

* * The weighting, L_w, in the model was optimised (L_w = 0.54 mm for uniform AFD and 0.47 mm for non-uniform AFD)

The Ahmad *et al*. (1982)'s law for horizontal flows predicts the modified Boiling number (Eq. 12) of water in horizontal 37-element bundles with a uniform AFD, with an average error of 3.8% and an RMS error of 12.3%.

The Francois and Berthoud (2003)'s law predicts the Boiling number of water in horizontal 37-element bundles with a uniform AFD with an average error of 4.7% and an RMS error of 13.3%. To get this level of agreement, the weighting factor was optimised to a value of 0.54 mm in uniformly heated 37-element bundles.

4.2 37-Element Bundles with Non-Uniform AFD

Fluid-to-fluid modelling with the modelling fluid (Freon-12), and working fluid (water) was examined for 37-element bundles with the same geometry, non-uniform AFD and RFD (radial flux distribution). The boiling-length-average (BLA) heat-flux approach was applied to account for the effect of axial heat-flux distribution on CHF:

$$q_{BLA} = \frac{1}{z_{DO} - z_{OSV}} \int_{z_{OSV}}^{z_{DO}} q_{local} dz \tag{18}$$

where z_{DO} and z_{OSV} are the axial locations at the dryout and the onset of significant void (OSV), respectively, q_{local} is the local heat flux in kW/m^2, and z is the axial distance in metres.

The Ahmad (1973)'s model was applied to horizontal flows to assess the applicability of the vertical law in horizontal flow, as presented in Figure 1, using water data sets: mass-flux ranged from 2,000 to 6,200 kg/m^{2}s. At mass flux model parameter greater than ~6 (around 4,000 kg/m^{2}s mass flux at 9.4 MPa), the model predicted water data with an average error of 1.4% and an RMS error of 5.9%, indicating that the Ahmad (1973)'s vertical law is applicable for mass fluxes in excess of 4,000 kg/m^{2}s in horizontal 37-element bundle flows with a non-uniform AFD. At mass flux model parameters lower than ~6, the prediction errors become larger and can be up to 120%. It is interesting to note that the Ahmad model predicts water data better for non-uniformly heated bundles than for uniformly heated bundles (see Table 2). The Katto (1979)'s vertical fluid-to-fluid model was also applied to horizontal flows, as shown in Figure 2. At *We* numbers higher than ~130 (around 4,000 kg/m^{2}s mass flux at 11 MPa), the model predicted water data with an average error of 3.0% and an RMS error of 6.1%. At lower *We* numbers, the prediction errors become larger and can be up to 85% in the present data range.

The Ahmad *et al.* (1982)'s horizontal fluid-to-fluid law was applied to the 37-element bundle with non-uniform AFD. The prediction showed a large bias with an average error of –13.3% and an RMS error of 15.9% (Table 2).

The Francois and Berthoud (2003) model was applied to the 37-element bundle with non-uniform AFD as shown in Figures 3 and 4. Figure 4 is shown additionally for this model to examine the error distribution with respect to the Boiling number. The prediction errors were obtained with an average of 0.6% and an RMS of 10.4%. All data are mostly within ±15% while some data showed higher errors up to 50% at modelling parameters lower than 10x10^{-10}. The weighting factor was obtained as 0.47 mm in non-uniformly heated 37-element bundles, which is different from the value of 0.54 mm for the uniformly heated 37-element bundle. Further investigation is required to assess the generality of the Francois and Berthoud model.

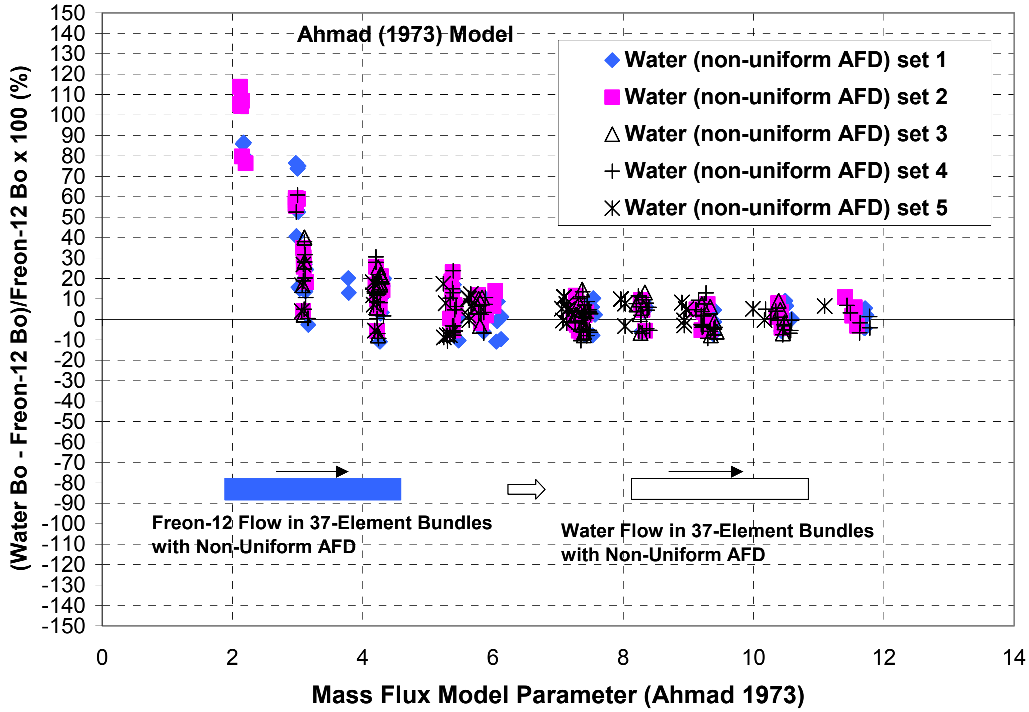

Figure 1 Application of Ahmad (1973)'s Vertical Law to Horizontal Flows in 37-Element Bundles with Non-Uniform AFD

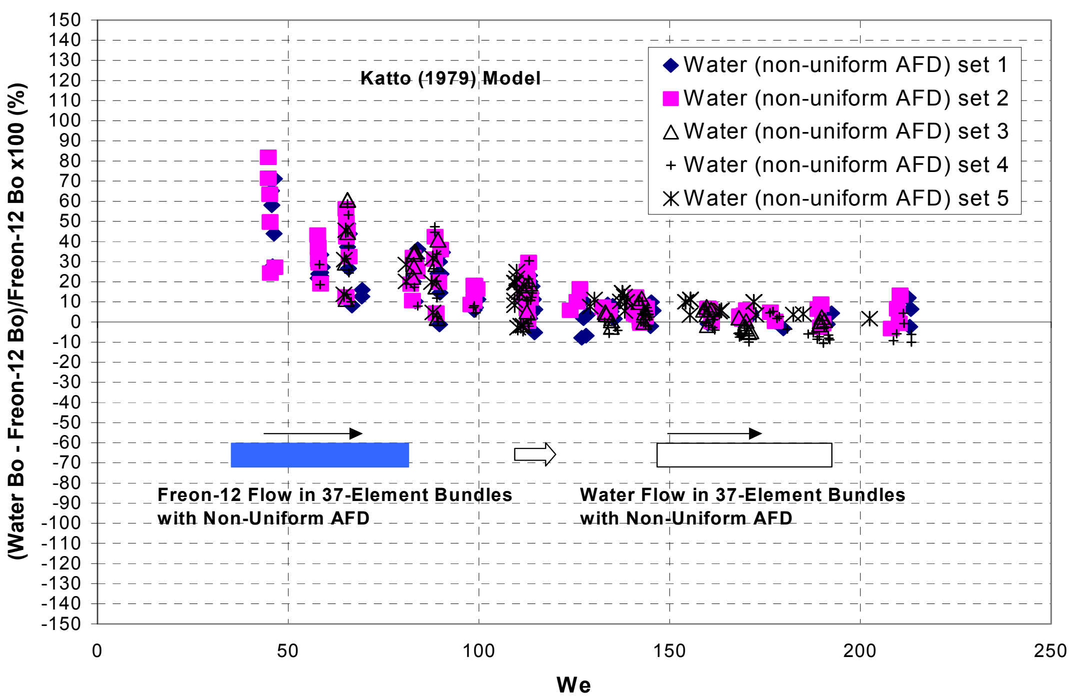

Figure 2 Application of Katto (1979)'s Vertical Law to Horizontal Flows in 37-Element Bundles with Non-Uniform AFD

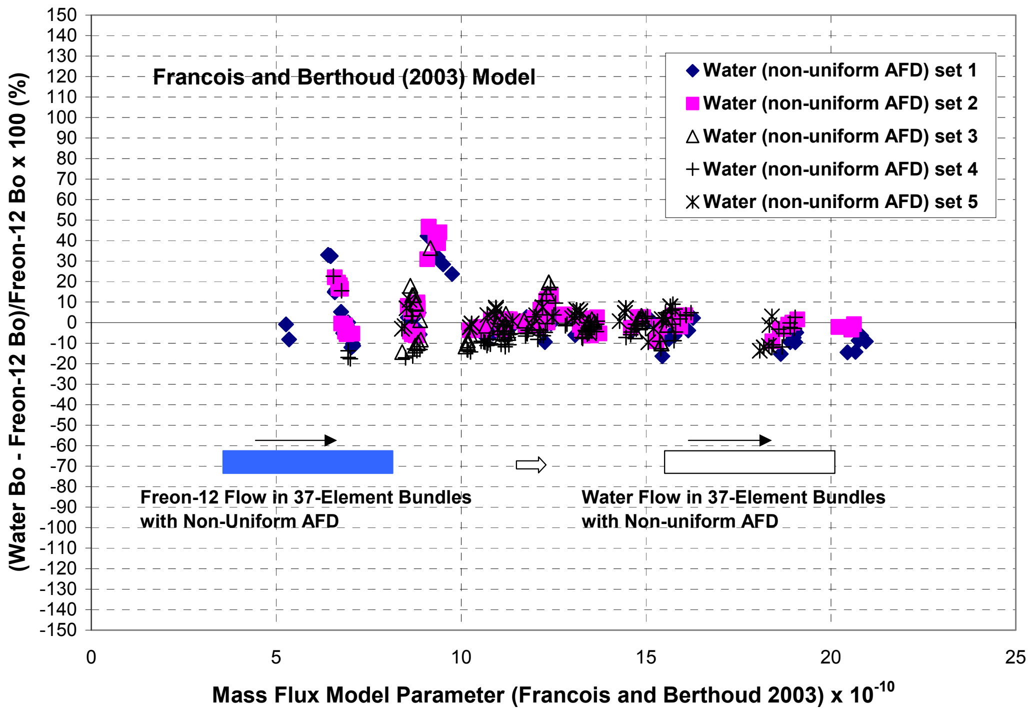

Figure 3 Francois and Berthoud (2003) Model in Horizontal 37-Element Bundles with Non-Uniform AFD

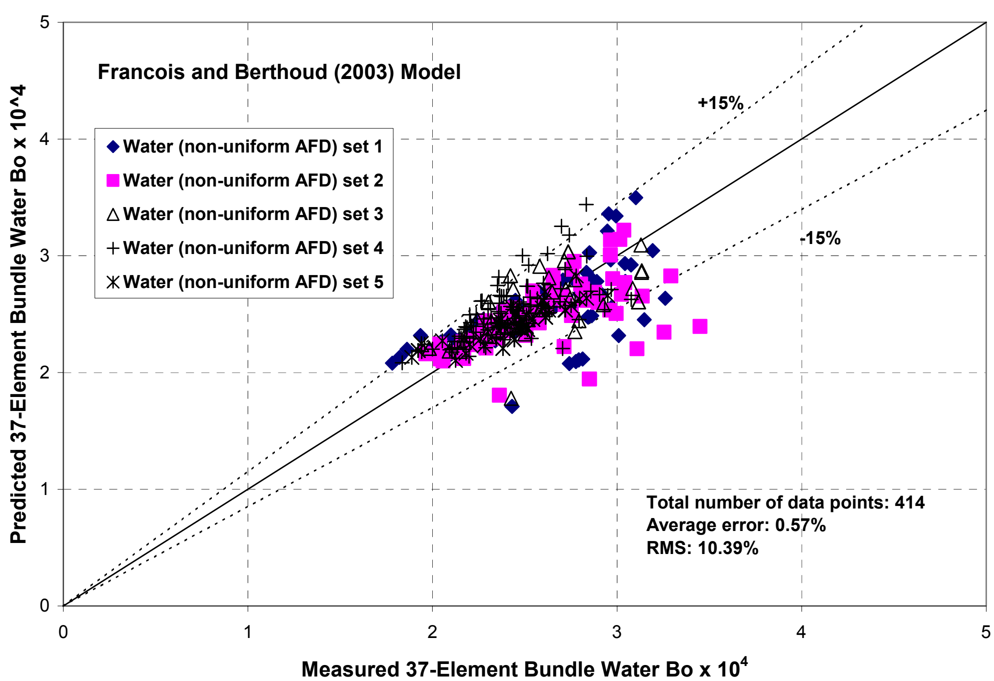

Figure 4 Comparison of Predicted and Measured Boiling Number for the Francois and Berthoud (2003) Model in Horizontal 37-Element Bundles with Non-Uniform AFD

5. CONCLUDING REMARKS

The available fluid-to-fluid scaling laws for critical heat flux were reviewed and assessed using available experimental data for horizontal 37-element bundle flows. The key findings from the study can be summarized as follows:

- Over the mass flux range of 4,000 to 6,200 kg/m^{2}s, the vertical fluid-to-fluid modelling laws (Ahmad 1973 and Katto 1979) predict CHF in uniformly and non-uniformly heated horizontal 37-element bundles with an average error of 1.4 ~ 5.2% and an RMS error of 5.9 ~ 8.4%. At mass fluxes below 4,000 kg/m^{2}s, gravity effects become important and the prediction errors become large, and can be up to 120% at the lowest mass fluxes.
- The Ahmad *et al*. (1982) horizontal fluid modelling law predicts CHF in uniformly heated 37-element bundles with an average error of 3.8% and an RMS error of 12.3% over the available range of 2,100 to 4,700 kg/m^{2}s. However, it does a poor job of predicting the non-uniform AFD data, with an average error of –13.3% and an RMS error of 15.9%.
- The Francois and Berthoud (2003) horizontal fluid modelling law predicts CHF with an average error of 4.7% and an RMS error of 13.3% in uniformly heated 37-element bundles, and with an average error of 0.6% and an RMS error of 10.4% in non-uniformly heated 37-element bundles over the available range of 2,000 to 6,200 kg/m^{2}s. However, the fluid-to-fluid law requires different weighting factors (L_w) for uniform and non-uniform AFD.
- The accuracy of the CHF correlations for the fluid-to-fluid modelling is affected by experimental uncertainties and limited parameter ranges of the data used, as well as the assumed linear form of the correlation.

NOMENCLATURE

Bo	Boiling number (q_c/GH_{fg})	_
Bo^*	Modified Boiling number ($q_cD/H_{fg}\mu_g$)	_
B_d	Bond number	_
D	Diameter in tubes or hydraulic diameter in bundles	m
G	Mass flux	kg/m^2-
g	Acceleration due to gravity	m/s^2
H_f	Liquid enthalpy at saturation condition	kJ/kg
H_{fg}	Latent heat of vaporization	kJ/kg
H_i	Liquid enthalpy at inlet condition	kJ/kg
ΔH_i	Inlet subcooling	kJ/kg
L	Tube or Bundle Length	m
L_W	Weighting factor	m
P	Pressure	kPa
q_c	Critical Heat Flux (CHF)	kW/m^2
V	Velocity	m/s
We	Weber number	_
x_{do}	Local quality at the axial dryout location	_

z	Axial location at the axial dryout location	m

Greek Symbol

θ	Angle from vertical axis	degree
μ_f	Liquid dynamic viscosity	$N\cdot s/m^2$
μ_g	Vapour dynamic viscosity	$N\cdot s/m^2$
ρ_f	Liquid density	kg/m^3
ρ_g	Vapour density	kg/m^3
σ	Surface tension	N/m
$\Psi_{Model\ para}$	Modelling parameter	–

Subscripts

do	Dryout
M	Modelling fluid
Model para	Model parameter
W	Working fluid

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