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FLUID-TO-FLUID MODELLING OF CRITICAL HEAT FLUX IN 37-ELEMENT BUNDLES

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ABSTRACT

The applicability of fluid-to-fluid modelling for critical heat flux (CHF) in 37-element bundles has been examined. CHF data obtained with 37-element bundle simulators from various Freon test programs at Chalk River Laboratories (CRL) were compared against those obtained from the water-test programs[1]. The comparison was based on a transformation of the Freon parameters (i.e., pressure, mass flux and CHF) into water-equivalent values (no transformation is needed for dryout quality, which represents the non-dimensional value of enthalpy). In addition, this study examined the impact of axial heat-flux distribution and channel orientation on fluid-to-fluid modelling. 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 effects of axial heat-flux distribution and channel orientation on bundle CHF have also been closely simulated with Freon at conditions of interest.

1. INTRODUCTION

Modelling fluids have often been used to obtain thermalhydraulic parameters for analyses of the primary cooling circuit in pressurized water-cooled nuclear reactors. These fluids have a much lower boiling point and latent heat of vaporization than water, and hence can significantly reduce the cost and risk of boiling heat-transfer experiments. The thermalhydraulic parameters obtained with these modelling fluids are transformed into water-equivalent values based on the fluid-to-fluid modelling parameters to provide (or supplement) information in analyses of a similar water-cooled system.

Until recently, chlorofluoro compounds were the most commonly used modelling fluids in critical heat flux (CHF) experiments for tubes (e.g., Tain (1994) and Stevens et al. (1965)) and rod bundles (Steven and Wood (1966)). Their thermalhydraulic characteristics are similar to water, while their operating conditions of interest require no refrigeration system; a definite advantage compared to other potential modelling fluids such as carbon dioxide and nitrogen. Most chlorofluoro compounds, however, have been phased out due to their ozone-depleting nature. They have been replaced with new refrigerants with similar operating conditions; Freon-134a has been adopted as the modelling fluid for boiling heat-transfer experiments. Several studies have been performed to verify the heat-transfer characteristics of Freon-134a using simple test sections, such as tubes (Groeneveld et al. 1997 and Tain 1994). These studies have verified that for plain and appendage-equipped tubes there is good agreement between water CHF data and the water-equivalent values of Freon-134a data (Piori et al., 1999, 2000).

AECL has been using chlorofluoro compounds to study thermalhydraulic characteristics of CANDU® fuel bundles since 1970. Most of the experiments were performed to obtain data on CHF with Freon-12 as coolant for simulators of a 37-element bundle string. Recently, Freon-134a was adopted as the new testing

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[1] The water CHF data used in the current assessment for the non-uniform bundle string were obtained under a research program funded by the CANDU Owners Group (COG).

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fluid, in compliance with environmental regulations. The CHF characteristics of Freon-134a were subsequently verified against the Freon-12 data for a 37-element bundle string. In addition, CHF experiments were performed using Freon-134a as coolant and a CANFLEX® bundle-string simulator, to provide licensing information in support of the demonstration irradiation at the Point Lepreau Generating Station.

The objectives of this study are to (i) verify the applicability of fluid-to-fluid modelling parameters for CHF in bundles and (ii) quantify the effects of axial heat-flux distribution and channel orientation on fluid-to-fluid modelling. This was done by comparing water CHF data to the Freon CHF data (after the transformation into water-equivalent values) at the same dryout conditions. The database contained CHF data obtained with both uniformly and non-uniformly heated bundle strings. However, the water data covered only horizontal flow while the Freon data covered both vertical and horizontal flows. This study focused only on the CHF data obtained with the 37-element bundle string since the full-scale water test for the CANFLEX bundle is currently in progress.

2. CHF DATA FOR 37-ELEMENT BUNDLES

A number of full-scale bundle tests were performed using electrically heated simulators of a 37-element segmented bundle string equipped with spacers and bearing pads. Sliding thermocouples were used to measure the surface temperature along the bundle string and were used to detect dryout occurrences. The radial heat-flux distribution (relative to elements in the outer ring) in these bundle strings is maintained at 0.7514, 0.7767, 0.8445, and 1.000 for elements in the centre rod, inner ring, middle ring and outer ring, respectively. This distribution corresponds to the end-of-life shape of bundles. In both Freon and water tests, two axial heat-flux profiles have been examined: a uniform and a downstream-skewed cosine profile. However, the skewed-cosine profile in the Freon tests varied in steps, while the one in the water tests was smooth. Figure 1 shows the difference in the skewed-cosine profiles between the Freon and water tests.

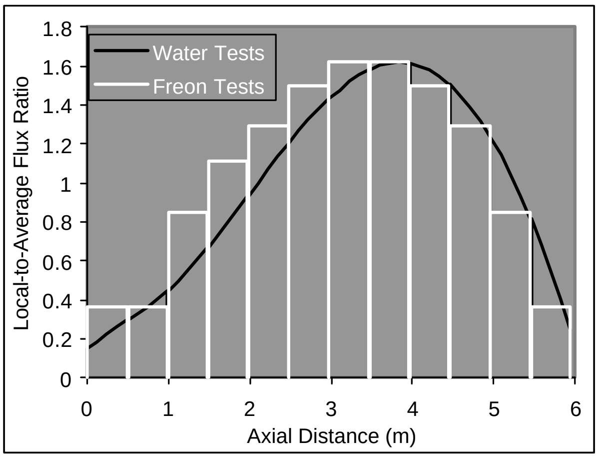

Figure 1: Non-Uniform Axial Heat-Flux Profiles of the Full-Scale Bundle Simulators in Water and Freon Tests.

3. MODELLING PARAMETERS FOR CHF

A number of non-dimensional groups have been proposed as fluid-to-fluid modelling parameters for CHF (Barnett 1964, Ahmad 1973, Katto and Ohno 1983). Among them, those suggested by Ahmad (1973) and Katto and Ohno (1983) are the most phenomenologically correct and have been recommended by Groeneveld et al. (1986) and Tain (1994). The density ratio is used to model the system pressure between the two systems, i.e.,

$$\left(\frac{\rho_f}{\rho_g}\right)_{water} = \left(\frac{\rho_f}{\rho_g}\right)_{Freon} \tag{1}$$

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The thermodynamic quality is used for the local enthalpy, i.e.,

$$x_{water} = x_{Freon} \tag{2}$$

The boiling number is used for the CHF in vertical flow, i.e.,

$$\left(\frac{CHF}{G\,H_{fg}}\right)_{water} = \left(\frac{CHF}{G\,H_{fg}}\right)_{Freon} \tag{3}$$

This parameter is applicable only for vertical channels at high-flow conditions since the boiling number becomes invalid at low vertical flows (approaching stagnant flow), while the buoyancy force becomes dominant at low horizontal flows. Merilo (1979) correlated a CHF parameter for horizontal-tube flow, which was extended to the horizontal 37-element bundle by Ahmad et al. (1982). These parameters have not been widely used.

Several parameters were introduced to model the mass flux in vertical flow (e.g., Ahmad (1973) and Katto and Ohno (1983)). Previous assessments based on tube data showed little differences between these parameters (e.g., Groeneveld et al. (1986)). Most studies recommended the use of the Weber number as the mass-flux modelling parameter (Katto and Ohno 1983), i.e.,

$$y_K = \left(\frac{G^2 D}{s\ r_f}\right)_{water} = \left(\frac{G^2 D}{s\ r_f}\right)_{Freon} \tag{4}$$

4. RESULTS OF THE ASSESSMENT

The current assessment focused on the design conditions of interest to fuel-channel analyses for a CANDU reactor (i.e., pressure of 10.5 MPa and mass-flow rate of 17 kg·s^{-1}). Data at similar flow conditions were selected from various data sets; minor adjustments were introduced to correct the test conditions to those of interest (based primarily on the deviation of CHF with respect to pressure and flow as shown in the reference water CHF data). The water CHF data shown in Figures 2 to 6 were all obtained in horizontal channels. For non-uniformly heated bundles, the boiling-length-average (BLA) heat-flux approach has been used to account for the effect of axial heat-flux distribution. Boiling was assumed to initiate at the onset of significant void (OSV). The BLA heat flux was calculated with

$$q_{BLA} = \frac{1}{z_{DO} - z_{OSV}} \int_{z_{OSV}}^{z_{DO}} q_{local}\, dz \tag{5}$$

A set of Freon-12 CHF data obtained with the vertical uniform-heated bundle string has been transformed with various mass-flux modelling parameters. As shown in Figure 2 for a mass-flow rate of 17 kg·s^{-1}, the mass-flux modelling parameters have little impact on the transformed

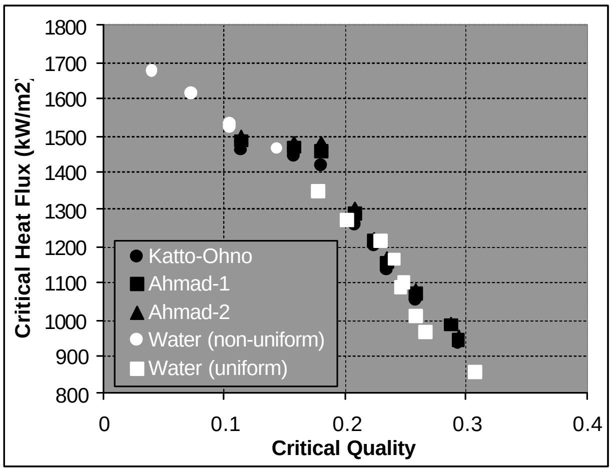

Figure 2: Comparison of Mass-Flux Modelling Parameters.

CHF values, which agree closely with the water data at similar local-flow conditions. The same agreement was observed for the data obtained at a mass-flow rate of 12 $kg\cdot s^{-1}$. Therefore, only the results based on the Katto and Ohno parameter (1983) are shown in the following comparison. Examining only the water data, the BLA heat-flux approach has aligned the data of the non-uniform-heated bundle with those of the uniform-heated bundle.

Figure 3 shows the comparison of water-equivalent values of various Freon data sets obtained with the vertical uniform-heated bundle strings. All Freon data sets (in water-equivalent values) are in excellent agreement with the water data (for horizontal bundles). Overall, the scatter among the Freon data is slightly higher at low qualities than at high qualities.

Figure 4 presents the comparison for the data of vertical non-uniform-heated bundle strings. Agreement is generally good between the water data and the water-equivalent Freon data for qualities beyond 0.1. It appears that the difference in CHF is small between smooth-cosine and stepped-cosine axial heat-flux distributions. Hence, the BLA heat-flux approach is valid for both water and Freon flow. The scatter among the Freon data is larger at low qualities than at high qualities. Comparing data of the two fluids, the Freon data are generally higher than the water data (for horizontal bundles) at low qualities.

The comparison of the horizontal water bundle data against the vertical Freon bundle data combines both the fluid and orientation effects. Figure 5 examines the fluid-modelling effect by comparing the water data to the Freon data obtained both in horizontal bundle strings. It appears that the Freon data follow two slightly different trends. Data in Sets 7, 8 and 9 are generally higher than those in Sets 10 and 11, and agree better with the water data. The differences are larger at low-quality conditions than at high-quality conditions. Overall, the fluid-to-fluid modelling approach has been shown valid for these data.

The effect of channel orientation on CHF is examined by comparing four data sets of uniform-heated and non-uniform-heated bundle strings.

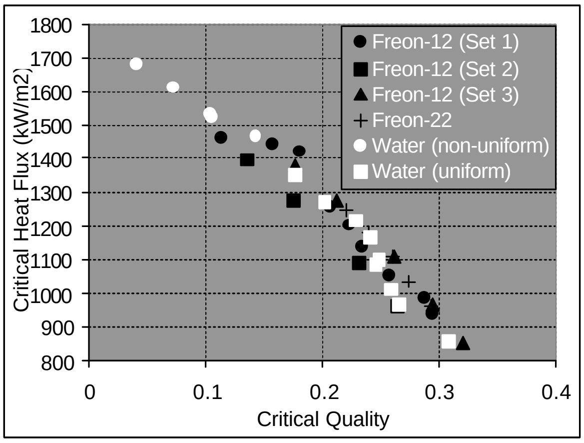

Figure 3: Data of Vertical Uniformly Heated Bundle Strings.

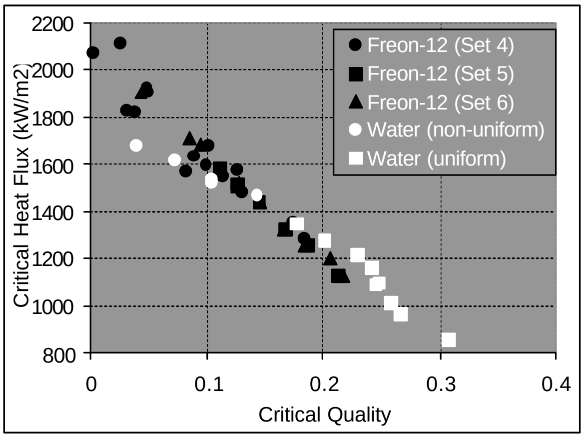

Figure 4: Data of Vertical Non-Uniformly Heated Bundle Strings.

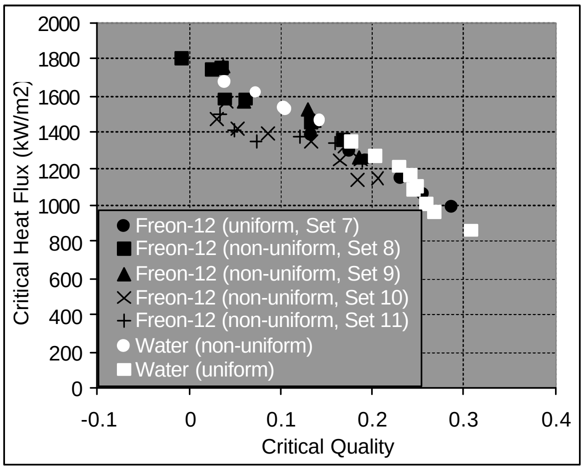

Figure 5: Data of Horizontal Bundle Strings.

Figure 6 shows that the data agree closely with others at critical qualities higher than 0.1 but deviate at low qualities. This implies that the orientation effect is negligible at high-quality conditions but has some impact at low-quality conditions. The horizontal Freon data follow closely the water data.

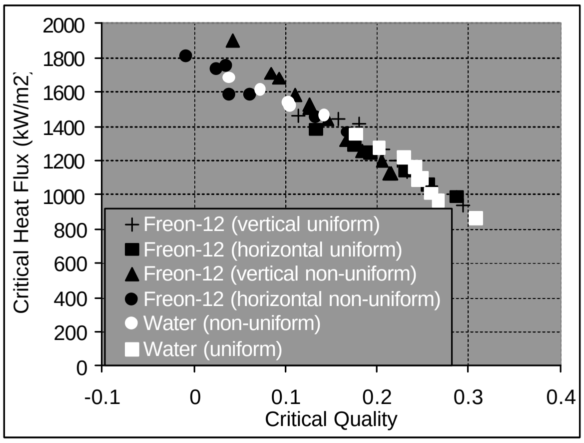

Figure 6: Effect of Channel Orientation on Bundle CHF.

5. CONCLUSIONS AND FINAL REMARKS

- The following modelling parameters are recommended for transforming CHF of 37-element bundles from Freon flow to water-equivalent values: the density ratio for system pressure, the Weber number for mass flux, the thermodynamic quality for local enthalpy, and the boiling number for CHF.
- The effect of axial heat-flux distribution and channel orientation on CHF in water flow has been modeled appropriately with Freon.
- The use of the boiling-length-average heat-flux approach aligns the data of uniformly and non-uniformly heated bundle strings for both water and Freon flow.
- The effect of channel orientation is negligible at high qualities but can be significant at low qualities for the current assessed flow conditions.
- The same approach is applicable to transform light-water CHF to heavy-water CHF (or vice versa), since thermodynamic and transport properties of heavy water are very close to those of light water while those of Freon are significantly different.

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