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Thermal-Hydraulics Code Validation for HIFAR Fuel Element Safety Analyses

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ABSTRACT

Among codes for thermal-hydraulic analyses of HIFAR (High Flux Australian Reactor) fuel elements, we use RELAP5 (Reactor Loss Of Coolant Analysis Program) and CFX-4 (a general purpose computational fluid dynamics {CFD} code). For accurate nuclear safety analyses, these computer codes must be validated for nuclear thermal-hydraulic conditions. Predictions of these codes for heat transfer in a HIFAR fuel tube have been compared. Predictions from the two computer codes for various subcooled boiling flows are compared with available experimental data.

INTRODUCTION

Computational analysis has played a unique role in nuclear reactor safety because full-scale demonstration experiments (or actual events) normally available for evaluating industrial accidents (e.g., involving automobiles or aircraft) are neither available nor practical to obtain in the case of nuclear reactors. The diversity of reactor system designs, and the numerous potential events to be considered, make the required large number of full-scale experiments prohibitively expensive. Consequently, a greater than usual responsibility has been placed on the reactor safety analyst to be rigorous and accurate in developing and testing analysis tools.

A number of advanced computer codes now are available for reactor thermal-hydraulic analyses. One of them is RELAP5, which was developed in the Idaho National Engineering Laboratory. This code was originally designed to analyse the thermal-hydraulic behaviour of light water and power reactor systems in which operating conditions are normally at high-pressures and high-temperatures. Because ANSTO's research reactor HIFAR operates at low-pressure and low-temperature conditions, and uses heavy water as coolant in multi-annular section fuel elements, the validation of RELAP5 computer code for HIFAR conditions becomes necessary.

We compared the abilities of RELAP5 and a general purpose CFD code, CFX-4, to predict vapour void fractions obtained in Zeitoun and Shoukri's (1997) low pressure subcooled flow boiling experiments and in Bartolomei et al's (1982) high-pressure subcooled flow boiling experiments. One of our findings is that RELAP5 code can accurately predict the subcooled boiling void fractions at high pressures but not at low pressures. Moreover, although CFX-4 better predicts void fraction at low pressure than RELAP5, some improvement of the CFX-4 boiling model is still required

RELAP5 COMPUTER CODE

The RELAP5 family of codes was developed at the Idaho National Engineering Laboratory and was sponsored by the U.S. Nuclear Regulatory Commission. The codes are for best-estimate transient simulations of water nuclear reactors and associated systems. The current RELAP5 code is based on a one-dimensional, transient analysis code for thermal-hydraulic systems, and it employs a nonhomogeneous and nonequilibrium flow model for two-phase regions to predict pressures, temperatures, void fractions and flow rates. The code uses a six-equation formulation to handle the phasic continuity, momentum and energy conservation equations (three equations for each phase). The code available at ANSTO is the ATR (Advanced Test Reactor) specific version, which incorporates aluminium type fuel, and D_2O coolant properties, and so in these regards is appropriate for HIFAR.

The RELAP5 computer code uses the Dittus-Boelter correlation to calculate heat transfer coefficients for single-phase forced liquid convection

$$h = 0.023\frac{k_f}{D_e}\mathrm{Re}_f^{0.8}\,\mathrm{Pr}_f^{0.4} \qquad (1)$$

This correlation was originally derived for smooth flow in tubes. As pointed out earlier, however, the HIFAR fuel element comprises a multi-annular section with 4 concentric fuel tubes and heavy water annuli between the fuel tubes. The experiments of the Zeitoun and Shoukri (1997) were carried out in a vertical concentric annular test section too. We found predictions from this were not accurate for the annular flow sections we considered. On the basis of Kays and Leung's (1963) study of heat transfer for single-phase flow in annular passages, we replaced the coefficient 0.023 in equation (1) by 0.027 for the annulus.

The nodalisation of RELAP5 model for the Zeitoun and Shoukri's (1997) experiment is illustrated in Figure 1. The inlet and outlet vertical annuli are modelled by annular components (382) and (332), respectively. The vertical concentric annular test section is modelled by an annular component (313) with 10 control volumes. Two time-dependent components with junctions are used to model the test loop.

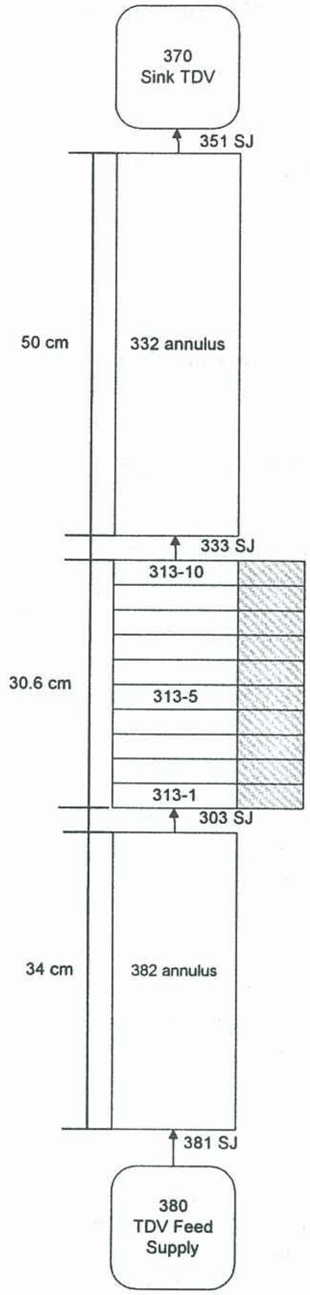

Figure 1 Schematic diagram of RELAP5 nodalisation.

CFX-4 COMPUTER CODE

CFX-4 is an advanced, general-purpose CFD code with a two-fluid model for predicting sub-cooled flow boiling. It is based on a conservative finite-volume formulation using a structured, multi-block, nonorthogonal, curvilinear coordinate grid with a colocated variable arrangement. The basic solution algorithm is the SIMPLEC pressure correction scheme that uses a variety of linear equation solvers. In this study, spatial discretisation is achieved through the HYBRID scheme and turbulent flows are modelled with a standard k-ε turbulence model.

The boiling model implemented consists of inter-phase mass, momentum and heat transfer correlations between a continuous liquid phase and a dispersed gas bubble phase. Each phase is treated as an interpenetrating continuum. That is, each phase is assumed to be present in each control volume, and assigned a volume fraction equal to the fraction of the control volume occupied by that phase. Transfer quantities interact via inter-phase transfer terms. The multi-phase model implementation is based on Inter-Phase Slip Algorithm (IPSA) of Spalding (1976). More details can be found from CFX-4.2 Solver (1997)

The most important part of the boiling model in the current CFX-4 version is the wall heat partition model. In this model, the total wall heat flux is separated into three parts: the heat transfer due to convection Q_f, the heat transfer due to quenching Q_Q and the heat transfer due to evaporation Q_e. The empirical correlations presented below are based on the work of Kocamustafaogullari and Ishii (1983), Unal (1983), and Del Valle and Kenning (1985).

The convective and quenching heat transfer rates are given in terms of heat transfer coefficients by:

$$Q_f = h_f(T_w - T_l) \tag{2}$$

$$Q_Q = h_Q(T_w - T_l) \tag{3}$$

Here T_w is the wall temperature and T_l is the liquid temperature in the cell next to the wall. The partitioning is defined by the following equations:

$$h_f = A_{1f} C_h \rho_l C_{pl} U_l \tag{4}$$

$$h_Q = \frac{2}{\pi^{0.5}} f A_{2f} (t_w k_l \rho_l C_{pl})^{0.5} \tag{5}$$

$$Q_e = \frac{\pi}{6} d_{Bw}^3 \rho_g f n h_{lg} \tag{6}$$

In these equations C_h is the local Stanton number, ρ_l and ρ_g are the densities of the phases, C_{pl} the specific heat of the liquid, k_l the thermal conductivity of the liquid, and U_l the liquid velocity in the cell next to the wall. Other parameters used in these equations are the nucleation site density (n), the bubble departure diameter (d_{Bw}), the fractions of wall area subjected to cooling by convection and to quenching (A_{1f} and A_{2f}), the bubble detachment frequency (f) and the waiting time t_w. These parameters are given by the following empirical correlations:

$$n = (185(T_w - T_{sat}))^{1.805} \tag{7}$$

$$d_{Bw} = 0.0014 \exp\left(\frac{T_{sat} - T_l}{45}\right) \tag{8}$$

$$A_{2f} = \pi d_{Bw}^2 n \tag{9}$$

$$A_{1f} = \max(1 - A_{2f}, 0) \tag{10}$$

$$f = \left(\frac{4 g \Delta\rho}{3 d_{Bw} \rho_l}\right)^{0.5} \tag{11}$$

$$t_w = \frac{0.8}{f} \tag{12}$$

The final part of the boiling model is for inter-phase mass transfer, including evaporation at the wall, and bulk condensation or evaporation. The inter-phase momentum transfer includes drag force, lift force, virtual mass force, wall lubrication force and turbulent dispersion force. The effect of dense concentration of bubbles can be included in the drag force term. The bubble diameters can vary linearly between two reference liquid sub-cooling temperatures. The standard k-ε model is modified to include bubble-induced turbulence effects. The inter-phase heat transfer term is based on a correlation developed by Ranz and Marshall (1952). The model assumes incompressible flow at a constant absolute pressure. The saturation temperature and the latent heat of evaporation are specified at this pressure. The model uses constant physical properties evaluated at the saturation temperature. The gas phase is assumed to be at the saturation temperature, so the model cannot predict super-heating of the gas phase after dryout.

RESULTS AND DISCUSSION

In this section, numerical predictions from model simulations using the two above-mentioned codes are compared with each other and with available experimental data.

HIFAR Fuel Elements with Coolant Annuli

As stated earlier, RELAP5 uses a heat transfer correlation originally derived for smooth flow in tubes. However, each HIFAR fuel element comprises a multi-annular section with 4 concentric fuel tubes, with heavy water coolant in the annular gaps between the fuel tubes. RELAP5 predicted higher fuel temperatures than those from both the CFX-4 simulation and analytical predictions. The difference is attributed to the single-phase heat transfer coefficient used in RELAP5 model, which is applicable to a pipe section. The heat transfer correlation has been modified in RELAP5 to account for the annular section. The predicted fuel tube temperatures from these models are shown in Figure 1. The older RELAP5 model predicts higher fuel temperature and the modified version of RELAP5 shows good agreement with CFX-4.

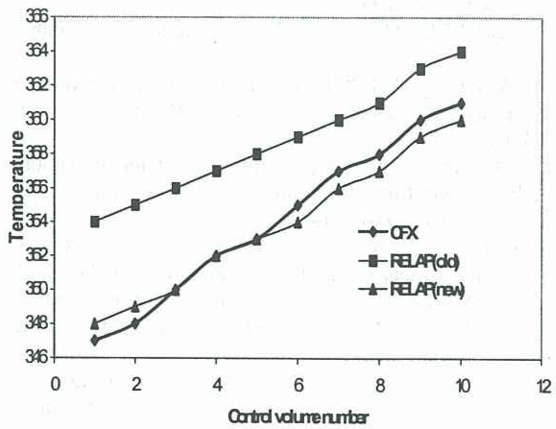

Figure 1 Comparison of predicted surface temperatures along a HIFAR fuel tube

Sub-cooled Boiling at High Pressure

The high pressure sub-cooled flow boiling experiments performed by Bartolomei et al (1982) were chosen to assess the validity of the numerical predictions from both RELAP5 and CFX-4. The experimental data is for subcooled boiling in tubes at a pressure of 68.9 bars; a mass flow rate of 985 kg/m^2 s; heat flux of 1.13MW/m^2; and an inlet subcooling of 68K. Figure 2 compares the predictions and the data. The predicted void fractions from both the RELAP5 and CFX-4 computer codes are in good agreement with the experimental data.

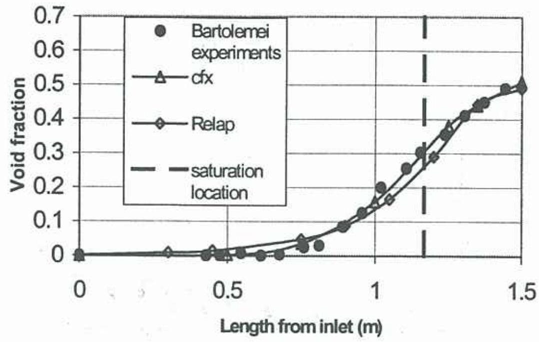

Figure 2 Comparison of predicted and experimental subcooled flow boiling void fractions.

Sub-cooled Boiling at Low Pressure

As stated earlier, the research reactor HIFAR at ANSTO operates at low-pressure and low-temperature conditions. Sub-cooled boiling models available in the RELAP5 computer code have been developed for, and tested at, high pressures typical for power reactors. It is well-known that, at atmospheric pressure, the rate of change of void with quality is far more significant than at high pressures. As a result, empirical models devised and verified for high-pressure situations may not be valid at low pressures.

The experiments of Zeitoun and Shoukri (1997) were carried out at low pressures in a vertical concentric annular test section. The outer tube was a 25.4 mm inner diameter plexiglass tube and the inner tube, which had an outside diameter of 12.7 mm, was made of three axial sections. The middle section of the inner tube was a 30.6 cm long, thin-walled stainless-steel tube (0.25 mm thickness), which was electrically heated. This heated section was preceded and followed by 34 cm long and 50 cm long, thick walled copper tubes, respectively. Heat was generated uniformly in the middle section where the sub-cooled boiling took place. The details of the experimental facilities and a variety of flow conditions are described in Zeitoun and Shoukri (1997).

Figures 4 and 5 show comparison of void fractions predicted with CFX-4 and RELAP5 with those obtained from Zeitoun and Shoukri's experiments. These figures cover a relatively low heat flux (q=213.6 kW/m^2) and a relatively high heat flux (q=480.7 kW/m^2). It can be seen from these figures that the void fractions predicted with CFX-4 are quite good, and that RELAP5 significantly under-predicts void fraction distributions. The limitations of the RELAP5 code for research reactor applications were also reported by Woodruff et al. (1997).

However, uncertainties in appropriate user-defined bubble diameters place limitations on the general application of the current version of CFX to any subcooled boiling flow. As seen in figures 4 to 6, our current bubble diameter choices yield accurate predictions for the data of figures 4 and 5, but not for the low flow, high heat flux data of figure 6. Further work is required here to ensure CFX predictions are accurate for HIFAR conditions.

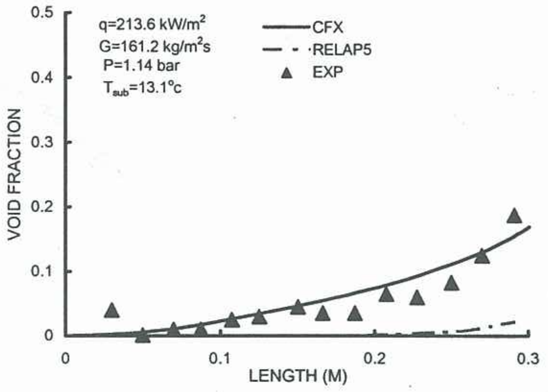

Figure 4 Comparison of predicted and measured low heat flux void fractions

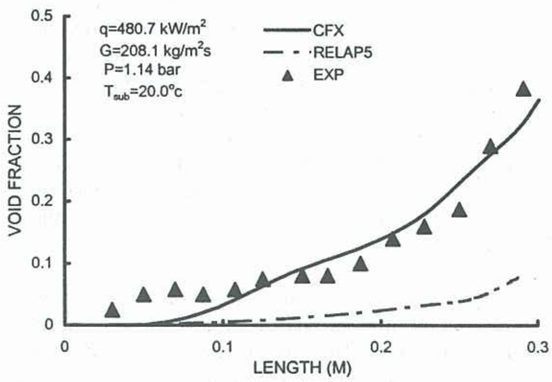

Figure 5 Comparison of predicted and measured moderate heat flux void fractions

CONCLUSION

In this paper, the numerical predictions using two computer codes, RELAP5 and CFX-4, have been compared. The heat transfer coefficient in the Dittus-Boelter correlation adopted by RELAP5 has been modified to account for the annular flow sections of HIFAR fuel elements. On the basis of experimental data, both RELAP5 and CFX-4 satisfactorily predict subcooled boiling void fractions at high pressures. At low pressures, subcooled boiling void fractions are better predicted with CFX-4. Further work is being performed on both codes to ensure their validity for all low pressure subcooled boiling flows.

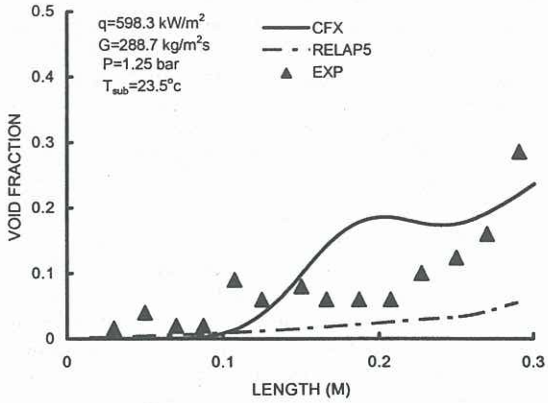

Figure 6 Comparison of predicted and measured high heat flux void fractions

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REFERENCES

BARTOLOMEI, G.G., BRANTOV, V.G., AND MOLOCHNIKOV, Y.S. et al. "An experimental investigation of true volumetric vapour content with subcooled boiling in tubes", Thermal Engineering, **29** (3), 132-135, 1982.

CFX-4.2 Solver Manual, CFX, AEA Technology, Didcot, Oxon, UK, 1997.

DEL VALLE, V.H. and KENNING, D.B.R. "Subcooled flow boiling at high heat flux", *Int. J. Heat Mass Transfer*, **28**, 1907-1920, 1985.

KAYS, W. M. AND LEUNG, E. Y., "Heat transfer in annular passages: Hydrodynamically developed turbulent flow with arbitraily prescribed heat flux", *Int. J. Heat Mass Transfer*, **6**, 537-557, 1963.

KOCAMUSTAFAOGULLARI, G. AND ISHII, M. "Interfacial area and nucleation site density in boiling systems", *Int. J. Heat Mass Transfer*, **26**, 1377, 1983.

RANZ, W.E. AND MARSHALL, W.R. Chem. Eng. Pro., **48**(3), 141, 1952.

SCDAP/RELAP5/MOD2 Code Manual, EG&G Idaho, Inc., 1989.

SPALDING, D.B. "The calculation of free-convection phenomena in gas-liquid mixtures", ICHMT Seminar, Dubrovnik, 1972.

UNAL, H.C. "Maximum bubble diameter, maximum bubble growth time and bubble growth rate", *Int. J. Heat Mass Transfer*, **19**, 643-649, 1976.

WOODRUFF, W.L., HANAN, N.A. AND MATOS, J.E. "A comparison of the RELAP5/MOD3 and PARET/ANL codes with the experimental transient data from the SPERT-IV D-12/25 Series", Report of Argonne National Laboratory, Argonne, 1997

ZEITOUN, O. AND SHOUKRI, M., "Axial void fraction profile in low pressure subcooled flow boiling", *Int. J. Heat Mass Transfer*, **40**, 869-879, 1997.