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Study on Characteristics of Subchannel Analysis Code at Low Flow Steam Line Break Condition

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Abstract

The subchannel analysis was performed to verify the behavior of hot channel characteristics and obtain the information to support the core thermal-hydraulic behavior at post-trip steam line break with low flow condition. During this postulated accident, buoyancy-induced cross flow occurs, and the coupled nuclear and thermal-hydraulic interactions become important. The code predictions with TORC are in good agreement with the test data. Under such conditions, the mass flow increase in the hot channel by buoyancy-induced cross flow depends on the parameter GR^* / Re^2, and buoyancy effect becomes more noticeable as GR^* / Re^2 increases.

1. Introduction

The main steam line break(SLB) will result in an increase of steam flow. Therefore, the steam released through the break in the affected steam generator extracts heat from the primary system which causes the primary coolant temperature and pressure to rapidly decrease.[1] The return to power following a steam line break may result in high power peaking factors because the most reactive control element assembly(CEA) is assumed to be stuck in its fully withdrawn position during this accident. Therefore, DNB may occur in spite of low power during this postulated accident.

In CE design methodology, the HRISE[2] is an analysis code that computes DNBR for SLB which causes the core heat flux to increase under the low pressure, low mass flow and low power level condition. However, because of the use of closed channel model in HRISE, the hot channel axial flow variation must be supplied through the input, and subchannel analysis code is used for providing axial flow rate with elevation. When this input is thoroughly examined, the mass flow rate in hot assembly increases with axial elevation, which is the reverse case of normal operating condition.

The purpose of this study is to verify the behavior of hot channel characteristics of TORC analysis results through the comparison with experimental data, and obtain the information about what causes the reverse results of normal operating condition at given SLB condition.

2. Subchannel Analysis Code - TORC

The TORC code[3] determines the coolant conditions in the reactor core. TORC solves the conservation equations(mass, momentum and energy) for a three-dimensional representation of the open-channel reactor core. To investigate the behavior of hot channel characteristics, the axial momentum equation should be reviewed. The total axial pressure drop across a node in a given flow is expressed by :

$$\begin{aligned}\Delta P_{Total} = \Delta P_{\substack{Fuel\ Rod \\ Friction}} + \Delta P_{Elevation} + \Delta P_{\substack{Spacer \\ Grid}} + \\ \Delta P_{\substack{Momentum\ Change \\ due\ to\ Heating}} + \Delta P_{\substack{Momentum\ Change \\ due\ to\ Diversion\ Crossflow}} + \Delta P_{\substack{Momentum\ Change \\ due\ to\ Turbulent\ Interchange}}\end{aligned} \tag{1}$$

3. Characteristics of TORC Code at SLB Condition

The reactor core has a highly skewed power distribution at SLB condition due to the assumption of stuck rod. Under such conditions, radial power peaking gradient is large and results in significant cross flow between assemblies near the withdrawn CEA.

3.1 Experimental Data

The Battelle-Pacific Northwest Laboratory[4] performed an experimental study to obtain fluid temperature and detailed velocity measurements in combined free and forced convection flows within an electrically heated rod bundle containing steep radial power gradient. The experimental rod bundle contained 12 electrically heated rods in a 2×6 rectangular array, as shown in Figure 1. The 12 rods were divided into two groups of 6 rods, each forming a 2×3 array that was connected to different, independently controlled power supply to get the desired radial power gradient.

3.2 TORC Analysis

To investigate the characteristics of the thermo-hydraulic subchannel analysis code TORC, the test data were analyzed using TORC code. Among the three experimental cases in Ref.5, the case No.3 which has the most severe power gradient is analyzed with TORC in this paper. The operating conditions for comparison are flow rate $\dot{w} = 2.47$ gpm, pressure $P = 60$ psia, inlet temperature $T_{in} = 60.9$ °F and the power gradient with 1.810 kW/rod(Rod No. 1,2,3,4,5,6) and 0.0 kW/rod(Rod No. 7,8,9,10,11,12),respectively. The comparison result of the TORC average subchannel velocities with the measured centerline velocities is shown in Figure 2. As shown in this figure, the predicted velocities are in general below the measured values, because

TORC values are subchannel averages compared to the experimental centerline peak velocities. In addition, the TORC results show a flow increase in the hot region of the bundle, which is consistent with the experimental data and this fact is the opposite trend to normal operating core situation. The pressure drop in subchannels is due to friction, spacer grid, acceleration, gravitation or buoyancy, and momentum change as shown in Eq.(1). Under such conditions - low mass flow rate and highly skewed power distribution, the buoyancy forces are more dominant and the velocity profile becomes more distorted because of significant cross flow between the low power regions and the higher power regions. The momentum equation in TORC contains the gravitational force term to account for the buoyancy effect. In order to identify this effect more clearly and quantitatively, the TORC results for axial flow rate distribution with and without gravitational force term at axial momentum equation are shown in Figure 3. The hot channel axial flow normalized by inlet mass flow rate considering the gravitational force in governing equation is much larger than 1 and this means that the axial flow rate is increased with axial elevation. Under the low mass flow rate and highly skewed power gradient condition, because of large difference of density between hot and surrounding channel, the pressure drop due to gravitation is more important than other components in Eq.(1). The amount of pressure drop in hot channel is relatively smaller than surrounding channels and a cross flow occurs toward hot channel. Morita etc.[5] defined this flow as buoyancy-induced cross flow and they apply THINC-IV code to analysis for such conditions.

In this study, non-dimensional parameter to describe the importance of buoyancy effect was introduced and the parameter can be defined as Eq.(2)

$$GR^* / \mathrm{Re}^2 \tag{2}$$

where, Modified Grashof No. $GR^* = [(g\beta \Delta T_B D_H^3)/\nu^2](\overline{Q}-1)$ (3)

Reynolds No. $\mathrm{Re} = U_B D_H / \nu$ (4)

g : gravitational acceleration
β : thermal expansion coefficient
ΔT_B : temperature difference across the bundle
D_H : hydraulic diameter
ν : kinematic viscosity
U_B : Bundle average velocity
$\overline{Q}$: Index factor defined as $2Q_H/(Q_H + Q_L)$
Q_H : Hot side heat flux
Q_L : Cool side heat flux

From Table 1, Run No. 1 is the case of the least inlet mass flux and the steepest power gradient and has the largest GR^* / Re^2 value among 4 cases. Thus, we can see that the buoyancy effects become more noticeable as GR^* / Re^2 increased and a threshold value where buoyancy effects can be neglected may exist.

4. Application to Core Thermal-Hydraulics

The subchannel analysis was done for the actual SLB conditions of YGN 3&4 initial core and the mass flow rate in hot assembly which are given for the HRISE input in order to calculate DNBR is shown in Figure 4. The TORC results show a flow increase in the hot assembly, which is consistent with the above description.

5. Conclusions

The characteristics of subchannel analysis code TORC have been investigated for low mass flow rate and high power gradient conditions with experimental data. Important findings of this study are summarized as follows :

(1) Under SLB conditions, buoyancy-induced cross flow due to strong density difference between hot and surrounding channels occurs, and TORC code predictions are in good agreement with this fact.

(2) The increase of mass flow in the hot channel is due to buoyancy-induced cross flow, these phenomena become more noticeable as GR^* / Re^2 increases.

(3) The TORC results for the actual SLB conditions at the reactor geometry also show a flow increase in the hot channel.

References

[1] E. Fentze et al, "Nuclear Safety Analysis Report for Kori 3/4", KWU B324/89/e416, KWU 1989.

[2] ABB-CE, "Users Manual for HRISE ON UNIX", ABB Combustion Engineering Nuclear Fuel, CE-CES-159 Rev.0-P, 1992.

[3] ABB-CE, "Users Manual for TORC", CE NPSD-628-NP Rev.02, July 1991.

[4] M. S. Quigley, C. A McMonagle and J. M. Bates, "Investigation of Combined Free and Forced Correction in a 2×6 Rod Bundle", BNWL-2216, Battelle-Pacific Northwest Laboratories, July 1977.

[5] T. Morita etc., "Subchannel Thermal-Hydraulic Analysis at AP600 Low-Flow Steam-Line-Break Conditions", Nuclear Technology, Vol.112, pp401-411, 1995.

Table 1. Comparison of Run Conditions and Results for Channel No. 9

Run No.	Inlet Mass Flux (Mlbm/hr-ft^2)	$Q_H : Q_L$	Avg. Heat Flux (MBtu/hr-ft^2)	GR^* / Re^2	Mass Flux Ratio of Outlet to Inlet
1	0.0675	1 : 0	0.01242	0.0378	2.221
2	0.0675	2 : 1	0.00411	0.00968	1.4402
3	0.3375	1 : 0	0.02463	0.00158	1.1434
4	0.3375	2 : 1	0.00932	2.33×10^{-4}	1.1137

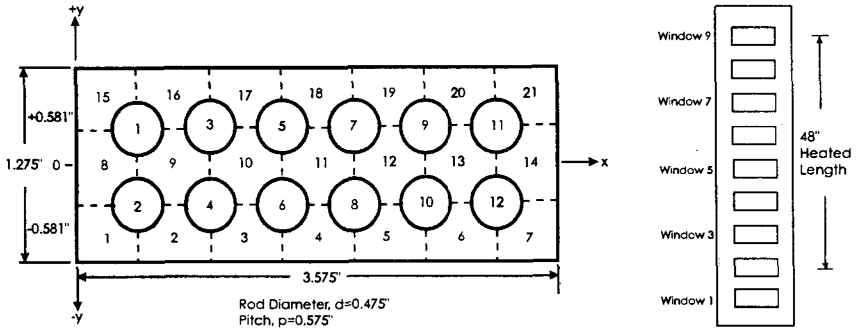
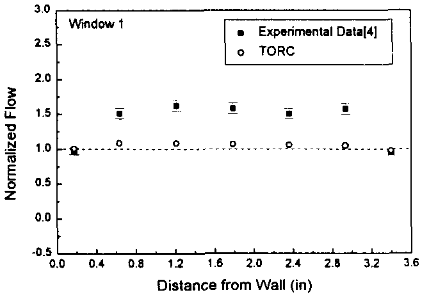
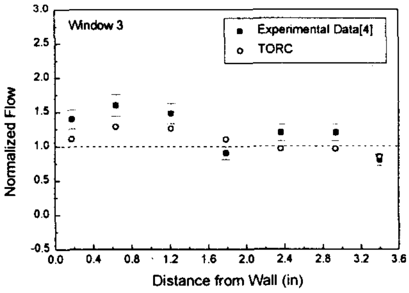


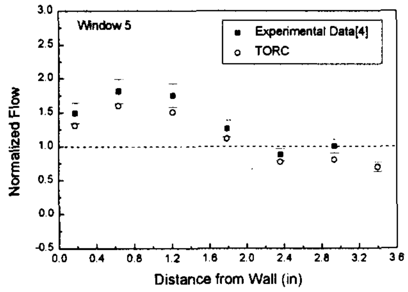
Figure 1. Subchannel Number and Dimensions



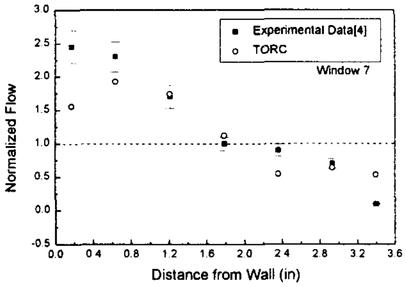
(a)



(b)



(c)



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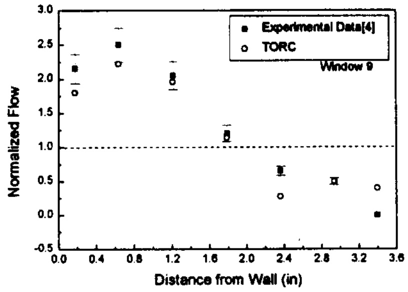

(e)

Figure 2 Comparison of TORC Flow Predictions to Experimental Data[4] at the various axial levels

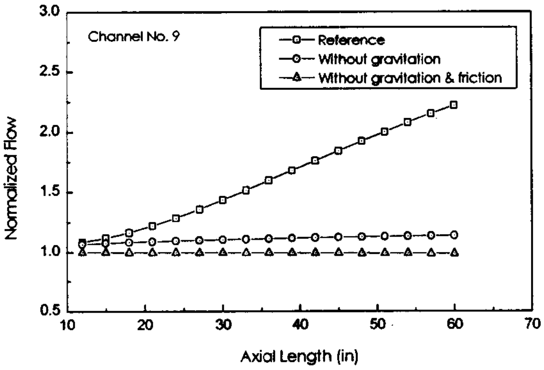

Figure 3 Comparison of Mass Flow Rate Prediction in Hot Channel

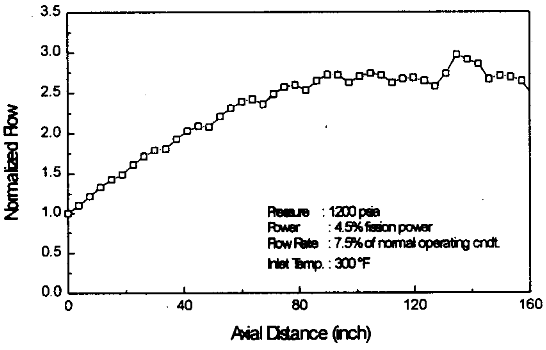

Figure 4. Mass Flow Rate in Hot Assembly for YGN 3&4 SLB Conditions