Thermal hydraulic analysis of flow inversion in a research reactor with downward core cooling

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1. Introduction

Research reactors with forced downward core cooling experience flow inversion if the primary cooling pump (PCP) is failed. If PCP failure occurs, the downward flow decreases into zero flow and eventually turn into upward flow by natural circulation. During flow inversion phenomenon, reactor cores may undergo the most unfavorable thermal hydraulic condition, which results in the highest coolant and fuel temperatures and lowest thermal margins [1]. The transient thermal hydraulic analyses of loss of flow accidents (LOFA) in IAEA 10MW benchmark MTR research reactor have been widely investigated by many institutes [2]. In this study, a transient thermal hydraulic model of flow inversion is developed and applied to IAEA 10MW benchmark MTR research reactor. The results are compared against other analyses.

2. Model development

If the fluid is assumed to be incompressible, the energy equation can be expressed as

$$\rho\frac{\partial h}{\partial t}+G\frac{\partial h}{\partial z}=\frac{q^{"}P_h}{A_z} \tag{1}$$

Using $dh = C_p dT$ the above equation can be expressed in terms of temperature;

$$\rho C_p\frac{\partial T}{\partial t}+GC_p\frac{\partial T}{\partial z}=\frac{q^{"}P_h}{A_z} \tag{2}$$

Using Euler's FTCS method (Forward Time and Central Space), the descritized form of the above equation is

$$\alpha\frac{T_i^{n+1}-T_i^n}{\Delta t}=\beta-\frac{T_{i+1}^n-T_{i-1}^n}{2\Delta z} \tag{3}$$

Let $\alpha=\dfrac{\rho}{G}$ and $\beta=\dfrac{q^{"}P_h}{A_zGC_p}$.

To rearrange the above equation for the temperature at time step *n+1*

$$T_i^{n+1}=T_i^n+\frac{\beta}{\alpha}\Delta t-\frac{\Delta t}{2\alpha\Delta z}\left(T_{i+1}^n-T_{i-1}^n\right) \tag{4}$$

According to Von Neumann analysis, Euler's FTCS method is unconditionally unstable [3]. To stabilize the numerical scheme, an averaged value of T_i^n is used.

$$T_i^{n+1}=\frac{1}{2}\left(T_{i+1}^n+T_{i-1}^n\right)+\frac{\beta}{\alpha}\Delta t-\frac{\Delta t}{2\alpha\Delta z}\left(T_{i+1}^n-T_{i-1}^n\right) \tag{5}$$

Flow inversion phenomenon can be explained by

$$\frac{dv}{dt}=-\frac{f}{2D_h}\left(\frac{\rho_i}{\rho_p}\right)|v|v+g\left(\frac{\rho_i}{\rho_p}-1\right) \tag{6}$$

For downward flow, the fictional and buoyant forces decrease the flow. For upward flow, the frictional force decreases the flow while the buoyant force increases the flow.

3. Core configuration and operating conditions

The core configuration of IAEA 10MW benchmark MTR research reactor and operating conditions are listed in Table 1.

Table 1. IAEA 10MW benchmark MTR research reactor

Number of fuel assembly	24
Number of plates per assembly	23
Fuel plate dimension	
Meat [mm]	0.51
Width [mm]	63.0
Length [mm]	600.0
Cladding thickness [mm]	0.38
Coolant channel	
Thickness [mm]	2.23
Width [mm]	66.5
Coolant flow rate [m3/h]	1000
Inlet coolant temperature [^{O}C]	38
Operating pressure [bar]	1.7
Axial power peaking factor	1.50
Radial power peaking factor	1.67

When PCP is failed, the pump coastdown curve is simulated as an exponential function with pump period τ of 1s and 25s. The reactor trips at 85% of the PCP flow rate. The decay heat is simulated by using ANSI/ANS-5.1-1979.

4. Results

Before analyze IAEA benchmark problem, the result of the transient analysis has to be confirmed with the steady state analysis. Figure 1 shows the axial coolant temperature for transient and steady state analyses [4]. The axial temperature distributions are comparable.

The fast LOFA (τ of 1s) reaches flow inversion at 3.8s. The 1st peak coolant temperature occurred at 0.5s after scram is approx. 64.64 ^{o}C, and the 2nd peak coolant temperature occurred at 11.7s is approx. 79.8 ^{o}C.

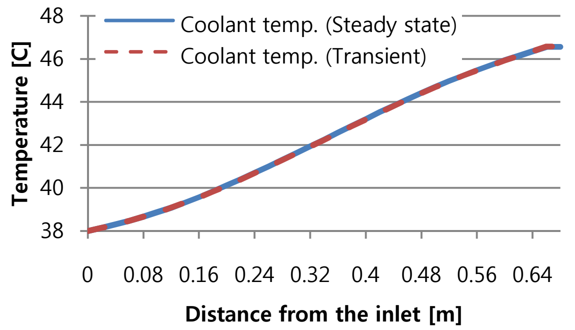

Figure 1. Axial coolant temperature distributions

The slow LOFA (τ of 25s) reaches flow inversion at 49.04s. The 1st peak coolant temperature occurred at 4.28s after scram is approx. 61.86 ^{o}C, and the 2nd peak coolant temperature occurred at 60.55s is approx. 72.52 ^{o}C.

Although the present model predicts flow inversion time slightly earlier than those predicted by others listed in Tables 2 and 3, the predictions of flow inversion time and 1st and 2nd peak coolant temperatures are comparable. The results demonstrate that the present model can effectively predict flow inversion phenomenon for the plate type fueled research reactor with downward core cooling.

Table 2. Main results of loss of flow transient (pump period of 1s)

	Present model	Kazeminejad (2008)	RELAP5/3.2	PARET	RETRAC-PC	EUREKA-PT
Institute	KAERI	AEOI	UPISA	ANL	LAS	JAERI
Power at scram	11.76 (0.363)	11.26 (0.370)	11.83 (0.190)	11.86 (0.295)	11.72 (0.185)	N/A
1st peak coolant temperature [C]	64.64 (0.50)	63.20 (0.490)	59.50 (0.504)	60.84 (0.601)	59.92 (0.465)	58.1 (0.480)
Flow inversion time [s]	3.80	4.60	7.40	4.415	7.36	N/A
2nd peak coolant temperature [C]	79.80 (11.70)	101.60 (17.97)	105.30 (11.90)	101.68 (9.14)	69.76 (N/A)	49.3 (10.0)

Table 3. Main results of loss of flow transient (pump period of 25s)

	Present model	Kazeminejad (2008)	RELAP5/3.2	PARET	RETRAC-PC	COSTAX-BOIL
Institute	KAERI	AEOI	UPISA	ANL	LAS	JEN
Power at scram	11.52 (4.263)	11.10 (4.280)	11.56 (4.102)	11.64 (3.860)	11.56 (4.050)	11.7 (4.060)
1st peak coolant temperature [C]	61.86 (4.28)	61.60 (4.310)	57.97 (4.300)	58.83 (4.075)	58.82 (4.272)	58.1 (4.270)
Flow inversion time [s]	49.04	57.56	57.40	62.84	57.26	N/A
2nd peak coolant temperature [C]	72.52 (60.55)	94.80 (76.62)	87.36 (64.20)	94.21 (70.74)	58.77 (57.26)	44.0 (45.0)

( ): time of parameter occurrence

(a)

(b)

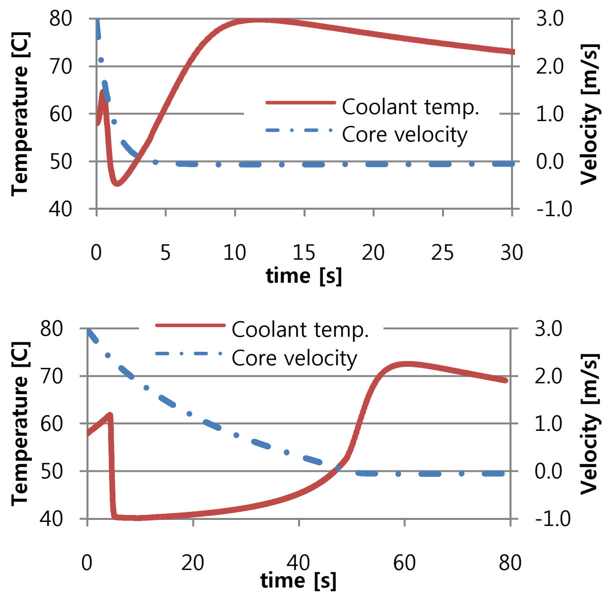

Figure 2. Coolant temperature and core flow velocity: (a) τ of 1s, (b) τ of 25s

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