Experimental Validation of a Thermal-hydraulic Analysis Code for REX-10

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1. Introduction

REX-10 is an environmentally-friendly and stable small-sized nuclear reactor to provide the electricity and district heating in micro-grid. To evaluate the thermal-hydraulic behavior and the system performance of the reactor, which adopts several new concepts of design, a system analysis code is under development on the basis of one-dimensional momentum integral model. A point reactor kinetics model for thorium-fueled core and the heat transfer model for helically coiled steam generator are implemented to the analysis code. A brief on the governing equation and numerical solution scheme used in the code is presented in this paper. In order to validate the accuracy of simulation results, the solution method is applied to the REX-10 test facility. The predicted natural circulation flow rate and coolant temperature at steady-state are compared to the experimental data. The validation is also performed for the transients in which the sudden reduction in the core power or the feedwater flow takes place.

2. Hydrodynamic Model and Solution Method

2.1 Basic Assumptions and Governing Equations

In the momentum integral model, fluid is considered incompressible and thermally expandable. Then the spatial dependence of the mass flow rate in the primary circuit vanishes. And the Boussinesq approximation is applied to simulate the natural convection, whereby the density is regarded as constant in momentum equation except for the gravitational form. In this model, the momentum equation is integrated over the entire loop so that the convection and pressure terms are eliminated as following:

$$\left(\sum_k \frac{L_k}{A_k}\right)\frac{\partial W}{\partial t} = -\frac{a}{2}\left(\sum_k \frac{D_{hk}^{b-1} L_k}{\upsilon_k^b A_k^{b+2}}\right)\frac{W^{b+2}}{\rho_0^{b+1}} - \sum_j \frac{K_j}{A_j^2}\frac{W^2}{2\rho_0} + g\beta\rho_0 \sum_k T_k L_k \cos\theta$$

where the friction factor is expressed in the form of $f = a\,\mathrm{Re}^b$.

In energy equation, the requirement that the coolant enthalpy be continuous around the loop is implemented, and the heat transfer to fluid at the core and the steam generator is taken into account. Detailed information on the point reactor kinetics and the heat transfer models for helical coil steam generator used in the analysis code are presented in Ref. [1].

2.2 Numerical Solution Scheme

On the basis of finite difference scheme, the implicit approach is utilized as a numerical method so that the numerical stability and the economical computation cost can be assured. Shown in Fig. 1 is the flow chart of the developed analysis code. From the initial conditions, energy equation is solved for primary circuit by implicit Euler method to acquire the new enthalpy distribution around the loop. Linear heat transfer rate is obtained from temperature of the previous time step. The energy equation is also solved for the secondary side of steam generator taking the pressure drop into account, and the heat conduction across the tube wall is computed simultaneously with Crank-Nicholson method for the time advancement.

The updated temperature in the primary loop is to calculate the buoyancy term in Eq. (1). Implicit scheme for the integrated momentum equation leads to the non-linear equation of the flow rate, whose solution is found by the iterative Newton-Raphson method. In the next time step, the mean fuel and coolant temperature are reflected to provide the negative feedback effects in the core.

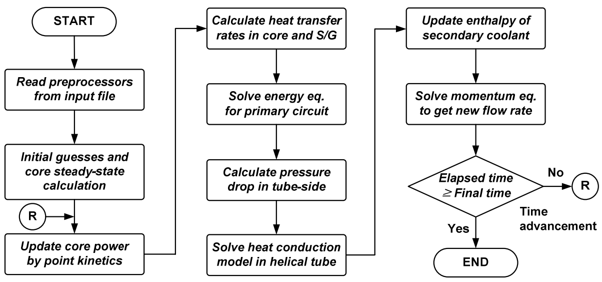

Fig. 1. Flow chart of developed analysis code

3. Comparison with Experimental Data

In order to validate the prediction of the system code, the models and the solution method are applied to REX-10 test facility (RTF). It is to experimentally evaluate the natural circulation capability of the prototype and investigate the thermal-hydraulic behavior of primary loop [2]. RTF consists of electrical heaters, riser, 4 hot legs, and helical coil heat exchanger. Its total height is 4.76m. The heater power, system pressure, and flow rate of secondary feedwater are controlled in the test.

3.1 Steady-state Natural Circulation

With varying the core power, the steady-state mass flow rate by natural convection in the primary loop is computed at 2.0 MPa. The simulation results obtained by the developed code are compared in Fig. 2. As can be seen in the figure, the calculated steady-state mass flow rates show excellent agreement with the test data. The maximum deviation is at most 3%. According to the theoretical investigation by Zvirin, the steady-state natural circulation flow rate is proportional to the total input power to the power of 1/3; the exponent is 0.368 in the simulations. The coolant temperature in the primary system is a little overestimated, but the error is within 10℃ as shown in Table I.

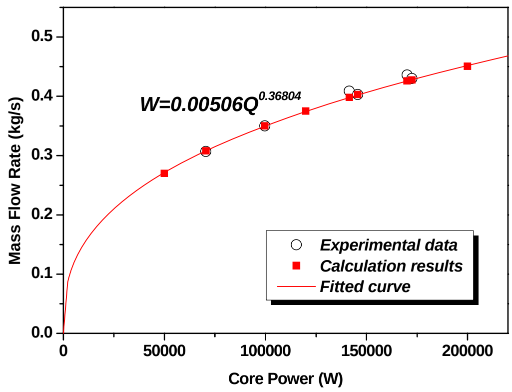

Fig. 2. Steady-state natural circulation with power

Table I: Results comparison – outlet temperature (℃)

Power	Core outlet		S/G outlet		2nd outlet	
(kW)	Exp.	Code	Exp.	Code	Exp.	Code
70.55	106.95	109.93	50.63	50.09	37.49	40.30
99.70	128.21	136.06	60.47	62.10	45.56	48.71
141.55	157.98	168.13	74.15	76.59	56.90	60.77
145.75	159.97	170.89	75.14	77.87	58.44	62.18
170.10	174.36	185.60	83.31	83.52	65.04	69.21
172.45	176.89	186.80	82.95	83.78	65.64	69.73

3.2 Transient Simulations

Figure 3 and 4 show the changes in the mass flow rate and coolant temperature when the core power falls to the half. The abrupt drop of heater power induces the rapid reduction in the natural circulation flow, followed by a slight overshot. Then the mass flow rate slowly decreases until the new stabilized state is established. It is noted that, immediately after the power reduction, the transient of mass flow rate in the experiment is a little bit sluggish compared to the calculated result. It arises from the heat transfer from the reactor internals to the fluid. That is, the stored energy in the structural walls serves as a heat source at the early stage of the transient, which is not taken into account in the simulation. The prediction of temperature variation by the developed code also seems to be acceptable as shown in Fig. 4.

In addition, the comparison results when feedwater flow is decreased by 45% are illustrated in Fig. 5. To conclude, inspection of the results reveals that the trend and new stabilized values are well predicted by the code.

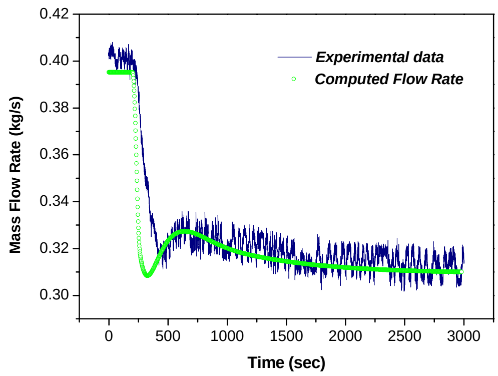

Fig. 3. Change of flow rate by heater power drop

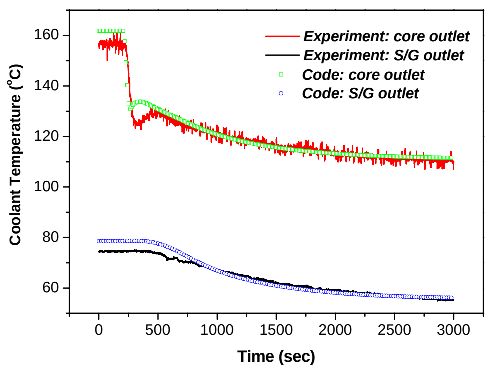

Fig. 4. Change of coolant temperature

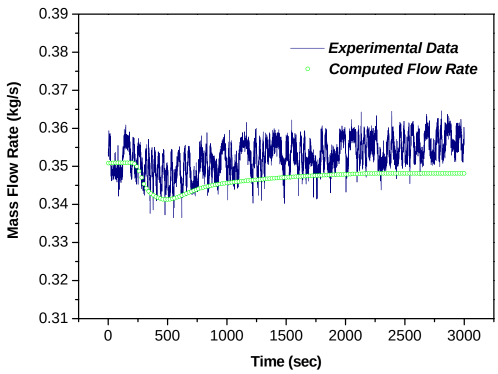

Fig. 5. Change of flow rate by feedwater reduction

4. Conclusions

On the basis of momentum integral model, a simple and fast-running system code is under development for thermal-hydraulic simulation of REX-10. The solution method is applied to the REX-10 test facility and the capability to predict the steady-state flow by the natural convection and the qualitative behavior of the primary system in transients in confirmed.

REFERENCES

[1] Y. G. Lee et al, Development of System Analysis Code for Thermal-Hydraulic Simulation of Integral Reactor, REX-10, Proc. of 2nd Intl. Workshop on Next Generation Regional Energy System Development, Dec. 7-8, 2009, Seoul, Korea

[2] B. I. Jang et al, Experimental Investigation of Natural Circulation in Regional Energy Reactor - 10MWth, Proc. of KNS Autumn Meeting, Oct. 29-30, 2009, Gyeongju, Korea.