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Development of an ECCS Injection Model By Gravity and Flow Rate Distributions in the Passive Reactor Systems

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비상노심냉각수의 중력에 의한 주입 및 피동형노심내의 흐름율 분포모델의 개발

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Abstract

In this study improvement of transient analysis model, KOTRAC, for the passive reactor has been performed. In the KOTRAC, mixture drift flux model is adopted to simulate thermal hydraulic behavior, which can simulate ECCS injection in the passive plant. However, there is a difficulty to handle complete phase separation phenomena due to the near-zero density, which may occur in the pressurizer surge line or horizontal flow paths. In this study, a couple of model changes to overcome Courant limit failure has been examined. One of key features is to substitute flow distribution parameters with Ishii's correlation. Corrected results are well compared to those of RELAP/MOD3 analysis.

요　약

이 연구에서는 피동형원자로의 과도현상을 분석하기 위한 KOTRAC 코드의 모델을 수정한 것이다. 이 코드에서 열수력학 모델로 도입하고 있는 mixture drift flux model은 피동형원자로와 같이 비상냉각수가 중력으로 주입되는 경우를 잘 모사할 수 있으나, 만일 가압기 밀림관 또는 수평관에서 상의 완전분리가 일어나게 될 때에는 증기상에서의 거의 영에 가까운 밀도로 인해 상당한 어려움이 존재하는 것이 밝혀졌다. 이 연구에서는 이러한 어려움을 극복하기 위해 일부 모델을 개선하였는데 가장 두드러진 것은 KOTRAC에서 사용하고 있는 flow distribution parameter를 Ishii 상관식으로 대체하여 코드를 수정하고 해석하였다. 이렇게 수정된 코드를 사용한 결과는 과도상태 해석코드인 RELAP5/MOD3 계산결과와 비교적 잘 일치함을 볼 수 있었다.

1. Introduction

The proposed passive plant concept is to use passive functions to inject the ECCS mainly by the gravity force. Therefore injected flow pattern may lie in the natural circulation region. To finalize this kind of new design concepts, passive flow characteristics should be verified, either throgh experiments or analysis. Many researches have been carried out in that sense[1, 2]. To simulate natural flow characteristics in the reactor core through gravity injection, a lot of simulation modules has been developed. One of them is KOTRAC[3]. In KOTRAC, for the basic thermal-hydraulic model, one-dimensional, area-averaged mixture drift flux model is employed. This tool is much simpler than the sophiscated accident analysis code, RELAP5, which solves six, two-fluid equations, but, it can handle some of accidents like SBLOCA in the passive plant. However, this code has not been completely proven to cover whole spectrum of accidents. We are in the process of developing simple real-time simulation module to use in the reactor LOCA analysis, and possibly to cover all transient analysis. Major difficulties arise in treating the low flow conditions. For the low flow density conditions, numerical scheme may induce the unexpected instability due to Courant limit. This may result in large uncertainties. In the passive reactor systems, such a low density conditions may occur in the pressurizer surge line or horizontal pipes. This study mainly contributes to resolve this difficulty and further to develop the complete analytic modules.

2. Passive Safety Injection Systems

For the reference plant for passive-type reactor, AP-600[4] is selected, since this system is composed of two Core Makeup Tanks(CMTs), two accumulators, and in-containment refueling water storage tank(IRWST), Also in this Plant, automatic depressurization system(ADS) and associated pipings and valves can be modeled to examine the passive characteristics. In AP-600, the safety injection systems are designed to inject emergency core cooling water mainly by gravity force. When SBLOCA at the cold-leg piping occurs, cold water can be injected from CMT to compensate the core pressure drop. If pressure in the reactor coolant system is reduced further, other passive safety functions can play roles to hold pressure drop. CMTs are located in each loop and not connected to cold legs, rather directly connected to downcomers through the direct vessel injection line(DVI) to promote the efficient injection. There are fail-open valves and check valves in the DVI line. And gravity-induced safety injection begins when fail-open valve is actuated. Actuation of fail-open valve is through the signal at the pressurizer low-low level. The check valve is designed to prevent reverse flow from the rector core to CMT. There are two pressure balancing lines in the upper part of CMTs, which one of them is connected to the pressurizer and the other is connected to cold leg. The pressure balancing line between CMT and pressurizer is designed to balance the pressure of CMT with that of primary collant, so that if balance is broken, the injection from the CMTs can begin. Another balancing line connected to cold leg is isolated by valve in the normal operation, but it is actuated when the void fraction at the cold leg exceeds 20%. If this valve is open, the balancing line may be filled with steam at the beginning. This may induce the flow reversely. To prevent flow reversal, there are two check valves attached in each of pressure balancing lines. The schematic digram for safety injection systems for AP-600 is shown in Fig. 1.

3. KOTRAC Module

In this section, main features of KOTRAC[3] thermal-hydraulic model are introduced very briefly. Basic thermal-hydraulic models adopted in the KOTRAC are one-dimensional, area-averaged mixture drift flux models. Major governing equations employed in the KOTRAC are as follows:

Mixture Continuity Equation

$$A_x \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho v A_x) = 0 \tag{1}$$

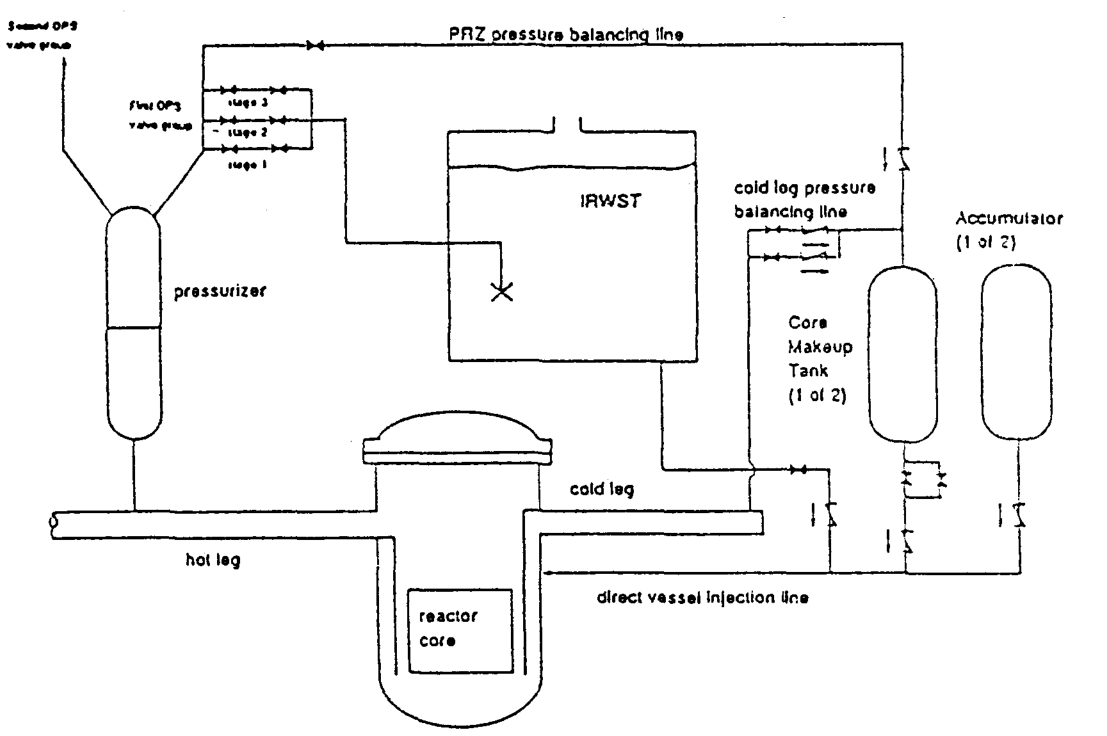

Fig. 1. AP 600 Passive Safety Injection System

Mixture Internal Energy Equation

$$A_x\frac{\partial}{\partial t}(\rho u)+\frac{\partial}{\partial z}(\rho u v A_x) = -P\frac{\partial}{\partial z}(vA_x) \qquad (2)$$

$$-P\frac{\partial}{\partial z}\left[\frac{\rho_l-\rho_g}{\rho} j_D^g\right] A_x$$

$$-\frac{\partial}{\partial z}\left[\frac{\rho_l\rho_g}{\rho}(u_g-u_l) j_D^g\right]A_x + q_w$$

Mixture Momentum Equation

$$\rho\frac{\partial v}{\partial t}+\frac{\rho}{2}\frac{\partial v^2}{\partial z} = -\frac{\partial P}{\partial z}-\frac{\tau_w P_w}{A_x} \qquad (3)$$

$$-\frac{1}{A_x}\frac{\partial}{\partial z}\left[\frac{\rho_l\rho_g}{\rho}\frac{1}{\alpha_l\alpha_g} j_D^{g2}\right]A_x+\rho g\sin\theta+\delta P_p$$

On the other hand, detailed models for the regime-dependent slip correlations are taken from TRAC [5] models. For each flow regime, the relative velocity can be obtained from the following equations:

Bubbly regime:

$$v_r = \frac{1.41}{\alpha_l}\left(\frac{\sigma g(\rho_l-\rho_g)}{\rho_l^2}\right)^{1/4} \qquad (4)$$

Slug regime:

$$v_r = \frac{0.345}{\alpha_l}\left[\frac{gD_h(\rho_l-\rho_g)}{\rho_l}\right]^{1/2} \qquad (5)$$

Churn-turbulent regime:

$$v_r = \frac{v}{(1-C_0\alpha)/(C_0-1)+\alpha\rho_g/\rho} \qquad (6)$$

Where $C_0 = 1.1$

Annular regime:

$$v_r = \frac{v}{[\ \rho_g(76-75\alpha)/\rho_l\sqrt{\alpha}]^{1/2} + \alpha\rho_g/\rho} \quad (7)$$

4. Modifications of KOTRAC Model

Actually KOTRAC code was developed to analyze transient plant behavior in the case of natural circulation. In this study we tried to analyze the flow characteristics in the case of SBLOCA. Unfortunately calculations cannot be completed due to density truncation error [6]. After detail lookup, some defect has been found not to accomplish the analysis. So we try to find the logical errors in KOTRAC model. In the original KOTRAC model, flow distribution parameter, C_0, was assumed as a constant of 1.1 in the drift flux correlation to calculate the relative velocity between liquid and vapor phase. However, this constant value may not be the right assumption for the cases of complete phase separation. This constant flow distribution parameter may give too fast velocity for the vapor, which is not the real velocity. In this study, we tried to find out the correct slip velocity to overcome density truncation errors due to vapor velocity. Newly adopted model is taken from Ishii's flow distribution correlation [7] to simulate the near-complete phase separation. Ishii made the following correlation based on the experimental data as follows:

$$C_0 = \begin{cases} \left(1.2-0.2\sqrt{\dfrac{\rho_g}{\rho_l}}\right)\left(1-e^{-18\langle\alpha\rangle}\right); & \textit{round tube} \\ \left(1.35-0.35\sqrt{\dfrac{\rho_g}{\rho_l}}\right)\left(1-e^{-18\langle\alpha\rangle}\right); & \textit{rectangular channel} \end{cases} \quad (8)$$

Main idea for Ishii's is that C_0 depends on the density ratio (ρ_g/ρ_l) and and the Reynolds number based on liquid properties.

$$C_0 = C_0\left(\frac{\rho_g}{\rho_l}, \frac{GD_H}{\mu_l}\right) \quad (9)$$

In assuming the dependencies, Ishii concluded that the ratio of the maximum velocity to the mean velocity reaches a theoretical limiting value of C_0 at $\alpha \to 0$ and $\rho_g/\rho_l \to 0$, since most of the bubbles are concentrated at the center region. Utilizing the lots of experimental data, Ishii made the limiting value for C_0 as follows:

$$C_\infty = \lim \frac{\langle \alpha j \rangle}{\langle \alpha \rangle \langle j \rangle} = \frac{\langle \alpha \rangle j_0}{\langle \alpha \rangle \langle j \rangle}$$

$$= 1.393 - 0.0155 \ln\left(\frac{GD_H}{\mu_l}\right) \quad (10)$$

If we use the above limiting value for fast vapor, the flow distribution parameter can be given as

$$C_0 = C_\infty - (C_\infty - 1)\sqrt{\rho_g/\rho_l} \quad (11)$$

Substituting the (Eq. 10) into (Eq. 11), we can get (Eq. 8). According to the experiments, for the flow in a round tube, C_0 can be approximately close to nearly constant of 1.2 and for rectangular channels, close to 1.35. However, in the region in which voids are still concentrated close to the tube walls, the mean velocity of vapor can be less than that of liquid, which gives the value of C_0, less than unity. For the low flow regime, like the case of natural circulation in the passive reactor, when the voids are generated at near the wall at the beginning of two-phase, C_0 may reach to a near-zero value. This phenomena can occur specially in the surge line and some of horizontal tubes98, 9, 100. The low value of C_0 can induce the density truncation error due to Courant limit. By utilizing Ishii's correlation, low density truncation is corrected to simulate such low flow conditions.

5. Benchmarking

To find the applicability of revised KOTRAC, 2" break SBLOCA analysis for AP-600 is chosen because there are lots of similar analysis already done. To benchmark the revised version, we try to see how well it forms the flow in the core by injection through gravity force. CMT water is used first as the emergency core cooling water, then accumulators, ADS and IRWST. The purpose of this work is to verify the natural convection conditions in the core, we excluded the reactor coolant pumps(RCPs) and steam generators (S/Gs) as boundary conditions. So AP-600 is modeled as a kind of open loop system. The boundary conditions are given at the regions in which RCPs and S/Gs are located, that is, at the inlets of cold legs and at the end of hot legs. The boundary conditions are generated from RELAP5/MOD3 analysis. With assuming the right boundary conditions, although the system modeled in this work is open loop in form, whole system characteristics can be analyzed as a closed loop.

In this analysis, the reactor system is nodalized into 60 control volumes and 62 connected junctions. The nodalization include two hot legs and three cold legs. The differences in the legs are to model the cold legs at the broken loop into two, which have the broken cold leg and intact cold leg. In other intact loop, one cold leg is assumed by doubling the flow area. In each loop, the reactor core, downcomer, lower plenum, core bypass, upper plenum and upper head are modeled. The core is divided into four volumes, among them two are modeled for power generation. The pressurizer is composed of five nodes and the surge line into three nodes. To see the validity of CMT function, CMT is divided into five nodes and the DVI line into two. Also the pressure balancing line between the pressurizer and CMT is taken into account. Schematics for AP-600 nodalization is represented in Fig. 2.

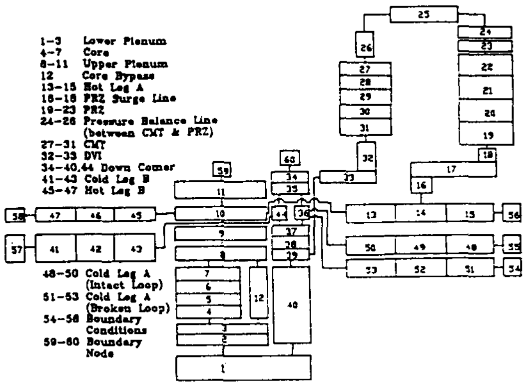

Fig. 2. AP600 Nodalization

6. Results and Conclusions

In this study, the 2 inch break is assumed to occur at cold leg(junction #51). Onset of break, pressure in the primary loop comes to decrease, mainly due to blowdown. When the primary RCS pressure reaches at 132 bar, which is the set point for the pressurizer low pressure, the reactor trip signal is actuated, and control rods start to insert. Delayed time for this action is designed to be 2 seconds. The assuptions for this analysis is listed in Table 1. In the analysis, decay heat is taken as 120% of ANS 73 decay heat model for conservatism. During the accident, pressure decreased to 117.21 bar, that is the low-low pressure setpoint of pressurizer, safety injection signal is generated. After two seconds of delayed time, CMT starts to inject the cold emergency water through DVI lines.

At first, the steady state conditions for the plant was simulated. These conditions can be obtained through the repeated calculations. This is necessary

Table 1. Assumed Accident Developing Conditions

2 inches break accident begins at cold leg	0.0 sec
reactor trip signal occurs	132.01 bar
trip signal delayed time	2.0 sec
safety injection signal occurs	117.21 bar
safety injection signal delayed time	2.0 sec

because the primary coolant flow rate distributions, pressure distributions and temperature distributions are closely related each other. The calculated steady state conditions are presented in Table 2, and calculated accident sequences in time shown in Table 3.

The revised model simulates the accident sequence quite well. After 21.5 seconds, reactor trip is initiated by the calculations. At 25.1 seconds, first injection is started from CMTs(Fig. 3). Before we corrected KOTRAC, the model cannot describe the low-density conditions, which gave very unstable oscillations in the calculations. By substituting Ishii's model for flow parameters, the results can be compared with those of RELAP5/Mod3. Some of comparisons are presented in the figures 3 to 7. The results can show that the revised model is sufficient to handle reactor transients analysis and some of accident analysis. The KOTRAC code is not the complete tool yet. However, this can prove the possibility of real time simulations even in the low flow conditions, specially in the case of a passive reactor design. To compare the CPU time, revised KOTRAC version has been completed within 25 seconds, while RELAP5/MOD3 takes couple of hours in the same case.

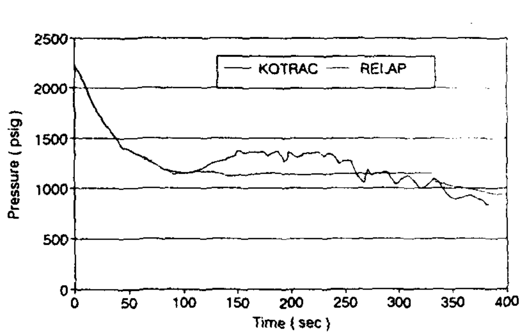

Fig. 3. Pressurizer Pressure

Table 2. AP600 Steady State Conditions for Analyzing SBLOCA

Reactor Power	1812 * 1.02 MWt
Core Inlet Temperature	546.2 K
Core Outlet Temperature	585.2 K
Hot Leg Mass Flow Rate	4684.4 Kg/s
Cold Leg Mass Flow Rate	2340.3 Kg/s
Hot Leg Pressure	157.6 bar
Cold Leg Pressure	158.5 bar
Pressurizer Pressure	157.2 bar
CMT Volume	56.0 m^3
CMT Temperature	337.8 K

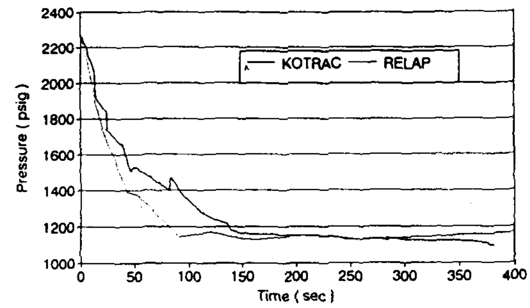

Fig. 4. Core Pressure

Table 3. Calculated Accident Developing Progresse in Time

	Time (s)
break accident begins	0.0
reactor trip signal	19.5
safety ijection signal occurs	23.1
safety injection begins	25.1

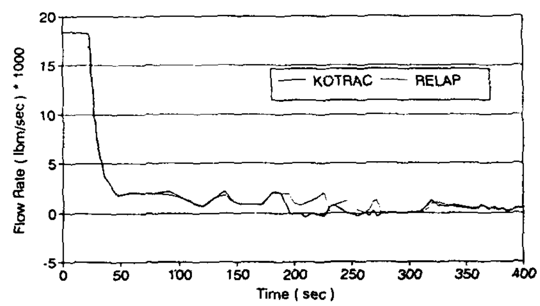

Fig. 5. Coolant flow rate in core

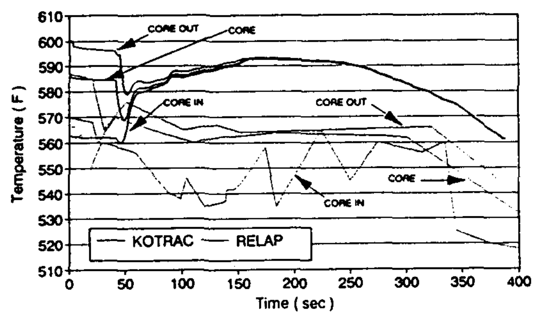

Fig. 6. Temp. in Core inlet and outlet

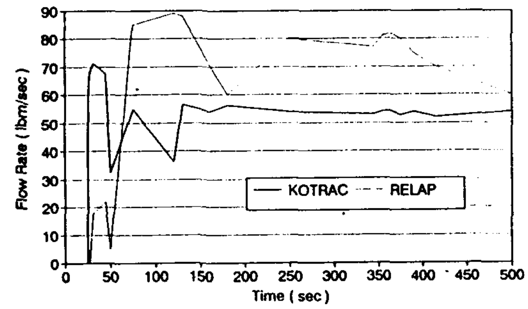

Fig. 7. Core Makeup Tank Flow Rate

Nomenclature

- A_k Cross Sectional Flow Area
- C_o Flow Distribution Parameter
- D_H Hydraulic Diameter
- g Gravitational constant
- j_D^g Drift Flux
- P Pressure
- P_w Wetted Perimeter
- q_w Wall Heat Transfer Rate
- u Internal Energy
- v Velocity
- v_r Relative Velocity
- α Void Fraction
- ρ Density
- σ Shear Stress
- τ_w Wall Shear Stress
- θ Angle of Inclination

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