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Study of the RETRAN Code for Upper Plenum Analysis in Very Small LOCA

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매우 작은 규모의 LOCA에 있어서 Upper Plenum 분석을 위한 RETRAN코드의 연구

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Abstract

In the application of the RETRAN code to the analysis of very small LOCA one of main concerns is placed on use of the bubble rise model in the upper plenum, because the bubble rise model may cause a numerical divergence problem and coefficients used to describe it are based on experimental results of large LOCA. In order to solve this problem, a method, which enables us to predict the mixture level in the upper plenum without use of the bubble rise model, was proposed. For this method the local void distribution in the core and upper plenum was derived by using a simplified slip model. It was shown that results predicted from the derived equation are in excellent agreement with experimental data. Additionally it was found that local void in the upper plenum has a uniform distribution unlike a linear distribution in large LOCA. Communication between the upper plenum and uppr head was investigated. By introducing the concept of Taylor instability, it was proved that counter-current flow between them is possible.

요 약

매우 작은 규모 LOCA 분석에 RETRAN코드 적용에 있어서 중요 문제점의 하나는 upper plenum에 Bubble rise model의 사용에 있다. 왜냐하면, Bubble rise model은 수리적 발산을 야기할 지 모르며, 그 모델에 사용되는 계수는 큰 규모 냉각재 상실 사고의 실험적 결과에 바탕을 두기 때문이다. 여기서, Bubble rise model을 사용하지 않고 upper plenum의 mixture level을 예측하게 해주는 방법이 제시되었다. 이 방법을 위해 노심과 upper plenum내의 지역 void 분포가 간단한 slip 모델을 이용해 유도되었다. 유도된 식으로부터의 결과는 실험 데이타와 매우 잘 일치한다는 것이 발견되었다. 또한, upper plenum에 있어서 지역 void는 대규모 LOCA에 있어서 선형 분포와는 달리 균일한 분포를 하고 있다는 것이 발견되었다. upper plenum과 upper head사이의 냉각재 교환이 연구되었다. Taylor instability 개념 도입에 의해 그들 사이에 counter- current flow가 가능하다는 것이 증명되었다.

1. Introduction

In the analysis of large LOCA the effect of the upper plenum on LOCA history is not significant, compared to the lower penum. However, in the analysis of very small LOCA such as in the TMI-2 accident, the effect of the upper plenum is expected to be considerable due to several reasons such as long-term transients, geometry, and location of the upper plenum.

The vapor region produced in the upper plenum has several important effects on the history of very small LOCA. Before the level of two-phase mixture goes down the level of exit, the vapor region in the upper plenum may control the system pressure in certain circumstances such as in the case of lack of ability of decay heat removal, which occurred in the TMI-2 accident. Lack of ability of decay heat removal results in high vaporization in the core and thus more phase separation in the upper plenum. More phase separation causes increase in pressure in the vapor region and thus in the system. After the level of two-phase mixture goes down belows the level of exit, only vapor passes through pipes to steam generators. Then heat transfer in steam generators is greatly reduced and two-phase flow in the outlet of steam generators may be expected. As a result, it may be inevitable to trip reactor coolant pumps in accordance with the emergency operating procedure to preclude the possibility of damage to the reactor coolant pumps from operation in two-phase flow. Moreover, the natural convection of two-phase mixture is not possible, because the level of two-phase mixture of the reactor vessel goes down below the exit. The primary system behaves like a boiling pot. The primary system level continues dropping and the top of the core begins to be uncovered under high pressure unless make-up mass flow from the high pressure injection system exceeds mass loss through break. Steam begins to be superheated in the uncovered region of the core. Function of the upper plenum as junction for several components raises the importances of the analysis of bubble development in the upper plenum. Some bubbles generated in the core are separated in the interface between the two-phase mixture and vapor region, and others pass through pipes. The prediction of thermodynamic variables in the upper plenum affects flow and heat transfer in pipes and steam generators. A long-term transient requires more complex analysis, because the communication between the upper plenum and adjacent components such as the upper head should be studied. The large mass inventory of the upper head prevents upper plenum from earlier drain. Longer drain time enables system to produce lower decay heat when the top of the core begins to be uncovered. Although the analysis of the upper plenum has been recognized to be very important, just few researches have been done due to complex geometry and complicated physical phenomena.

2. RETRAN Code Description

RETRAN(1) represents a computer code approach developed from the RELAP series(2) for analysing the thermal-hydraulic response of Nuclear Steam Systems (NSSS) to LOCA and operational transients. RETRAN is a combination of three models; 1) a thermal and hydraulic model, 2) a conduction model, and 3) a nuclear model.

A thermal and hydraulic model in RETRAN-2 consists of dynamic slip, equilibrium, and one dimensional flow equations. The basic fluid model is based on mass and energy balances on control volumes that are connected by junction. Momentum equations are solved to obtain flow through the junctions. The code capabilities allow many complex flow systems such as an upper plenum and lower plenum to be analysed. Heat can be added to or subtracted from any control volume by appropriate specification of input. This is done with conduction models to represent heat conduction within fuel rods, heavy-section walls, and heat exchangers. These conduction models are connected to the fluid control volumes with heat-transfer coefficients that are selected. Heat transfer correlations are applied on both the primary and secondary sides of a steam generators.

Both of point-kinetics and one-dimensional kinetics models can be used in RETRAN-2 to calculate a normalized core power. The reactivity includes a time-dependent contribution to account for scram and a contribution to account for feedback effects in each core region. Fission-product decay is calculated as the sum of the direct fission power and the radioactive-decay power. Other capabilities of RETRAN include the ability to represent various types of values at junctions that are controlled by a trip time or a property (such as pressure) sensor. Leak and fill junctions (specified outflow and inflow) are available. Models are available in the code to represent the pumps in a nuclear system, and the metal-reaction between the zirconium cladding on the fuel rods and the water.

Basically the control volume approach does not allow phase separation in certain vertical sections and only represents mixed average values over a control volume. Thus, RETRAN introduces a phase separation model, termed the bubble rise model which is a combination of a semi-empirical relation for vapor phase or bubble distribution and a differential equations for the mass of vapor at any time in a volume. This model assumes that the partial density of bubbles increases linearly in the vertical direction within the two-phase mixture. This linear variation is an input to the code for each control volume. In addition, a steam dome on the top of this volume is allowed. Use of the bubble rise model presents difficulty when convergence is investigated. In particular, subdivision of a volume into a series of vertical volumes exhibits a layer-cake effect of steam or top of water in each of these volumes that does not converge with increasing subdivision.

The bubble rise model depends on the assumed linear distribution in two-phase mixture below the steam dome, linear-gradient-of void coefficient Co and bubble velocity at the interface. The assumed linear distribution is questionable in very small LOCA, because in very small LOCA most of bubbles in the upper plenum are generated in the core by evaporation rather than flashing in the upper plenum due to depressurization.

Also, since the recommended bubble velocity, 3ft/sec, was obtained by experimental data of simulated large LOCA with pump trip, a modification is needed.

3. Prediction of Mixture Level in Upper Plenum from Dynamic Slip, Equilibrium Model (SEM) without Bubble Rise Model

As shown before, use of the bubble rise model results in several problems such as divergence and thus use of SEM without use of the bubble rise model facilitates calculation. However, since SEM without the bubble rise model does not allow phase separation and only represents mixed average values, the mixture level of the upper plenum remains to be unknown. Let us derive an equation which leads to the prediction of the mixture level and is expressed in terms of parameters defined by SEM.

The parameters defined by SEM are as follows:

1) Volume and property parameters; average quality ($\bar{X}$), total fluid mass (M_T), saturated vapor density (ρ_V), saturated liquid density (ρ_l), pressure

2) Junction parameters; void fraction at the exit of the core (α_{in})

3) Input parameters; total volume (V_T), flow area of the upper plenum (A), height of the upper plenum (L_T)

By volume conservation,

$$L_T = L_s + L_m, \qquad \text{Eq. (1)}$$

where L_s and L_m are the heights of the steam dome and two-phase mixture in the upper plenum, respectively.

By mass conservation,

$$M_T = M_s + M_b + M_l, \qquad \text{Eq. (2)}$$

where M_s, M_b, and M_l are vapor mass in the steam dome, and bubble and liquid mass in the mixture, respectively.

$$M_s = L_s A \rho_v$$

$$M_b = L_m A \alpha_m \rho_v$$

$$M_l = L_m A (1-\alpha_m)\rho_l, \qquad \text{Eq. (3)}$$

where α_m is the void fraction of mixture in the upper plenum. In the coming section the following relationship will be proved.

$$\alpha_m = \alpha_{in} \qquad \text{Eq. (4)}$$

By the definition of average quality $\bar{X}$

$$\bar{X} M_T = M_s + M_b \qquad \text{Eq. (5)}$$

Substituting Eq. (3) into Eq. (5) and rearranging the results, we obtain the mixture level

$$L_m = \frac{L_T A \rho_v - \bar{X} M_T}{A \rho_v (1-\alpha_{in})} \qquad \text{Eq. (6)}$$

In Eq. (6) void fraction at the inlet of the upper plenum, α_{in}, can be calculated from an equation derived by a simplified slip model in the following section.

4. Simplified Slip Model

Since the assumed linear vapor distribution is not valid for very small LOCA unlike large LOCA, the following analytical solutions derived by Vea and Lahey[3] is modified in order to obtain more reasonable void distribution in the core and upper plenum.

$$\frac{d\alpha}{dz} = \frac{\left[\dfrac{\Gamma}{\rho_v} - C\alpha\dfrac{\partial j}{\partial z} - \dfrac{\alpha}{\rho_v}\dfrac{d\rho_v}{dp}\cdot\dfrac{dp}{dt}\right]}{\left[Cj + \alpha\dfrac{dV_{vj}}{d\alpha} + V_{vj}\right]} \qquad \text{Eq. (7)}$$

where Γ : volumetrical evaporation rate

j : superficial velocity

C : vapor concentration coefficient

V_{vj} : drift velocity

Assumptions used for the derivation of Eq. (7) are as follows:

1) one dimensional two-phase flow with constant cross section

2) thermodynamic equilibrium

3) neglecting kinetic and potential energy

Confining ourselves to very small LOCA, we can simplify the above equation. In very small LOCA, the amount of vapor produced by flashing is very small, compared to that by heat. Also after system pressure reaches saturation pressure, pressure changes very slowly with time. Therefore, we can neglect dp/dt. Then, Equation (7) becomes.

$$\frac{d\alpha}{dz} = \frac{\dfrac{\Gamma}{\rho_v} - C\alpha\dfrac{\partial j}{\partial z}}{Cj + \alpha\dfrac{dV_{vj}}{d\alpha} + V_{vj}}, \qquad \text{Eq. (8)}$$

A well established relationship for V_{vj} is

$$V_{vj} = V_\infty (1-\alpha)^n, \qquad \text{Eq. (9)}$$

where V_∞ : terminal rise velocity of bubbles

Taking $n=0$ for churn-turbulent formulation, which was recommended by Vea and Lahey, we obtain the following equation

$$\frac{d\alpha}{dz} = \frac{\dfrac{\Gamma}{\rho_v} - C\alpha\dfrac{\partial j}{\partial z}}{Cj + V_\infty} \qquad \text{Eq. (10)}$$

Introducing the average volumetric mass exchange rate $\bar{\Gamma}$, we have

$$j = j_0 + \bar{\Gamma}\frac{\rho_l - \rho_v}{\rho_l \rho_v} z, \qquad \text{Eq. (11)}$$

where j_0 : superficial velocity at the inlet of the core

z : axial position from the inlet of the core

$$\bar{\Gamma}=\frac{1}{z}\int_0^z \Gamma dz \qquad \text{Eq. (12)}$$

$$\Gamma=\frac{q'' P_H}{h_{fg}\rho_v A}, \qquad \text{Eq. (13)}$$

where q'' : heat flux

P_H : perimeter of fuels

Substituting Eq. (11) into Eq. (10) and integrating the results from the inlet to z, we obtain void fraction.

$$\alpha(z)=\frac{\frac{\bar{\Gamma}}{\rho_v}z+[Cj_0+V_\infty]\alpha_{in}}{\frac{\rho_l-\rho_v}{\rho_l\rho_v}\bar{\Gamma}Cz+[Cj_0+V_\infty]} \qquad \text{Eq. (14)}$$

Justification of Eq. (14) can be shown in Figs (1) and (2) which present results calculated from Eq. (14) and Carl's experimental data[4]. The results from Eq. (14) are in good agreement with data.

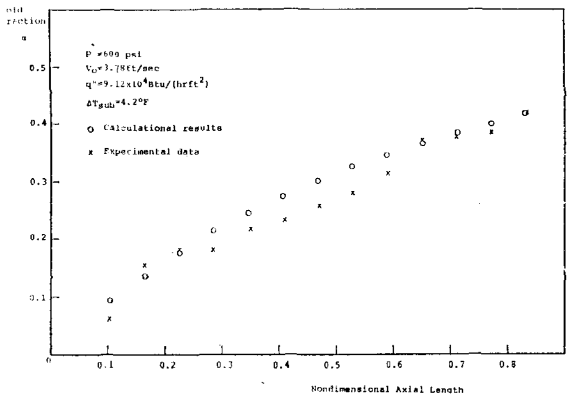

Fig. 1. Comparison between Experimental Data and Calculational Results

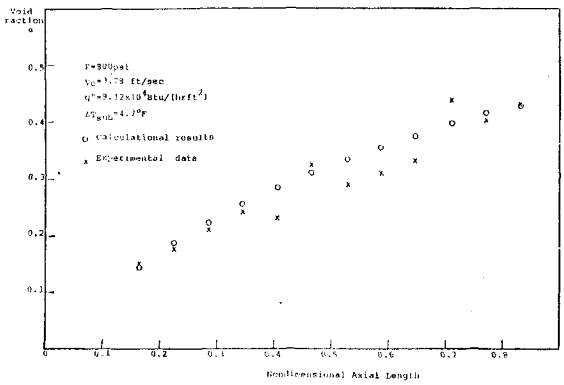

Fig. 2. Comparison between Experimental Data and Calculational Results

Let us obtain local vapor distribution in the upper plenum from Eq. (14). In the upper plenum there is little vapor generation ($\bar{\Gamma}=0$). Then we have uniform void distribution in the upper plenum. Therefore, the zero value for the gradient of void coefficient C_0 is recommended instead of 0.8 recommended in RETRAN, if the bubble rise model is used in the analysis of very small LOCA.

5. Communication Between Upper Plenum and Upper Head

The upper core support structure consists of the upper support assembly and upper core plate between which there are support columes and guide tube assemblies. The support columns establish the spacing between the top support plate assembly and upper core plate and are fastened at top and bottom to these plates. Also the upper core plate and upper support plate act as the boundaries for the upper plenum at the outlet of the core. Each UHI column has a central axial flow passage for conveying core cooling water to the core when it is injected into the vessel head. The water enters the flow passage through a small hole on the side of the top of the UHI system. The upper guide tubes for the control rod also serve to transport UHI water from the upper region to the upper plenum directly above the fuel assemblies. In very small LOCA a question is raised whether counter-current flow between the upper head and upper plenum is possible or not. It was known that water is retained by atmosphere pressure in an inverted tumbler whose mouth is closed by gauze of sufficiently fine meshes. The mesh size should not exceed $0.5\lambda_c$ in order to retain water in the tumbler.

$$\lambda_c=2\pi\left[\frac{\sigma}{g(\rho_l-\rho_{air})}\right],$$

where σ and g: surface tension and gravitational acceleration

ρ_l and ρ_{air}: water and air density, respectively

According to the above result it can be said that the disturbances of the interface becomes unstable when the wavelength is longer than the cutoff wavelength λ_c. This instability is called Taylor instability. Then we may conclude that, when the diameters of flow passage through the upper support column and upper guide tube are greater than $0.5\lambda_c$, the counter-current flow occurs between the upper head and upper plenum. At 1,200 psi and 560°F $0.5\lambda_c$ is equal to 0.23 in., which is considerably less than the diameters of flow passage through the upper support column and upper guide tube. Therefore, the counter-current flow between the upper head and upper plenum is possible.

6. Conclusions

Importance of the upper plenum in the analysis of very smally break LOCA was emphasized here; the prediction of the mixture level, void fraction, and thermodynamic variables in the upper plenum has a strong effect on pressure, flow, and heat transfer in system. For use of SEM without the bubble rise model in the analysis of very small LOCA, an equation was derived which leads to the prediction of the mixture level in the upper plenum. Local void fraction in the core and upper plenum was derived by using a simplified slip model. The results from the derived equation are in good agreement with data. It was found that the void distribution in the upper plenum is uniform. The zero value of C_0 is recommended instead of 0.8 for the analysis of very small break LOCA, if the bubble rise model is used. By introducing the concept of Taylor instability, it was proved that counter-current flow between the upper head and upper plenum is possible.

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