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Improvement of Direct Contact Condensation Model of RELAP5/MOD3.1 for Passive High-Pressure Injection System

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ABSTRACT

A simple set of the transition criterion of the condensation regimes and the heat transfer coefficients on the direct contact condensation of the core makeup tank is developed, and implemented in RELAP5/MOD3.1. The condensation regimes are divided into two regimes: supply limit and condensation limit. In modeling the transition criterion between two regimes, a large-eddy model developed by Theofanous is used, and the empirical coefficient of the present large-eddy model is close to that of the large-eddy model. It turns out that the modified code better predicts the experimental data, especially the injection flow rate and the water level trend than the original code does.

1 Introduction

At Center for Advanced Reactor Research(CARR) in Korea, a passive PWR concept named CARR Passive Reactor(CP-1300) has been developed by adopting a passive engineered-safety-feature-system as shown in Figure 1. The CP-1300 is a large passive PWR with the power of 1300MWe because of the lack of a plant site and a decrease of construction costs per power. The CP-1300 adopts the core of Korea Standard Nuclear Power Plant(KSNPP) such as YGN units 3 and 4 PWRs and Ulchin units 3 and 4 PWRs. The RCS of the CP-1300 consists of 2 hot legs and 4 cold legs (2 loop), which is the same as those of KSNPP and System 80+. Instead of canned motor pumps used in AP600, sealed pumps are used. A natural circulation loop with two heat exchangers immersed in the pool is installed in the secondary side of each S/G to achieve passive residual heat removal system(PRHRS). In addition, two natural circulation loops serve as passive containment cooling system(PCCS). The CP-1300 passive safety injection system consists of Passive High-Pressure Injection System(PHPIS), accumulators, and In-Containment Refueling Water Storage Tank(IRWST), which are used to supply emergency core cooling water at high, intermediate, and low pressure, respectively. In order to provide RCS with IRWST water at low pressure, automatic depressurization system(ADS) is installed.

The PHPIS consists of the core makeup tanks(CMTs) with a sparger and the pressurizer pressure balancing line(PRZ PBL). The PHPIS can provide cold water at any RCS pressure by gravity force because the pressure of the CMT is equilibrated with the reactor coolant system through lines connecting the inlet of the CMT to the pressurizer. The major merit of the PHPIS is that it is considered to have a potential to establish a more reliable means to replenish the reactor coolant inventory without operator's intervention.

RELAP5/MOD3.1 [1] developed at Idaho National Engineering Laboratory (INEL) has been widely through the world to develop advanced reactors. However, there is no reliable model in

RELAP5 that can deal with the direct contact condensation of steam in the pool like the CMT. To simulate the accidents of passive advanced reactors like the CP-1300 by using RELAP5, it is essential to develop the condensation regime map and the model for the interfacial heat transfer coefficients of the direct contact condensation of steam in the pool.

In present study, to improve the direct contact condensation model of the core makeup tank, a simple set of the transition criterion and the heat transfer coefficients is developed, and implemented in RELAP5/MOD3.1 based on the experiments [3]. Also, to investigate the degree of the improvement of RELAP5/MOD3.1, the experiments are siumlated by the original and modified codes.

2 Transition criterion and interfacial heat transfer coefficients

2.1 Condensation regimes according to steam supply limit

As suggested by Block [4], mixing in the pool and creation of additional interface can lead to such potentially high rates of condensation, and the actual rate of condensation is limited by the rate at which the system can supply steam to the interface. This regime is named "supply limit" in the present study. The supply limit is also limited by the choking flow phenomenon.

Through the experiments [3], it is observed that as soon as the injection valve is opened, the pressure of the test section decreases below the atmospheric pressure. The pressure of the test section begins to increase just after the injection starts. During this period, the pressure of the test section can not increase because the steam supplied by the steam generator completely condense in the test section. In this period, though the capability of the liquid to absorb the latent heat of the steam is larger than the amount of the steam supply, the condensation rate is limited by the steam supply rate. This condensation region belongs to "supply limit".

There exists the transition moment at which the condensation rate becomes smaller than the steam supply rate. This transition results from the decrease of the capability of the liquid to absorb the latent heat of the steam because of an increase in the water temperature. In this regime, the condensation rate is limited by the ability of the liquid to absorb the energy released through the steam condensation. This regime is called "condensation limit".

After the regime in the test section is converted into the condensation limit, the pressure in the test section begins to increase because of the buildup of the steam which does not condense in the test section. As a result, the pressure of the top of the test section recovers and then the water in the tank begins to inject.

2.2 Regime transition criterion

Block [4] suggested the thermodynamic ratio, R_T, as the transition criterion for constructing universal regime map for the direct contact condensation. The definition of R_T is as follows:

$$R_T = \frac{c_{pf}(T_g - T_f)W_f}{h_{fg}W_g}. \tag{1}$$

However, it is hard to define a liquid flow rate for the present system. From the energy and mass balance for the condensation limit, this ratio can be replaced by the following equation:

$$R_T = \frac{h_i A_i(T_g - T_f)}{h_{fg}W_g}. \tag{2}$$

This parameter, which is related to the Jacob number, expresses the capability of the liquid to absorb the latent heat of the steam that is injected into the pool. $R_T > 1$ means that the capability of the liquid to absorb the latent heat of the steam is greater than the energy transferred by the steam. This means the complete condensation of the steam in the pool. This regime is classified as the supply limit. $R_T < 1$ means the incomplete condensation of the steam in the pool. This regime is classified as the condensation limit.

If the proper expressions for h_i and A_i can be found, a criterion for the condensation limit can be developed by using Eq.(2). As observed from experiments [3], at the transition condition, the water level drops just below the top of the tank, and at the center of the tank, the steam cavity forms. Since the steam cavity is small compared with the tank area, A_t, the associated interfacial area, A_i, can be regarded as the tank area, A_t.

The remaining step in developing the transition criterion is to find an appropriate expression for the interfacial heat transfer coefficient, h_i. Liang [2] predicted the interfacial heat transfer coefficient for modeling the transition criterion between the bubbling and the subsonic jet by using the two-layer eddy transfer model. This model is developed by Theofanous, et al [6]. They proposed that there are two kinds of eddies controlling the transport process, the large and small eddies. The large eddies have the energy-containing motions, while the small eddies do the energy-dissipating ones. The heat transfer analogies of the equations obtained by Theofanous et al. for gas absorption in turbulent liquids are [7]:

$$Nu_t \sim C_{UET} Re_t^{3/4} Pr^{1/2} \qquad for\ Re_t > 500, \tag{3}$$

$$Nu_t \sim C_{IMA} Re_t^{1/2} Pr^{1/2} \qquad for\ Re_t < 500, \tag{4}$$

where the values of C_{UET} and C_{IMA} recommeded by Theofanous et al. are 0.25 and 0.70, respectively. C_{UET} is a universal constant independent of the particular geometry and other macroscopic variables of the system. However, C_{IMA} is not expected to be universal due to greater sensitivity of the large scale motions to macroscopic flow details [6].

To use Eqs.(3) or (4), the possible range of the turbulent Reynolds number, R_t must be estimated. To evaluate Re_t, the appropriate scale of the turbulent intensity, V, and the characteristic length, L must be defined.

Assuming that all the kinetic energy of steam injected into the pool is transferred to the energy inducing the energy-containing motions, the following energy balance equation is used for determining the turbulent intensity, V:

$$\rho_f \frac{V^3}{L}(\delta_w A_t) = \rho_g v_g (\frac{1}{2} v_g^2) A_j, \tag{5}$$

where A_t and A_j are the areas of the tank and the steam pipe, respectively, and v_g is the steam velocity at the exit of the steam pipe.

From the knowledge of the single phase free turbulence, it is known that the ratio between the characteristic length(V) to the layer thickness (δ_w) is about 1/5 [2]. Therefore, the above equation can be simplified as:

$$V \approx 1.4(\frac{A_j}{A_t})^{1/3}(\frac{\rho_s}{\rho_f})^{1/3} v_g. \tag{6}$$

The characteristic length, L, can be scaled roughly by the dimension of the steam inlet diameter. That is:

$$L = D_j. \tag{7}$$

Using Eqs.(6) and (7), it is found that the range of the turbulent Reynolds is less than 500. Therefore, the proportionality constant, C_{IMA}, has to be determined from the present experiment. Using Eqs. (6), (7) and (4), Eq. (2) can be expressed as follows:

$$R_T = 1.183 C_{IMA} N_A^{-5/6} N_\rho^{1/6} N_\nu^{-1/2} Pr^{-1/2} Re_s^{-1/2} Ja. \tag{8}$$

After fitting with the experimental data of Tests GI021 and GS021 [3], it is found that the values of C_{IMA} is 0.545 and 0.989, respectively. The values are within 40% of the coefficient of the large-eddy model, 0.70.

2.3 Interfacial heat transfer coefficients

The volumetric interfacial heat transfer coefficient for the supply limit can be easily obtained because the steam injected into the pool completely condenses:

$$H_{if} = \frac{\rho_g v_g A_j h_{fg}}{V_t(T_g - T_f)}, \tag{9}$$

where V_t is the volume of the highest cell in the tank.

By experimental observation [3], as soon as the transition occurs, the water injection starts. In the condensation limit, the main flow pattern is the vertical stratified flow. Therefore, the interfacial heat transfer coefficient can use MacAdam's correlation which is used for RELAP5/MOD3.1:

$$Nu = 0.27(GrPr)^{0.25}. \tag{10}$$

In the code, the transition criterion, R_T is checked to identify whether the flow regime is the supply limit or the condensation limit. After that, the appropriate heat transfer coefficient is used to calculate H_{if}.

3 Simulation

Figure 2 shows the experimental facility which is used for the gravity injection experiments [3]. RELAP5 nodalization used to simulate the experiments is represented in Figure 3. The model is based on 43 volumes connected by 43 junctions and 3 heat structures for the electric heaters.

At 10sec, the injection valve, V_6 is opened within 0.1sec. When the injection valve is opened , the water drains to the atmosphere which is modeled as a time dependent volume (200). If the large pressure drop occurs in the test section, there exists the possibility for air to enter the test section through the injection line. To prevent this, a check valve is installed at SJ171.

It is reported [5] that the results simulated by RELAP5 show the different trend at the different node number and size, and that 1-node and 2-node models predicts better the experimental data than the multi-node models do. It is shown that the heat of the upper node does not transfer to the lower node at all because the code with the 1-D model does not account for internal circulation. Therefore, it is recommended that the test section is modeled by pipe having 2 volumes so that the code may represent the thermal stratification as shown in Figure 3 of Ref. [3]. The upper node simulates the hot layer of thermal stratification.

To predict the injection time, it is important to estimate the thickness of the hot layer. To estimate the thickness of the upper node of the test section, the following energy balance can be used:

$$\sum_{upper,\ lower\ nodes} [(\rho_f A_t L_n c_{pf} T)_{t=t_{inj}} - (\rho_f A_t L_n c_{pf} T)_{t=t_i}] = h_{fg} \int_{t_i}^{t_{inj}} W_g dt, \tag{11}$$

where the parameters can be obtained from the experimental data. By using Eq.(11), the calculated lengths of the upper node for Tests GI021 and GS021 are 0.53 and 0.21m, respectively. The node sizes of 160-1 for Tests GI021 and GS021 are 0.5m and 0.22m, respectively.

Tests GI021 and GS021 are simulated by the original and modified codes of RELAP5/MOD3.1 to estimate the degree of the improvement of RELAP5/MOD3.1. The test conditions of Tests GI021 and GS021 are shown in Table 2 of Ref. [3].

Figure 4 show the comparison of injection flow rates between the calculated results and the experimental data. The modified code better predicts the time of the injection initiation than the original code does. Also, it well predicts the injection flow rate. As shown in Figure 5, the modified code better predicts the experimental data of the water level than the original code does. However, the results of the modified code for Test GS021 show that the gradient of the decrease of the water level of the modified code is larger than that of the experimental data. This seems to be due to the uncertainty of the interfacial heat transfer coefficient for the condensation limit regime.

4 Conclusions

The primary objective of the present study is to improve the model of RELAP5/MOD3.1 on the direct contact condensation in the CMT. From the present study, it is found that the condensation regimes are divided into two regimes: supply limit and condensation limit. In modeling the transition criterion, the large-eddy model by Theofanous is used, and the constant, C_{IMA} empirically determined here is close to that of large-eddy model. it turns out that the modified code better predicts the experimental data, such as the injection time, the injection rate, and the water level than the original code does.

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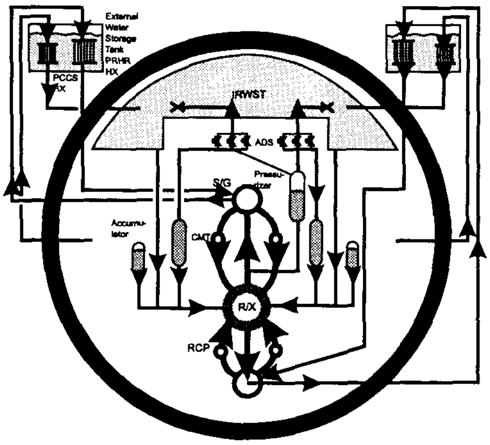

Fig. 1 A schematic diagram of CARR Passive Reactor

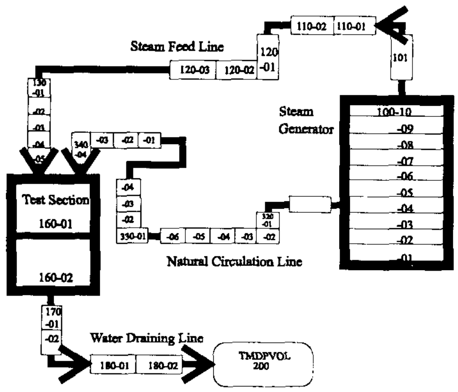

Fig. 3 RELAP5 nodalization

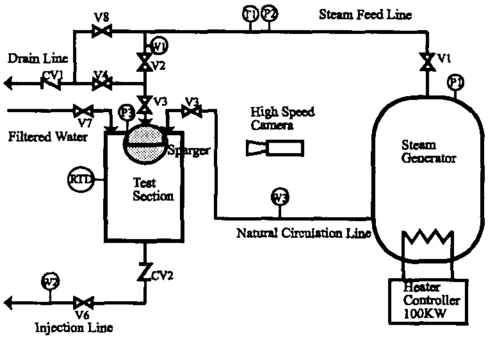

Fig. 2 A schematic diagram of test facility

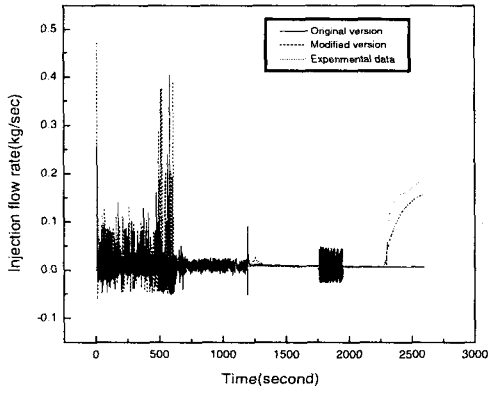

Fig. 4 Comparison of injection flow between original and modified versions for Test GI021

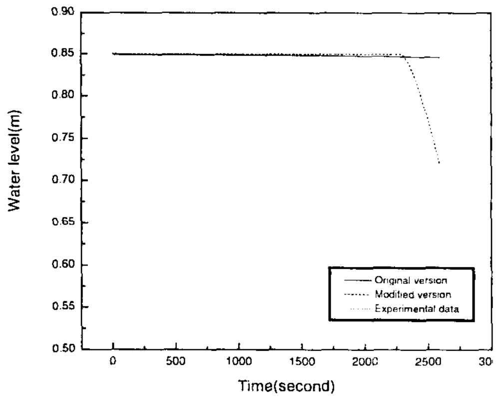

Fig. 5 Comparison of water level between original and modified versions for Test GI021