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Preliminary Study on Interfacial Transfer Models on Water Surface to Predict Steam Pressurizer Behaviors

Minkyu Lee [a*] and Seungyeob Ryu [a]
[a] *Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, 34057, Republic of Korea*
[*] *Corresponding author: leemk@kaeri.re.kr*

1. Introduction

A pressurizer (PZR) is one of the main components of Reactor Coolant System (RCS), and it functions to pressurize the primary system and to maintain the reactor coolant in the subcooled state during normal operation. The pressurizer accommodates the volume changes of the reactor coolant, and it controls the RCS pressure within Limiting Conditions for Operation (LCO) on normal transient conditions.

A steam pressurizer, which saturated steam and water coexist in the pressurizer, has been adopted for commercial Pressurized Water Reactors (PWRs), because it has various advantages for the pressure controls. Many researches have been studied to predict thermal-hydraulic behaviors in the steam pressurizer; thus, various models and theories are established since the 1950s.

Two typical models (single-region and two-regions) and interface transfer model on water surface are summarized. The models are implemented in an in-house code (developed in MATLAB language) to assess the effects of condensation and evaporation factors. In this paper, the models and results of sensitivity studies with varying the factors are described for the preliminary studies to apply the steam pressurizer model.

2. Analysis Models

To predict the steam pressurizer behaviors, the single-region model and two-region model are used for steam and water region [1, 2]. In two-region model, the flashing and rain-out condensation are calculated when the system pressure decreases during out-surge transient. Additionally, the kinetic theory of gas for direct condensation and evaporation is considered on the steam-water interface [3].

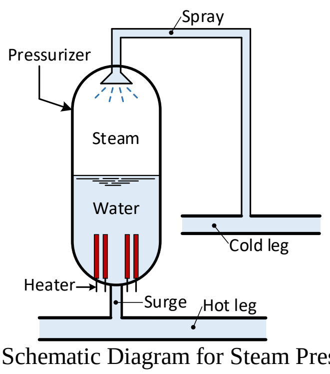

Figure 1. Schematic Diagram for Steam Pressurizer.

2.1 Single-region Model

Single-region model considers that steam and water coexists on saturation states in single control volume; thus, the only total mass and internal energy are calculated by using boundary conditions [2]. This model is simple, but it could not calculate the amount of phase changes between steam and water.

2.2 Two-region Model

Two-region model considers that the pressurizer is divided into steam and water region. This model can calculate heat and mass transfer rates by using various phase change models like flash boiling, rain-out condensation, and direct condensation and evaporation on interface [2].

2.3 Interfacial Transfer Models for Direct Condensation and Evaporation on Water Surface

Direct condensation and evaporation are interface phenomena which have studied from the kinetic theory of gas as depicted in Figure 2. This theory determines the interfacial transfer rate based on the frequency of molecular motion and collisions on the interface between water and steam. This approach fundamentally differs from diffusion model which is considered that transfer phenomena is governed by concentration gradients in the domain. The kinetics theory is based on the difference between two quantities – a rate of arrival of molecules from the steam to water surface and a rate of departure from the water to the steam space. The simple kinetics theory on the interface is as follows:

$$j_{\text{interface}} = j_g - j_f = F_{\text{interface}} \left(\frac{M}{2\pi R} \right)^{0.5} \left(\frac{P_g}{T_g^{0.5}} - \frac{P_f}{T_f^{0.5}} \right) \qquad (1)$$

where, j, $F_{interface}$, M, and R stand for molecular flux (or mass transfer rate per unit area), interface factor, the molecular weight and the universal gas constant, respectively.

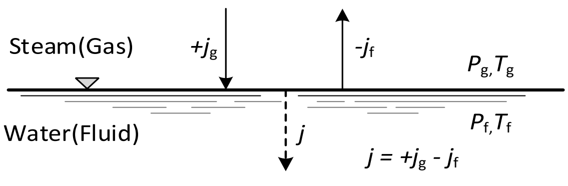

Figure 2. Kinetic Theory of Gas on Water Surface

The temperatures of steam (gas) and water (fluid) region are assumed to be equal on the interface, and the equation can be simplified and the mass flow rate can be obtained by considering the interface area as follows:

$$j_{\text{interface}} = j_g - j_f = F_{\text{interface}} \left(\frac{M}{2\pi R T_{sat}} \right)^{0.5} \left(P_g - P_f \right) \quad (2)$$

$$\dot{m}_{\text{interface}} = \left(j \times A \right)_{\text{interface}} \quad (3)$$

The mass flow rate and heat transfer rate of condensation and evaporation are calculated as follows:

$$\dot{m}_{\text{interface}} = \begin{cases} F_{CND} A_{\text{interface}} \left(\frac{M}{2\pi R T_{sat}} \right)^{0.5} \left(P_g - P_f \right) & (P_g > P_f) \\ F_{EVP} A_{\text{interface}} \left(\frac{M}{2\pi R T_{sat}} \right)^{0.5} \left(P_g - P_f \right) & (P_g < P_f) \end{cases} \quad (4)$$

$$\dot{Q}_{\text{interface}} = \begin{cases} \dot{m}_{CND} h_{fg} & (P_g > P_f) \\ \dot{m}_{EVP} h_{fg} & (P_g < P_f) \end{cases} \quad (5)$$

where subscript *EVP* and *CND* stand for evaporation and condensation, respectively.

3. Analysis Results

4.1 Effects of Condensation and Evaporation Factors

The series of sensitivity studies on condensation and evaporation factors were conducted to evaluate the effects on the transients of pressure and water level. The PACTEL test results were used for the validation and verification [4]. The time for evaluating the condensation factor was set to be 221 sec because the time is that pressurizer reaches its maximum pressure. The time for condensation factor was 254.8 sec because the sufficient depressurization point prior to flashing. The results of sensitivity analyses are presented in Figures 3 and 4. The factors were obtained as 0.024 for condensation and 0.016 for evaporation.

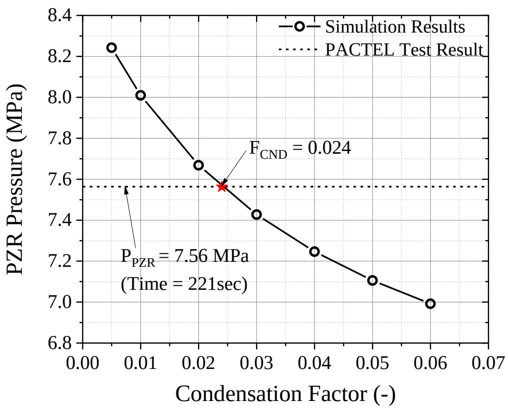

Figure 3. PZR Pressure with varying Condensation Factor during Pressurization Transient (F_{EVP}=0.020)

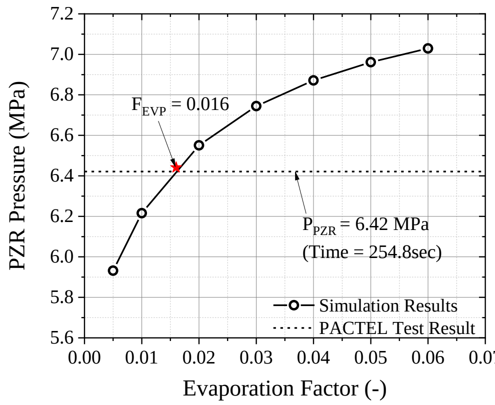

Figure 4. PZR Pressure with varying Evaporation Factor during Depressurization Transients (F_{CND}=0.024)

4.2 Thermal-hydraulic Behaviors during In-surge and Out-surge Transients

The transients of pressurizer pressure and water level are presented in Figures 5 and 6. The single region model assumes that the saturated steam and water coexists in a single control volume. The model assumes a uniform spatial distribution of mass and energy; thus, it under-estimates pressure changes during transients even the water level is accurate. The water level is estimated by using the quality of control volume.

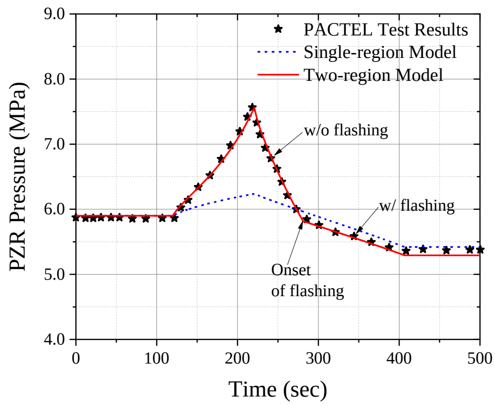

Figure 5. PZR Pressure Changes using Evaporation and Condensation Factors during Transients

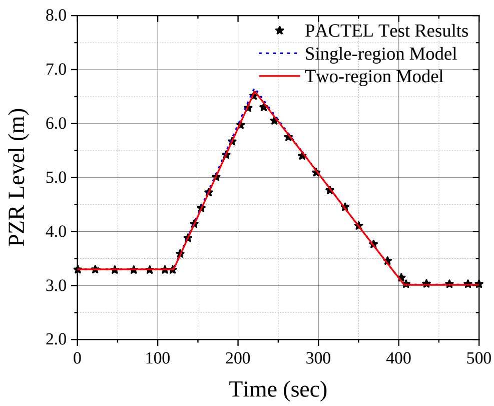

Figure 6. PZR Level Changes using Evaporation and Condensation Factors during Transients

The two region model predicts the both pressure and water level changes with good agreement when the factors, obtained from sensitivity studies, were used in transient analysis. The model exhibits more rapid pressure change than single region model because it accounts for the compressibility effects. The model characteristics indicates that the interfacial model between steam and water region mitigates compressibility effects for better accurate analysis.

Additionally, the effects of flashing phenomenon, which occurs when the system pressure decreases sufficiently to the saturation pressure, was observed in two region model. The phenomenon leads to additional mass and energy transfer to the steam region, and it moderates the depressurization rate.

5. Conclusion

The interfacial phenomena such as evaporation and condensation affects the thermal-hydraulic behaviors of steam pressurizer. The sensitivity study on condensation and evaporation factors were conducted to find appropriate pressurizer behaviors. The appropriate factors of condensation and evaporation under various range of thermal-hydraulic conditions are a significant design factor to predict steam pressurizer behaviors.

ACKNOWLEDGEMENT

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