Preliminary Calculation of Vapor Generation through Flashing Phenomenon for Natural Circulating Nuclear Reactor

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1. Introduction

Natural circulation is an effective mechanism for reactor safety because it does not require an active system. However, since the cooling effect is not significant compared to the reactor power, it was only considered in accident situations before. Today, the small size reactors with integral system and passive safety concept are becoming important. The natural circulation is suitable for those purposes, so being used even in normal operation has been drawing much attention.

The advantage of using natural circulation is that it can replace the RCP (reactor coolant pump). The RCP is susceptible to failure, which can induce core damage eventually. Therefore a natural circulating reactor is significantly safe, by removing the RCP.

Besides, applying flashing phenomenon makes the system more advanced and passive. The flashing effect induces natural boiling in the long riser part and generates a vapor without any active heater. It enhances the capability of natural circulation or can be used for self-pressurization [1].

Therefore, flashing phenomenon in the long riser was studied in this paper. The reference reactor is AHR400 (Advanced Heating Reactor 400MWth), which is a conceptually designed plant for nuclear desalination system [2]. Its feasibility for a natural circulating operation was studied in the previous research without considering the flashing phenomenon [3]. Therefore, the feasibility is expected to be enhanced because the AHR400 is suitable for flashing-driven passive operation due to its low operating pressure and pool type characteristic. A preliminary calculation was performed using MARS (multi-dimensional thermal-hydraulic system analysis code) and MATLAB to figure out the flashing effect.

2. Methods

Flashing phenomenon is a thermal non-equilibrium process between superheated liquid and vapor. The most sophisticated and accurate method of many other models is the two-fluid model, which consists of a total of 6 equations: mass, momentum and energy equations for each phase. However, with the drift-flux model and saturation assumption for vapor, one velocity equation and vapor energy equation can be discarded. Finally, 4 equations model was developed in this study.

2.1 Governing equations

The governing equations consist of liquid mass conservation (1), mixture mass conservation (2), mixture momentum conservation (3), and liquid energy conservation (4). The wall friction in the momentum equation is ignored due to the low velocity of the flow and the large riser diameter. Detailed information about the equations can be found in the MARS manual [4].

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f\right) + \frac{\partial}{\partial x}\left(\alpha_f \rho_f v_f\right) = \Gamma_f \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_m) + \frac{\partial}{\partial x}(\rho_m v_m) = 0 \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_m v_m) + \frac{1}{2}\alpha_g \rho_g \frac{\partial v_g^2}{\partial x} + \frac{1}{2}\alpha_f \rho_f \frac{\partial v_f^2}{\partial x} = -\frac{\partial P}{\partial x} - \rho_m g - \Gamma_g (v_g - v_f) \tag{3}$$

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f U_f\right) + \frac{\partial}{\partial x}\left(\alpha_f \rho_f U_f v_f\right) + P\frac{\partial}{\partial x}\left(\alpha_f v_f\right) = -P\frac{\partial \alpha_f}{\partial t} + \frac{h_g}{h_{fg}} H_{if}(T_{sat} - T_f) \tag{4}$$

2.2 Constitutive relations

Other required equations include the drift-flux model (5), (6), thermodynamic relations (7), and the interfacial exchange model (8). For the interfacial mass transfer, the modified Lee and Ryley model was used [5].

$$v_g = v_m + \frac{\rho_f}{\rho_m} V_{gj} \tag{5}$$

$$v_f = v_m - \frac{\alpha_g}{1-\alpha_g}\frac{\rho_g}{\rho_m} V_{gj} \tag{6}$$

$$\left(\frac{\partial U}{\partial T}\right)_P = C_p - P v \beta \tag{7}$$

$$\Gamma_f = \frac{H_{if}(T_{sat} - T_f)}{h_{fg}}, \quad H_{if} = \frac{k_f}{d_b}\left(2 + 0.74 Re_b^{0.5}\right) a_{gf} \tag{8}$$

2.3 MATLAB calculation

The AHR 400 provides the riser geometry information. The total length, diameter and system pressure are 15.095 m, 2 m, and 15 bar respectively. Several assumptions were made to model flashing phenomenon:

- Mass flow rate was fixed at 1600 kg/s
- 1-D axial calculation with the area-averaged value

- No subcooling for the riser inlet; core outlet temperature is at the saturation temperature

Firstly, a vapor generation rate was calculated using the given model. Then mass conservations were solved to update ρ and α. With the values, velocities were updated from the momentum conservation and the drift-flux model. Also, internal energy of liquid was obtained from the energy conservation. Lastly, with the thermodynamic relations, a degree of superheat was obtained which can update the vapor generation.

2.4 MARS calculation

To verify the MATLAB result, MARS calculation was also conducted. The riser was divided into 10 pipe volumes, and other initial values were given from MATLAB calculation. Input geometry is presented as Fig. 1.

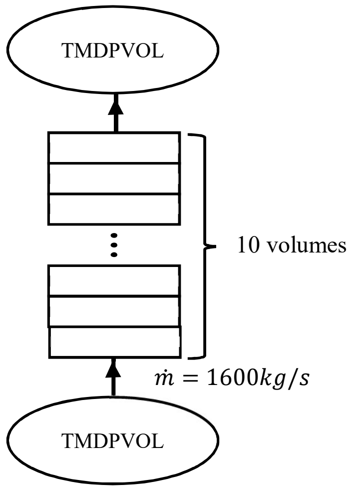

Fig. 1. MARS input geometry

3. Result

Fig. 2 and Fig. 3 show the void fraction dependency against time at different elevations. They show a slight different convergence trends and values between them. MATLAB result underestimates the vapor generation at lower elevations but overestimates it at higher elevations. This becomes more apparent from Fig. 4. Such differences are mainly attributed to the method used for modeling the flashing effect. MARS uses the two-fluid model and different numerical scheme. Nevertheless, the differences are acceptable even if MATLAB model in this study is simplified. Both results show that the amount of vapor generation is not small, because the system pressure is much lower than the typical PWR's pressure. The vapor increase the capability of natural circulation and can be used for self-pressurization.

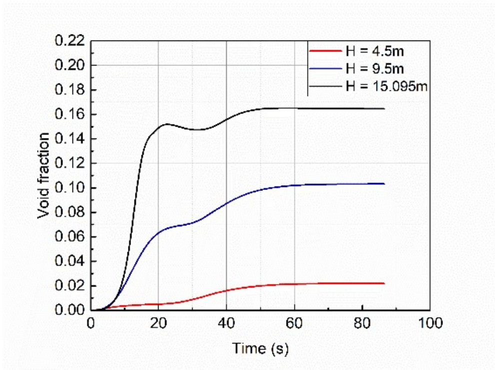

Fig. 2. Void fraction in the riser with time from MARS calculations at different elevations.

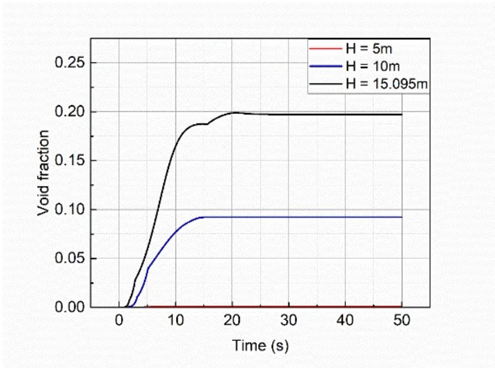

Fig. 3. Void fraction in the riser with time from MATLAB calculations at different elevations.

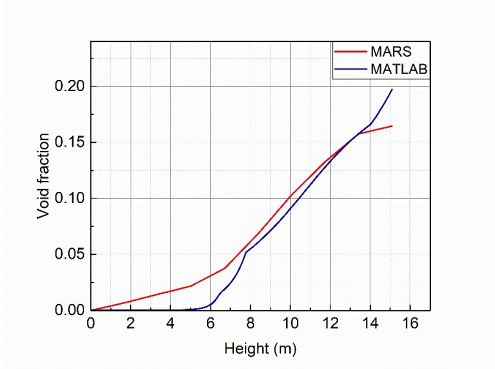

Fig. 4. Converged void fraction distribution in riser from MARS and MATLAB calculations.

4. Conclusions

Flashing phenomenon in long riser was studied for the natural circulating reactor with low pressure. The reference reactor design was AHR400. The results from two codes show slightly different behaviors with each other, but both of them show that a substantial amount of vapor is generated. The overall void fraction is not large, but it still can play a significant role to enhance the natural circulation capability, especially in low mass flow rate regions. In addition, the generated vapor is condensed in the upper part of the reactor pressure vessel, from which the reactor can control system pressure by itself without any active system. Those features will improve the AHR400 and make it operated by passive method. Also, the code will be more reliable by adopting advanced model and scheme in the future.

Notation

α	Void fraction	$[-]$
ρ	Density	$[kg/m^3]$
v	Velocity	$[m/s]$
g	Gravitational acceleration	$[m/s^2]$
Γ	Volumetric vapor generation rate	$[kg/m^3 \cdot s]$
U	Internal energy	$[J/kg]$
P	Pressure	$[Pa]$
h	Enthalpy	$[J/kg]$
T	Temperature	$[K]$
V_{gj}	Drift velocity	$[m/s]$
C_p	Heat capacity	$[J/kg \cdot K]$
ν	Specific volume	$[m^3/kg]$
β	Thermal expansion coefficient	$[K^{-1}]$
H_{if}	Volumetric heat transfer coefficient	$[W/m^3 \cdot K]$
k	Thermal conductivity	$[W/m \cdot K]$
d_b	Bubble diameter	$[m]$
Re_b	Bubble Reynold number	$[-]$
a_{gf}	Interfacial area per unit volume	$[m^{-1}]$

Subscript

f	Liquid
g	Gas
m	Mixture

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