Implementation and validation of a condensation heat transfer model to the MARS-KS code for modeling passive residual heat removal system

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1. Introduction

The passive safety systems have been widely implemented to advanced reactors in order to increase the inherent safety. SMART (System-integrated Modular Advanced ReacTor) which have been developed by Korea Atomic Energy Research Institute (KAERI) has a passive residual heat removal system (PRHRS) to remove the residual heat from the core by natural circulation [1]. Main function of the SMART PRHRS is to remove the residual heat when the secondary heat removal systems are not available after the reactor trip and bring the reactor to the initiation condition of the Shutdown Cooling System (SCS) within 36 hours by natural circulation. A train of SMART PRHRS includes a water compensation tank, emergency cooling tank, and valves and related piping. Some advanced reactors use the nitrogen pressurized compensation tank. The nitrogen used for the pressurization can diffuse to the coolant in the PRHRS during the normal operation of the plant and play a role of the thermal resistance against the condensation heat transfer during the operation of the PRHRS. Since the noncondensable gas reduces the condensation heat transfer considerably, the effect of the nitrogen against the condensation heat transfer should be considered in the evaluation of the PRHRS performance appropriately.

The MARS-KS code [2] has been selected as a basis for the development of the SMART-specific regulatory safety evaluation code. In MARS-KS, a correlation suggested by Colburn and Hougen [3] was implemented to predict the condensation heat transfer coefficient in the presence of noncondensable gas. However, an assessment for an experiment on the condensation heat transfer indicated that the correlation in the MARS-KS code is insufficient to model the condensation heat transfer in the PRHRS. Therefore, it has become of interest to improve the MARS-KS code to cope with the PRHRS evaluation.

2. Condensation Heat Transfer Correlation

In order to improve the capability of the MARS-KS code for the PRHRS evaluation, an empirical correlation of the condensation heat transfer coefficient suggested by Lee and Kim [4] has been implemented into the MARS-KS code since it was developed on the basis of the experiment covered a wide range of the heat transfer coefficient and the mass fraction of the noncondensable gas. In addition, it is expected with this correlation that the effect of the geometry on the condensation heat transfer coefficient is negligible since the experiment was conducted using a condenser tube with the same inner/outer diameter to that of the SMART PRHRS.

The implemented correlation of the condensation heat transfer coefficient is as follows:

$$f = \frac{h_{\exp,mix}}{h_{Nu}} = {\tau^*_{mix}}^{0.3124}\left(1 - 0.964 \cdot W_{nc}^{0.402}\right) \quad (1)$$

where, f : degradation factor
h : heat transfer coefficient
τ : dimensionless shear stress
W : noncondensable gas mass fraction.
exp : experiment
Nu : Nusselt theory

The dimensionless shear stress is defined as

$$\tau^*_{mix} = \frac{\tau_{mix}}{g\rho_f L} = \frac{1/2\rho_{mix}u_{mix}^2 f_{fric}}{g\rho_f L} \quad (2)$$

where, u_{mix} : mixture velocity $\left(= \frac{\mathrm{Re}_{mix}\,\mu_{mix}}{\rho_{mix}D_i}\right)$

L : characteristic length $\left(= \left(\frac{\nu_f^2}{g}\right)^{1/3} = \left(\frac{\mu_f^2}{\rho_f^2 g}\right)^{1/3}\right)$

f_{fric} : fanning friction factor :

$$= 0.079\,\mathrm{Re}_{mix}^{-0.25} \quad \text{for } \mathrm{Re}_{mix} > 2300$$
$$= \frac{16}{\mathrm{Re}_{mix}} \quad \text{for } \mathrm{Re}_{mix} < 2300$$

The correlation is valid when $0.06 < \tau^*_{mix} < 46.65$ and $0.038 < W_{nc} < 0.814$. If the thermal hydraulic condition is out of the valid range of the correlation, the original model in the MARS-KS code is employed.

3. Verification and Validation

The modified MARS-KS code has been verified and validated against an experiment conducted at Postech [5]. Fig. 1 shows the experimental facility at Postech. It consists of a steam boiler, a condenser tube, a cooling jacket, nitrogen supplier, and a mixer. The steam and nitrogen mixture enter the test section are condensed by the heat transfer with cooling jacket, and the temperature of the outer wall and the bulk are measured by K-type thermocouples mounted on 13 different axial locations of the outer surface and inside of the condenser tube. The pressure in the condenser tube and the cooling jacket is an ambient pressure.

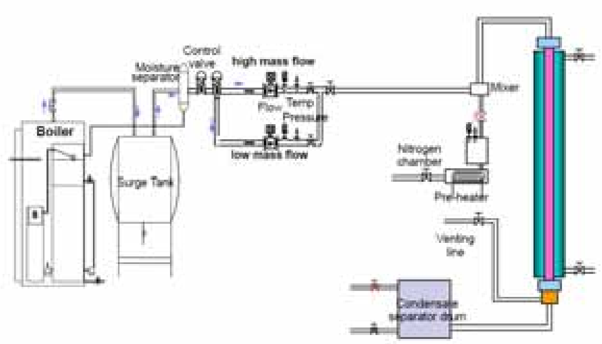

Fig. 1 Schematic Diagram of the Experimental Apparatus [5]

Among the cases in the experiment, case MB42 used in Ref. [4] was selected as a reference case for the verification and validation. In MB42, total mass flow rate at inlet was 15.31 kg/h and the mass fraction of the nitrogen was 10.2 %. The flow rate and temperature of the coolant through the cooling jacket were 292.06 kg/h and 289.4 K, respectively.

Fig. 2 depicts the heat transfer coefficients from the experiment and the calculations. From the comparison, it was found that the correlation by Colburn and Hougen originally included in the MARS-KS code predicts the degradation of the heat transfer due to the presence of noncondensable gas inappropriately. Especially, the original model in the MARS-KS code overpredicts the heat transfer coefficient at the upper part of the test section. Obviously, it is not a conservative result from the safety point of view since the code predicts higher heat removal performance than the actual. On the other hand, the modified MARS-KS code shows a good agreement with the experimental result. Based on the calculation result, it is concluded that the modified MARS-KS can predict the condensation heat transfer coefficient in the condenser tube more accurately in the presence of noncondensable gas.

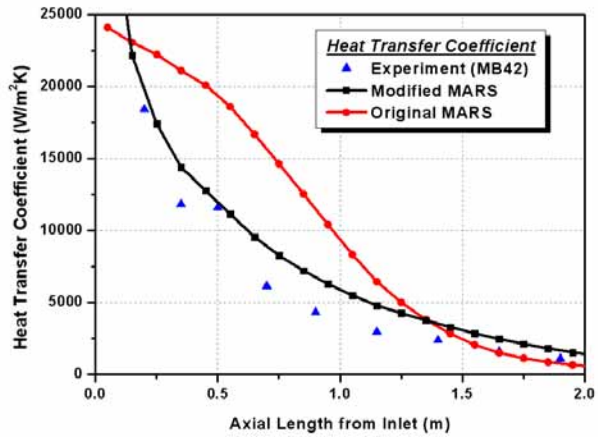

Fig. 2 Condensation Heat Transfer Coefficients

3. Conclusions

In order to improve the MARS-KS code to cope with the condensation heat transfer phenomena in the PRHRS, an empirical correlation for the condensation heat transfer coefficient has been implemented. A calculation for the verification and validation indicates that the modified MARS-KS code can predict the condensation heat transfer coefficient more accurately than the original code in the presence of noncondensable gas.

REFERENCES

[1] M.H.Chang, et al., “Basic Design Report of SMART”, KAERI/TR-2142/2002, Korea Atomic energy Research Institute, 2002.

[2] MARS-KS 1.2, Korea Institute of nuclear Safety, 2010.

[3] A. P. Colburn and O. A. Hougen, Design of Cooler Condensers for Mixtures of Vapors with Noncondensing Gases, Industrial and Engineering Chemistry. Vol. 26, p. 1178, 1934.

[4] K.Y.Lee and M.H.Kim, Effect of an Interfacial Shear Stress on Steam Condensation in the Presence of a Noncondensable Gas in a Vertical Tube, International Journal of Heat and Mass Transfer, Vol. 51, Issue 21-22, p. 5333, 2008.

[5] K.Y.Lee, “The Effects of Noncondensable Gas on Steam Condensation in a Vertical Tube of Passive Residual Heat Removal System”, Ph.D. Thesis, Pohang University of Science and Technology, 2007.