Analysis of steam condensation in the presence of noncondensable gases using MARS-KS code

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1. Introduction

The condensation is one of the important phenomena in the heat transfer process. When the phase of the steam changes into the water, the volume and pressure are reduced significantly. In the event of loss-of-coolant accident, the coolant abruptly evaporates to generate steam. Consequently, the pressure of the containment is significantly increased. Therefore, the steam condensation is used as a heat removal process in safety systems such as the passive containment cooling system in order to decrease the pressure inside the containment.

The condensation heat transfer of the steam is affected by the fraction of the noncondensable gas. The condensation heat transfer coefficient is decreased when the fraction of the noncondensable gas increased. Several experimental studies have been performed on the steam condensation in the presence of a noncondensable gas. Among them, Dehbi [1] performed experiment to determine the dependence of the condensation heat transfer on pressure, wall temperature subcooling, tube length, and the noncondensable gas ratio of the mixture.

In this study, the Dehbi's experiment was numerically simulated using the MARS-KS code, and the experiment data of Debhi and the calculation results were compared. The effect of nodalization of the test vessel on the condensation heat transfer coefficient was evaluated.

2. Heat transfer coefficient

The Colburn-Hougen diffusion method is used to solve for the liquid/gas interface temperature in the presence of noncondensable gases. The formulation is based on the principle that the amount of heat transferred from condensing vapor to the liquid-vapor interface is equal to the heat transferred through the condensate.

The heat flux due to condensation of vapor mass flux, j_v, flowing toward the liquid-vapor interface is,

$$q_v'' = j_v \cdot h_{fgb} = h_m h_{fgb} \rho_{vb} \ln\left(\frac{1-\frac{P_{vi}}{P}}{1-\frac{P_{vb}}{P}} \right) \tag{1}$$

where, q''_v, j_v, h_m, h_{fgb}, ρ_{vb}, P_{iv}, P_{vb} is heat flux of vapor, vapor mass flux, enthalpy of mixture, difference of enthalpy of at steam partial pressure, vapor density from bulk, pressure of vapor interface, and pressure of bulk vapor, respectively. The heat flux from the liquid film to the wall is calculated by

$$q_l'' = h_c \left(T_{vi} - T_w \right) \tag{2}$$

where, q''_l, h_c, T_{vi}, T_w is heat flux of liquid, condensation heat transfer coefficient, temperature of vapor interface and wall temperature, respectively. In steady-state, heat flux of eq. (1) is equal to heat flux of eq. (2). So,

$$q_v'' = q_l'' \quad or \quad h_c \left(T_{vi} - T_w \right) = h_m h_{fgb} \rho_{vb} \ln\left(\frac{1-\frac{P_{vi}}{P}}{1-\frac{P_{vb}}{P}} \right) \tag{3}$$

Total heat flux is calculated by

$$q'' = h_c (T_{wall} - T_{sppb}) \tag{4}$$

where, T_{sppb} is saturation temperature of steam partial pressure. In this study, heat transfer coefficient is calculated by using the control variable as:

$$h_c = \frac{q''}{(T_{wall} - T_{sppb})} \tag{5}$$

3. Condensation experimental apparatus

3.1 Condensation experimental apparatus

Figure 1 shows the experimental apparatus of Dehbi. It is stainless steel vessel with 4.5 m height and 0.45 m in diameter. The copper pipe of 3.5 m height and 0.038 m in diameter is located inside vessel. The vessel is fully insulated. So heat transfer takes place only through the copper wall. And steam is generated by the heater located at the vessel bottom. Thus it maintains a constant pressure and temperature of the steam in the vessel. The coolant is supplied into the bottom of the copper pipe. And it takes the heat of the gas mixture. The Reynolds number of the coolant is lower than 1500 which corresponds to natural turbulent convection.

The experiments are conducted at the each vessel pressures of 1.5, 3.0, and 4.5 atmospheres. The air mass fraction is range from 25 to 90 %.

3.2 MARS-KS code nodalization

Figure 2 is the nodalization of Dehbi's apparatus for the MARS-KS code. The test vessel of the test facility was modeled in two different ways: Fig. 2. (a) describes the case in which the vessel is divided into 12 volumes and (b) shows that the vessel is simulated with only single-volume. Inlet and outlet of the vessel is set up to have constant pressure and the mass rate of the air-steam mixture.

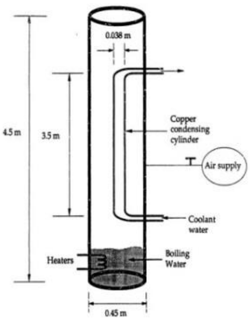
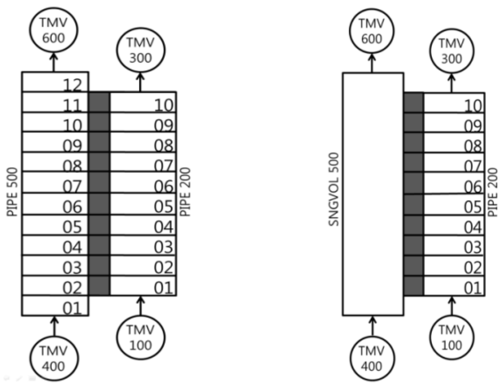


Fig. 1. Schematic of the steam condensation experiment.

The copper pipe was modeled by the heat structure which consists of 10 volumes. Heat transfer takes place through the heat structure. Inlet and outlet of coolant is connected by time-dependent volume. The Reynolds number of the coolant is set to less than 1500 as described in the literature of Dehbi. However, the coolant boiled in some cases at 3.0 and 4.5 atm. In that case, the mass flow rate of the coolant was adjusted so that the fluid temperature cannot reach the saturation temperature.

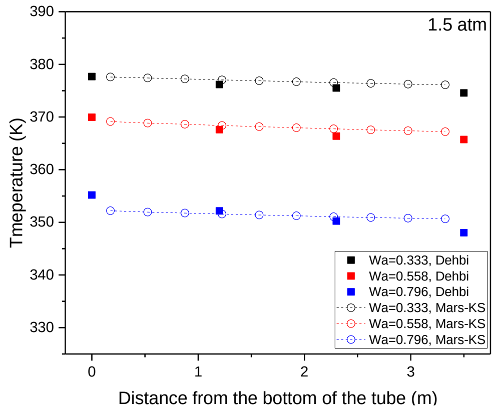


(a) (b)

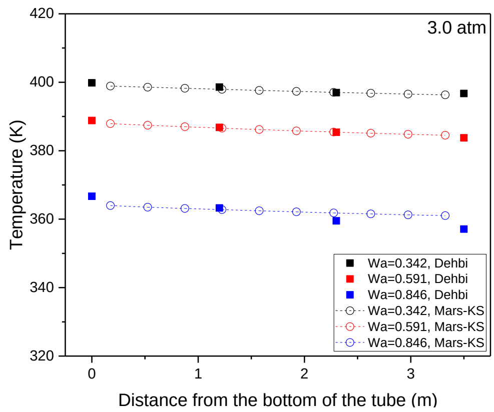
Fig. 2. MARS-KS nodalization of the steam condensation experiment.

4. Results

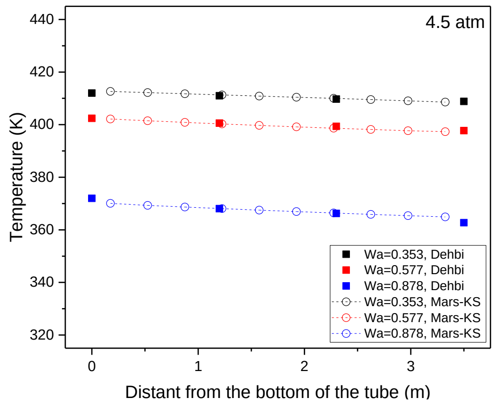
Figure 3 ~ 5 are compared result of MARS-KS code with experimental data of Dehbi. Figures show mixture temperature, wall temperature and air mass fraction along the heat transfer tube length, respectively. There is little difference between results of MARS-KS code and experimental data of Dehbi in Figure 3, 5. This trend could find at other pressures.



(a) 1.5-vessel pressure



(b) 3.0-vessel pressure

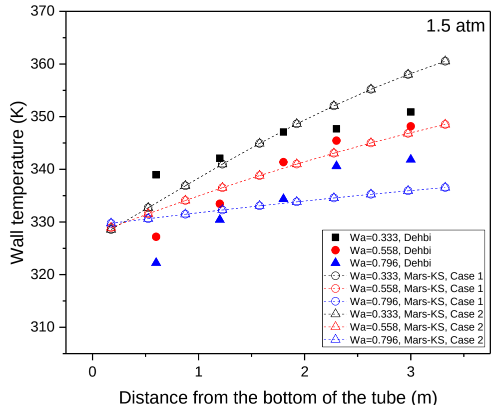


(c) 4.5-vessel pressure

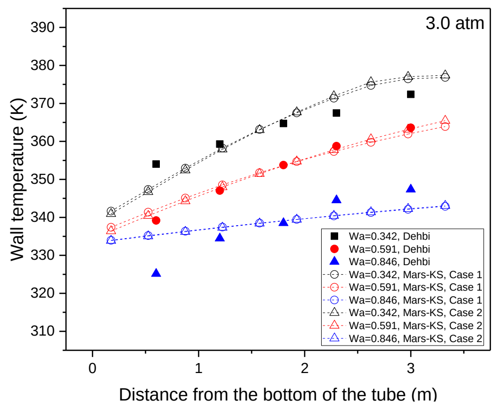
Fig. 3. Bulk temperature for 1.5, 3.0, 4.5-atm vessel pressure.

Figure 4 is shown the difference of wall temperature distribution between Dehbi's experimental data and result of MARS-KS code. Because the mass rate was not indicated in Dehbi's paper, therefore, a any value has been applied in calculation of MARS-KS code. It was changed the initial mass rate of MARS-KS to have a similar the wall temperature distribution of Dehbi. But, the heat transfer coefficients have no difference between the modified initial mass rate and the existing value.

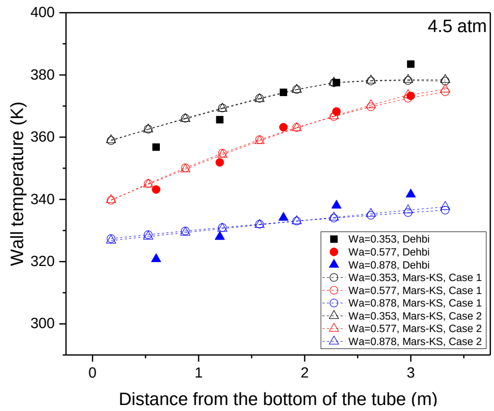
Figure 6 shows the variation of the condensation heat transfer coefficient with the air mass fraction at 1.5 atm. The heat transfer coefficient obtained by experiment is about 2.2 ~ 2.4 times higher than the predicted value of the MARS-KS code.



(a) 1.5-vessel pressure

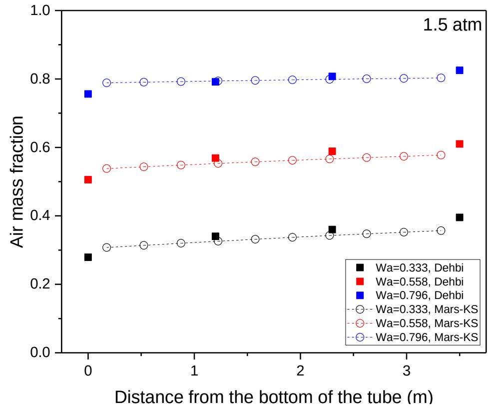


(b) 3.0-vessel pressure

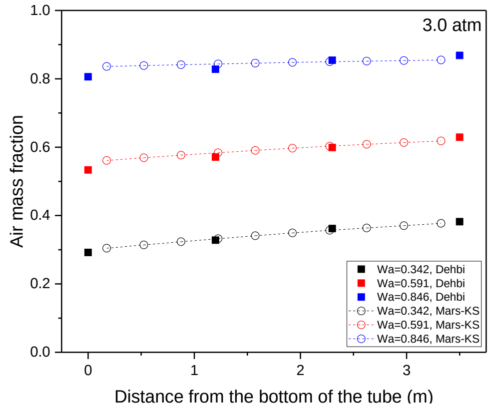


(c) 4.5-vessel pressure

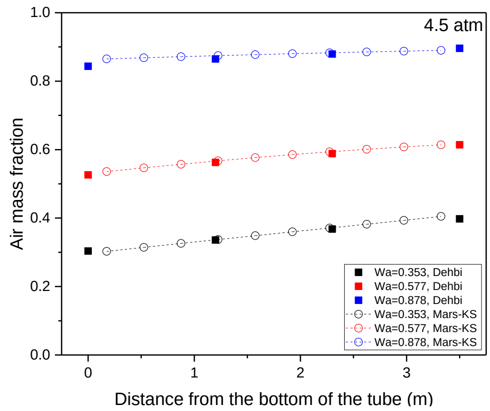
Fig. 4. Wall temperature for 1.5, 3.0, 4.5-atm vessel pressure.



(a) 1.5-vessel pressure



(b) 3.0-vessel pressure



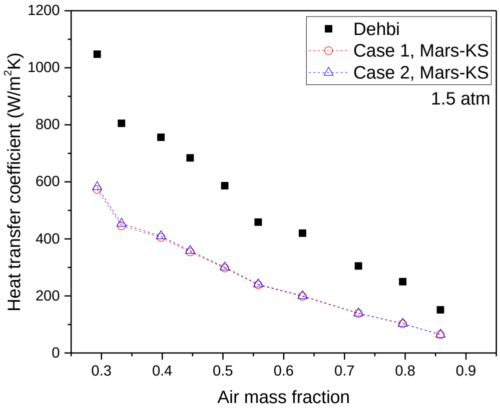
(c) 4.5-vessel pressure

Fig. 5. Air mass fraction for 1.5, 3.0, 4.5-atm vessel pressure.

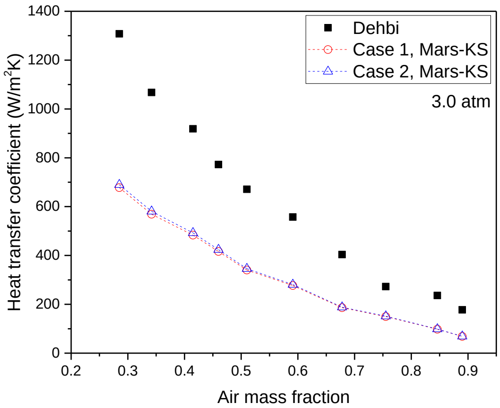
5. Conclusions

This study compared the result of MARS-KS code and steam condensation experiment of Dehbi in the presence of noncondensable gas. MARS-KS code performed each 10 cases when vessel pressure is 1.5 atm, 3.0 atm and 4.5 atm, respectively. And the code calculated heat transfer coefficient for air mass fraction.

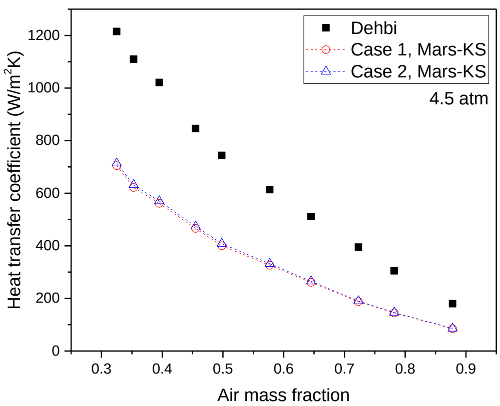
It is little difference of wall temperature, mixture temperature and air mass fraction between the result of MARS-KS code and experiment data of Dehbi. But heat transfer coefficient of experiment is 2.2 ~ 2.4 times higher than result of MARS-KS code. Obtaining a heat transfer coefficient calculated by MARS-KS code, it is lower than the result obtained by experiments of Dehbi. Consequently, it is expected to improve the heat transfer correlation in the future. Before that, the heat transfer coefficient will be compared with obtained through experiment of Liu.



(a) 1.5-vessel pressure



(b) 3.0-vessel pressure



(c) 4.5-vessel pressure

Fig. 6. Heat transfer coefficient for 1.5, 3.0, 4.5-atm vessel pressure.

REFERENCES

[1] A. A. Dehbi: The effects of noncondensable gases on steam condensation under turbulent natural convection conditions, 1991

[2] Thermal Hydraulic Safety Research Department, MARS Code Manual Volume I: Code Structure, System Models, and Solution Methods, Korea Atomic Energy Research Institute, 2007