Study on the wall heat transfer of condensation in the presence of NC gases

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1. Introduction

Wall condensation phenomena is occurred near a cold wall when hot steam flows into internal or external flow channel along the wall. A vapor containing non-condensable (NC) gases mostly is involved in the cases for many postulated accident scenarios of the conventional PWRs. To predict the influence of NC gases on condensation, the Colburn-Hougen model [1] has been widely used in thermal-hydraulic system code like as MARS, TRACE and RELAP. The SPACE code [2] also employed the same model to consider the effect of NC gases on condensation.

The NC gases reduce the heat transfer and condensation rates even though they are present in the bulk vapor in a small amount. In this regard, a large number of analytical and experimental studies [3-5] have been carried out with interest only whether NC gases exists or not. Furthermore, most of studies have been conducted within a small amount of NC gases

To clearly understand the wall condensation phenomena in the presence of NC gases, it is required to assess the wall heat transfer model on condensation in a large amount of NC gases.

This study aims to clarify the effect of NC gases on wall heat transfer with the present model for wall condensation. To assess the model, MIT condensation test [6] is introduced. They were conducted for air/steam mixture inlet temperature 100 to 140 °C with varying the inlet air mass fraction from 10% to 35%.

2. Model description

2.1 Colburn-Hougen model

The basic concept of Colburn-Hougen model is based on the energy conservation principal that the amount of heat transfer (q''_{vb}) by condensing vapor to the vapor-liquid interface by diffusing through the NC gases film is equal to the one of heat transfer (q''_{vi}) through the condensate. The heat flux from the liquid film to the wall is calculated by $q''_{vi}=h_{cond}\left(T_{vi}-T_w\right)$. The heat flux due to condensation of vapor mass flux (j_v) flowing toward the liquid-vapor interface is $q''_{vb}=j_v \cdot i_{fg,b}$. Where $i_{fg,b}$ is phase change enthalpy. According to heat and mass transfer analogy, Eq. (1) can be easily derived with mass transfer coefficient, mole fraction, vapor density and pressures.

$$\begin{aligned} q''_{vb} &= j_v \cdot i_{fg,b} \\ &= h_m \frac{\rho_{vb}}{x_{vb}} \ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right) \cdot i_{fg,b} \end{aligned} \qquad (1)$$

Where, the value of mass transfer coefficient(h_m) is the maximum value from laminar [7], turbulent [8] and natural convection [9] correlation. Following the basic concept of the Colburn-Hougen model, Eq. (2) can be derived.

$$h_{cond}\left(T_{vi}-T_w\right) = h_m \frac{\rho_{vb}}{x_{vb}} \ln\left(\frac{1-P_{vi}/P}{1-P_{vb}/P}\right) \cdot i_{fg,b} \qquad (2)$$

Finally, the interface pressure and temperature will be calculated by iterations. Based on the find heat flux, heat transfer coefficient for each phase can be determined according to the temperatures for each phase.

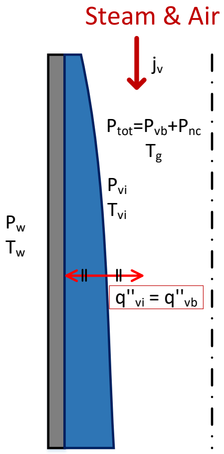

Fig. 1. Schematic of film-wise condensation on a vertical surface

2.2 SPACE modeling

MIT test were conducted under force convection condition with different NC gases. Hot air/steam flow down into the pipe and a cold water inflow into lower part of annulus region. So, the coolant flows upward. In this study, two different flow conditions for air/steam mixture were selected as shown in Table I. In order to simulate this test, test section was modeled with 9 cells to match the cell-center location with the local measurement points in the experiments as shown in Fig. 2. And, only gas mixture tube was modeled and the outer wall temperature was applied as BCs to focus on the wall film condensation heat transfer inside tube.

Table I. Test matrix for MIT condensation tests

Run no.	Inlet Air mass fraction	Inlet Temp.	Inlet Press	Steam inlet flow rate	Air inlet flow rate
	(-)	(℃)	(Mpa)	(kg/s)	(kg/s)
7	0.08	119.9	0.209	2.609E-03	2.277E-04
18	0.12	100.0	0.110	5.562E-03	7.386E-04

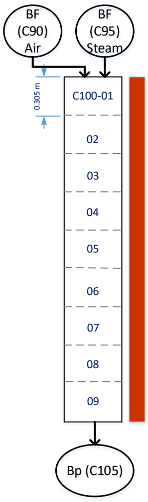

Fig. 2. SPACE modeling for MIT condensation tests

2.3 Preliminary calculation

The preliminary calculation results for gas mixture temperature at the centerline using the SPACE code for test No. 7 and 18 were compared with experimental data. For test No. 18, the calculation results are well matched with experimental ones. However, a big discrepancy of gas mixture temperature for test No. 7 is appeared. We focused on why this result came out. Basically, the Colburn-Hougen model is assumed that the sensible heat transfer through the diffusion layer to the interface was not considered. In other words, liquid film temperature is approximately equal to saturated temperature of vapor partial pressure. Actually, it is acceptable when the interface temperature is equal to saturated temperature. Especially, if large amount of NC gases existed, heat transfer from wall to gas mixture should be deteriorated. Even though in this situation, big temperature between liquid film and wall should be existed. Then liquid film temperature can be decreased and it can also affect to gas mixture temperature. However, we didn't consider these kinds of heat transfer by using only the Colburn-Hougen model for wall heat transfer. It may cause a tendency to underestimate the wall heat transfer between wall and liquid film in a rare steam condition. In this regard, the tendency of liquid and gas mixture temperature in our calculation are normally higher than experimental ones. Based on this, we conclude that wall heat transfer from wall to liquid film should be additionally considered.

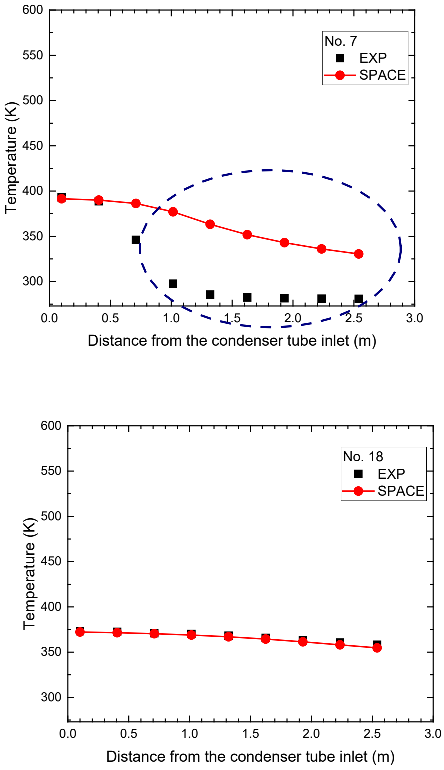

Fig. 3. Comparion of gas mixture termperature at the centerline of pipe for test No. 7 & 18.

3. SPACE results

In order to consider the heat transfer from wall to liquid film, the model originally embeded into the SPACE code for single-phase liquid heat transfer is applied in the cases of larger amount of NC gas fraction. If NC gas fraction is above the certain value, which is used as 0.75 in this study and determined by iterative calculations of validation cases, the weighted single phase heat transfer coefficient according to a NC gas fraction is applied. All cases are recalculated by using this method as shown in Fig. 4~6.

The SPACE results are well matched with experimental results. For the local heat transfer coefficient for test No. 7, there is the jumped results in the calculation, which is cause by the addition of heat transfer to liquid side. However, our results cannot be directly compared in those regions because they didn't calculate the local heat transfer in the reference.

4. Conclusions

Wall film condensation in the presence of noncondensible gases has used the Colburn-Hougen model as default model in the SPACE code. The SPACE code can predict the overall behavior of wall film condensation in the presence of NC gases. As NC gas mole fraction is higher, the temperature discrepancy between experimental data and the SPACE calculation results was occurred. By considering wall heat transfer to liquid phase in a rare steam conditions, the SPACE results were improved and well-matched with experimental ones.

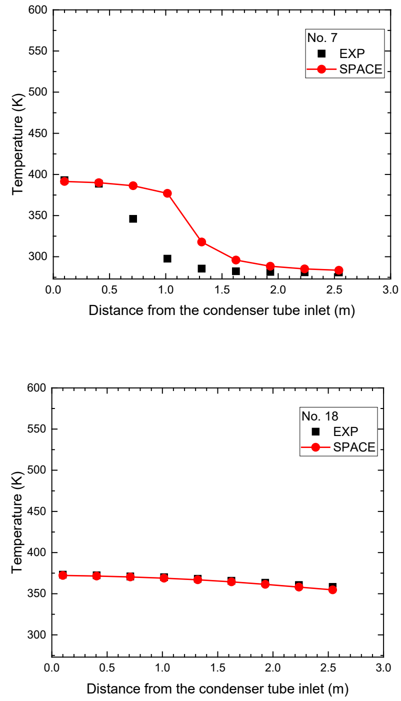

Fig. 4. Gas mixture temperature at the centerline of pipe

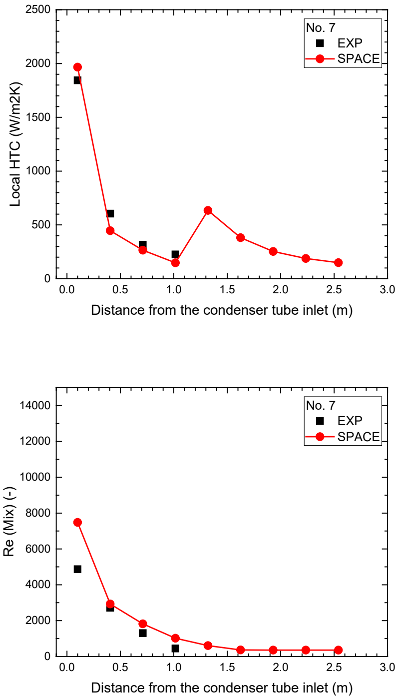

Fig. 5. Local heat transfer coefficient

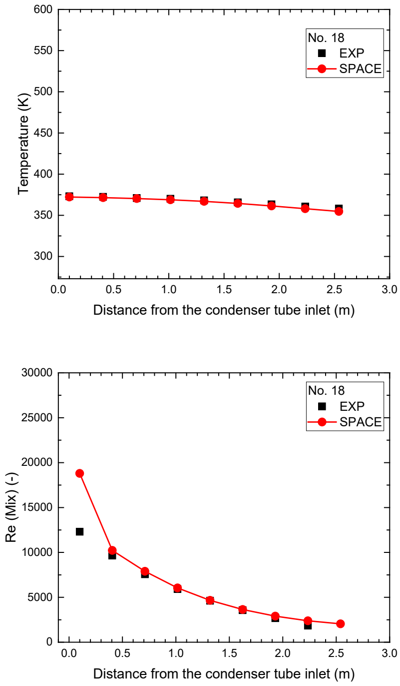

Fig. 6. Reynolds number of gas mixture

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