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Review of the Heat Partitioning Model for Film Boiling of the SPACE Code

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1. Introduction

To simulate the post-critical heat flux (CHF) behavior, the SPACE code [1] has adopted the AECL 2006 CHF look-up table (LUT) and AECL 2004 film boiling (FB) LUT for the CHF and FB heat transfer model, respectively. These LUTs are very effective and convenient for a user to simulate the various experiments with a variety of conditions. However, they provide only total critical heat flux or total heat transfer coefficient, not those to each phase. Therefore, an additional method is required to divide the total heat transfer into three fields, i.e., liquid, vapor and droplet. In this study, current heat partitioning method for FB heat transfer of SPACE will be reviewed and evaluated with the experimental data from Bennett's heated tube.

2. Film Boiling Heat Transfer Model of SPACE

2.1 AECL 2004 Film Boiling LUT

As mentioned earlier, the SPACE code uses the AECL 2004 FB LUT [2], which is a four-dimensional array that is a function of pressure, mass flow rate, equilibrium dryness, and wall superheat. It consists of a total of 32,448 grid points with pressure ranging from 100 kPa to 20,000 kPa, mass flux ranging from 0 to 7000 kg/m^2·s, equilibrium quality ranging from -0.2 to 2.0, and wall superheat ranging from 5 K to 1200 K.

The heat transfer coefficients from the LUT are normalized values based on an 8 mm vertical tube, so a correction factor as shown in Eq. (1) is required for application to pipes of different diameters [2].

$$(1)\quad k_1 = \left({}^{0.008}/_{D_h}\right)^{0.2}$$

2.2 Current Heat Partition Model of SPACE

Since the AECL 2004 FB LUT gives an overall heat transfer coefficient that includes heat transfer by convection, conduction, and radiation, the total heat flux based on this must be divided into heat fluxes to each phase (continuous liquid, dispersed droplet, and continuous gas phase). The partitioning method of heat flux in SPACE is as follows [3]. First, the heat flux to the continuous gas phase is obtained by the Dittus-Boelter correlation and radiative heat transfer, and the heat flux to the continuous liquid is calculated using the Bromley correlation by conduction heat transfer and radiative heat transfer. The heat flux to the droplet phase is assumed to be radiative heat transfer only. The magnitude of the heat flux remaining after subtracting the vapor phase heat flux from the total heat flux by the LUT, is then compared to the sum of the continuous liquid phase and droplet phase heat fluxes calculated above, and the larger value is allocated to the continuous liquid film and dispersed droplets. The heat flux distribution ratio between the continuous liquid film and the dispersed droplets is determined by the heat flux ratio described above.

2.3 Modified Heat Partition Model of SPACE

The heat flux partitioning method described in Section 2.2 focuses on the continuous vapor phase, so that sometimes the total heat flux could exceed the heat flux by the LUT especially when the heat flux remaining after subtracting the vapor phase heat flux from the total heat flux is less than the sum of the continuous liquid phase and droplet phase heat fluxes. Therefore, modified heat partitioning method (OPTN-803) to preserve the total heat flux by the LUT was implemented into SPACE as shown in Eq. (2), and comparison of existing and modified partitioning methods has been performed using experimental data.

$$(2)\quad \begin{aligned} q_l &= q_{LUT} \cdot \left({}^{q_{l,correl}}/_{q_{total}}\right), \\ q_v &= q_{LUT} \cdot \left({}^{q_{v,correl}}/_{q_{total}}\right), \\ q_d &= q_{LUT} \cdot \left({}^{q_{d,correl}}/_{q_{total}}\right) \end{aligned}$$

where,
q_{LUT} : total heat flux by the LUT
q_{total}: total heat flux by the correlations
$(= q_{v,correl} + q_{l,correl} + q_{d,correl})$

3. Comparison of Partitioning Methods

3.1 Bennett's Heated Tube Test

The Bennett's heated tube tests [4] were conducted to measure temperature distributions in the post-CHF region, focusing on film boiling heat transfer to subcooled water at 6.89 MPa flowing upward in a vertically electrically heated tube with an inner diameter of 12.6 mm and a length of 5.54 m. A schematic diagram of the Bennett's tests is shown in Fig. 1.

To compare the heat flux partitioning methods, eight Bennett's tests were selected based on mass flux and inlet subcooling conditions. The boundary conditions for the selected tests are presented in Table I.

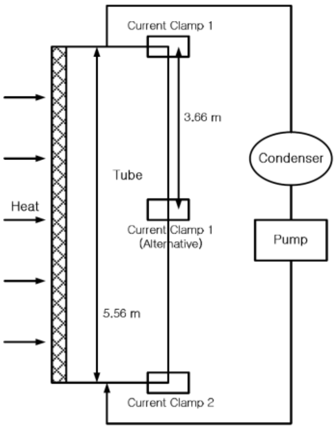

Fig. 1. Schematic diagram of the Bennett's tests [5]

Table I: Test conditions of Bennett's tests

Run	Pressure (MPa)	Mass flux (kg/m^2 s)	Heat flux (MW/m^2)	Subcooling (K)
5358	6.9	393	0.512	34.4
5336	6.9	665	0.821	26.3
5271	6.9	1004	0.798	23.0
5246	6.9	1356	0.816	24.4
5294	6.9	1953	1.097	18.8
5312	6.9	2536	1.165	19.3
5379	6.9	3798	1.709	11.0
5394	6.9	5181	1.759	13.8

3.2 Analysis Model of SPACE

The SPACE code model for the Bennett's heated tube test consists of a pipe component with 32 vertical cells for the active heating zone, two pipe components composed of three cells of length 0.1 m for uniform flow distribution at the inlet and outlet, two TFBCs for setting boundary conditions at the inlet and outlet, and a heat structure with a number of axial nodes corresponding to the vertical cells. Fig. 2 shows the analysis model of the SPACE code with the lower part of coarse axial nodes and the upper part of fine axial nodes. All heat transfer model options were defaulted, and the AECL 2006 CHF LUT and AECL 2004 FB LUT were used for the CHF and film boiling heat transfer, respectively.

To evaluate the effect of the heat partitioning method on the axial temperature, the analysis results of the model with the existing partitioning method and the modified partitioning method (OPTN-803) were compared.

3.2 Analysis Results

Fig. 3 ~ 10 show the SPACE simulation results versus the measured temperatures. From the figures, it can be seen that the difference in SPACE simulation results based on the heat partitioning method is significant in Runs 5271, 5336, and 5358. In these cases, the temperature predicted by the existing heat partitioning method is more accurate, which means that the effect of single-phase vapor heat transfer is significant in all three cases. Fig. 11 shows that the void fractions where CHF occurs in all three cases are greater than 0.95. Such a high void fraction leads to a situation where the effect of single-phase vapor heat transfer is dominant and finally, applicability of the AECL LUT becomes low. Therefore, applying OPTN-803 to maintain the heat flux of the LUT underestimates the effect of single-phase vapor heat transfer, resulting in a significant overprediction of the wall temperatures after the CHF in Run 5271, 5336, and 5358. In conclusion, considering the heat flux for the single-phase vapor independent of the LUT, as in the existing heat flux partitioning method, leads to better prediction performance than preserving the heat flux by the AECL LUT.

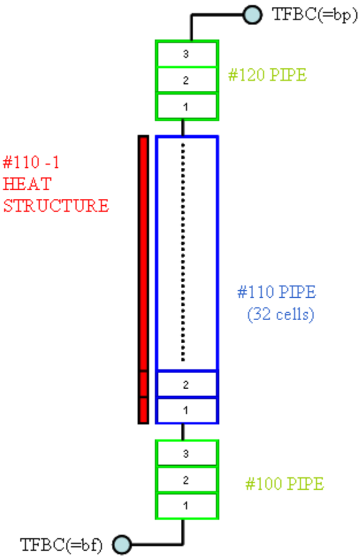

Fig. 2. SPACE analysis model for Bennett's tests

3. Conclusions

To evaluate the heat partitioning method of SPACE, the existing method and a modified method that preserves the total heat flux calculated by the AECL LUT, were compared using Bennett's heated tube test data. The comparison results show that the existing heat partitioning method focusing on single-phase vapor heat transfer, has better prediction capability compared to the modified heat partitioning method focusing on preserving the heat flux by the AECL LUT, thus confirming that the current heat partitioning method for the film boiling of SPACE is reasonable.

ACKNOWLEDGEMENT

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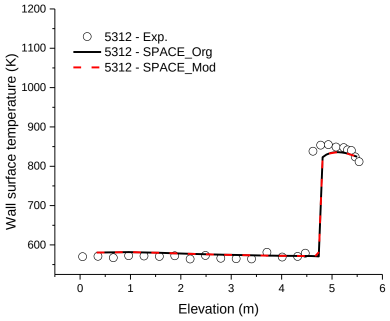

Fig. 3. Axial temperature distribution (Run 5312)

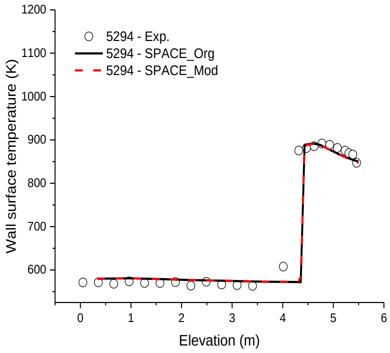

Fig. 4. Axial temperature distribution (Run 5294)

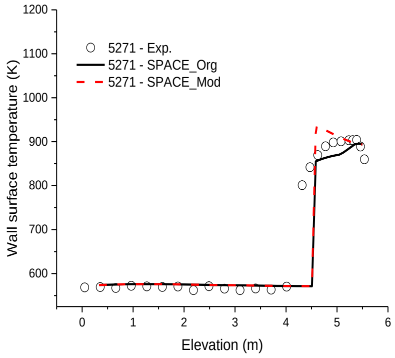

Fig. 5. Axial temperature distribution (Run 5271)

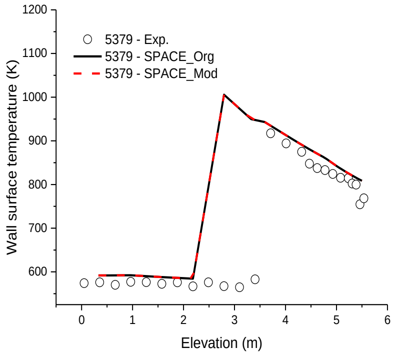

Fig. 6. Axial temperature distribution (Run 5379)

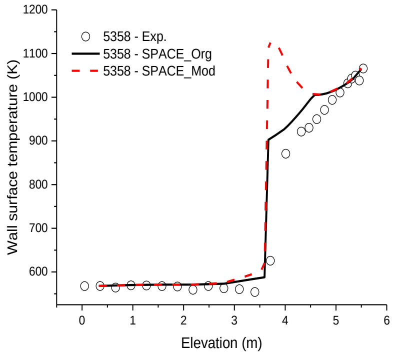

Fig. 7. Axial temperature distribution (Run 5358)

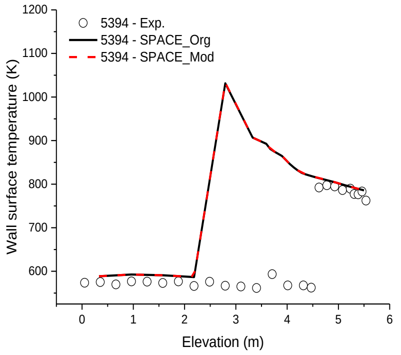

Fig. 8. Axial temperature distribution (Run 5394)

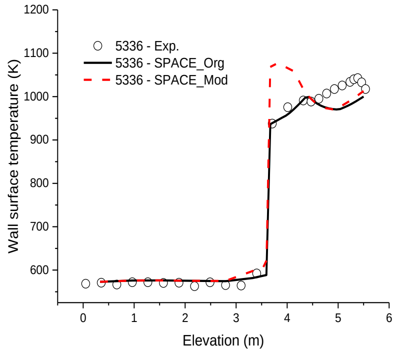

Fig. 9. Axial temperature distribution (Run 5336)

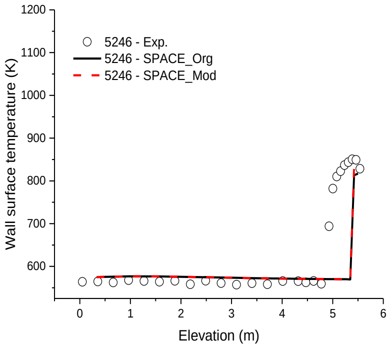

Fig. 10. Axial temperature distribution (Run 5246)

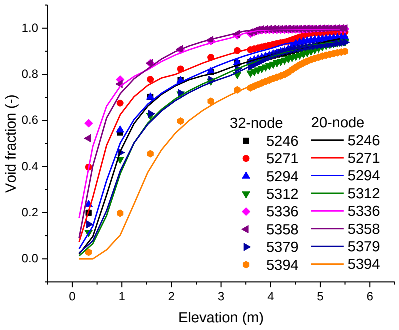

Fig. 11. Axial void fraction distribution