Assessment of Boiling Heat Transfer Models for the SPACE Code

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1. Introduction

SPACE (Safety and Performance Analysis Code) which is based on a multi-dimensional two-fluid, three-field model is under development for a licensing application of pressurized water reactors [1]. Several research and industrial organizations including KAERI, KHNP, KOPEC, KNF, and KEPRI have participated in the collaboration. KAERI is in charge of developing the physical models and correlation packages; i) a flow regime selection, ii) a wall and interfacial friction, iii) an interfacial heat and mass transfer, iv) a droplet entrainment/de-entrainment, and v) a wall heat transfer package. This paper briefly introduces a wall-to-fluid boiling heat transfer models and the assessment results of Bennett's test experiments. The objectives of these assessments are to examine the prediction capabilities of CHF and post-CHF heat transfer models. A detailed description of the overall heat transfer package can be found in the design document [2].

2. Wall-to-Fluid Heat transfer Package

The wall-to-fluid heat transfer package consists of a heat transfer mode transition map and heat transfer models for each mode. The energy partition into wall-to-vapor, wall-to-liquid, and wall-to-droplets should be considered.

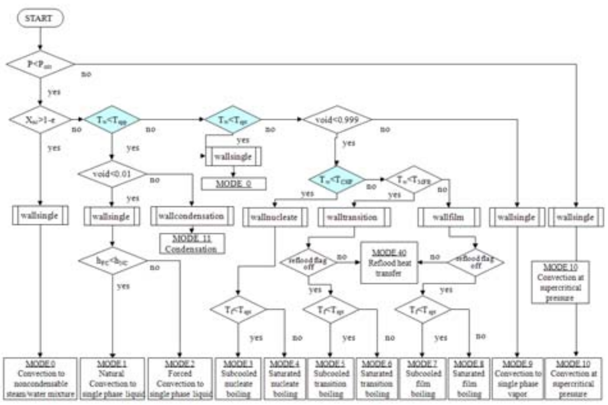

Fig. 1. Heat transfer mode transition map

Heat Transfer Mode Transition Map

The heat transfer transition map consists of 13 heat transfer modes; a liquid phase natural convection, a liquid phase forced convection, a nucleate boiling, a critical heat flux, a transition boiling, a film boiling, vapor phase convection, a condensation, and a reflood heat transfer. The heat transfer mode is determined based upon pressure, non-condensable gas quality, void fraction, bulk fluid temperature, and wall temperature as shown in Fig. 1.

Liquid phase convection

SPACE calculates both natural convection and force convection heat transfer coefficients. Then, it takes the maximum value.

Nucleate boiling

The Chen's model is used for both the subcooled and the saturated nucleate boiling. A net vapor generation (NVG) model and an energy partition model are also included in a subcooled nucleate boiling condition.

Critical heat flux (CHF)

An accurate prediction of CHF is essential to estimate a peak cladding temperature during the LOCA. Due to its accuracy and extensibility, the recent look-up table (LUT) [3] is selected for the SPACE code. A CHF temperature is calculated iteratively by using the nucleate boiling model:

$$T_{CHF} = T_{sat} + q''_{CHF} / h_{NB}(T_{CHF}).$$

Transition boiling

Transition boiling is an unstable heat transfer region which has both a nucleate boiling and a film boiling characteristics. SPACE considers as a sum of a nucleate boiling and a film boiling heat transfer, weighted by wetted-wall fraction. The minimum film boiling temperature is calculated by the Carbajo model [4].

Film boiling

The film boiling heat transfer mechanisms are conduction across vapor film to continuous liquid, convection to vapor, and radiation to all three fields. LUT [5] is used for an overall film boiling heat flux. To partition the total heat flux into three fields, the heat flux to each field calculated by the appropriate correlations. The heat flux to a vapor phase by convection is estimated by a Dittus-Boelter correlation and the conduction heat flux to a continuous liquid by a Bromley correlation [6]. Three radiation heat fluxes are obtained by the radiation model. Total heat flux obtained by LUT is partitioned proportional to the calculated heat flux to each phase by correlations.

3. Assessment of Boiling Heat transfer Models

The Bennett heated tube experiments [7] were conducted using a vertical, 1.26 cm diameter tube that was electrically heated. Water at a pressure of 6.9 MPa flowed upward in the tube. The test section of the

Bennett experiment was modeled with a pipe with 32 cells and a heat structure with 32 axial meshes. Initial and boundary conditions for the tests are presented in Table 1.

The calculated wall temperature from SPACE, MARS, and TRACE are compared with the Bennett test data for the low, intermediate, and high mass flux tests in Fig. 2 through Fig. 4. In general, the calculated wall temperature and CHF location are reasonable compared to the data for all three test cases. For the low mass flux case, the results matched the CHF location and the post-CHF wall temperature quite well. The other two cases show the CHF location occurring at a higher elevation (Test 5294) or at a lower elevation (Test 5394). The wall temperature for post-CHF condition was reasonably predicted for the low and intermediate mass flux cases. But for the high mass flux case, the wall temperature was over-predicted. This may be caused by less droplet entrainment at high flow condition and by ignoring the heat transfer enhancement in the developing film boiling region since LUT is developed based on fully developed film boiling [8].

Table I: Boiling heat transfer assessment matrix

Bennett test number	5358	5294	5394
Heat flux (MW/m^2)	0.512	1.09	1.75
Mass flux ($kg/s\text{-}m^2$)	380.	1953.	5181.
Subcooling (K)	34.41	18.8	13.78

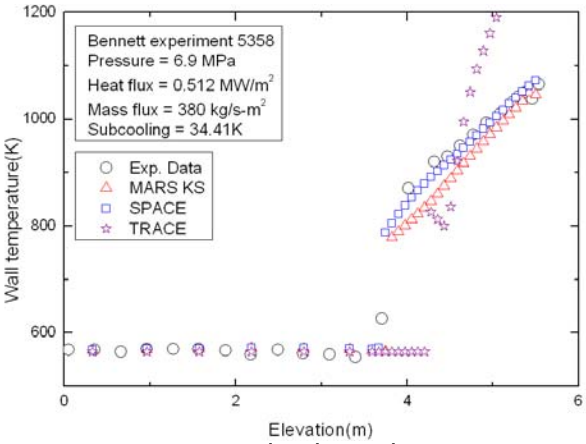

Fig. 2. Wall temperature profiles for low flow case: test 5358.

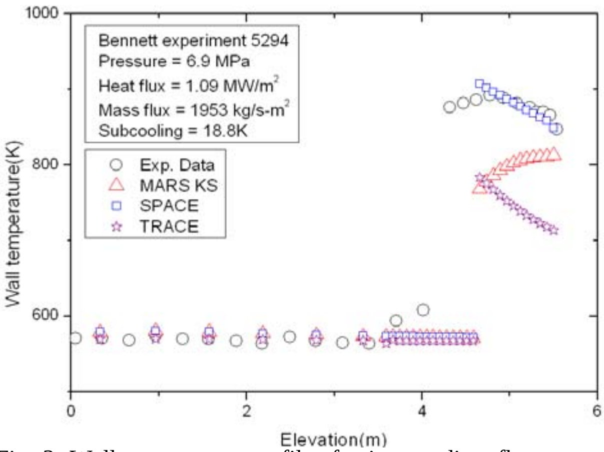

Fig. 3. Wall temperature profiles for intermediate flow case: test 5294.

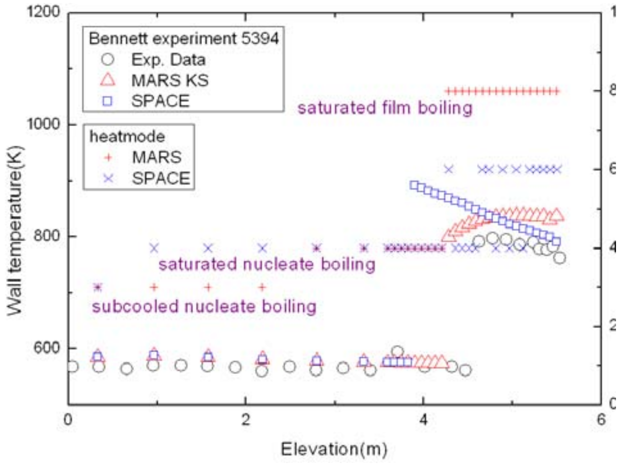

Fig. 4. Wall temperature profiles for high flow case: test 5394.

3. Conclusions

The physical model and correlation packages was developed and integrated into a main body of the SPACE code. As a part of V&V activities, Bennett heat tube experiments were assessed. The calculation results shows that wall-to-fluid boiling heat transfer models can predict the CHF location and the wall temperature in the post-CHF condition quite well. We found much room for model improvement during this assessment. Model improvement and more rigorous V&V will be performed in near future.

ACKNOWLEDGEMENT

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