Improvement of the subcooled boiling model in MARS for low-pressure conditions

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1. Introduction

Subcooled boiling is characterized by boiling occurring adjacent to the heated surface while the bulk liquid is at a subcooled condition. Subcooled boiling phenomena occur in hot channel under a steady state as well as a transient or accident in nuclear reactors. The void behavior in subcooled boiling has a great effect on flow and heat transfer characteristics and, thus, it is important to predict well the subcooled boiling phenomena in nuclear reactors.

During the last several decades, many experiments [1] were conducted to observe the subcooled boiling phenomena, such as a bubble generation, a bubble departure, and a bubble condensation. Some models [2] were developed for application in thermal-hydraulic computer codes, e.g., RELAP5, TRAC, CATHARE and MARS. Some of these efforts have been particularly focused on the subcooled boiling at low pressure over the past 20 years to analyze the safety of research reactors operating near atmospheric pressure [3] and to investigate the long-term core cooling during a LOCA of advanced light water reactors. However, the prediction of void behavior in subcooled boiling flow at low pressure still has great uncertainty, caused by the sensitivity of void behavior to various parameters.

In this work, the subcooled boiling model of the MARS code has been assessed, mainly focused on low-pressure conditions, through which some problems are identified. To solve these problems, some modifications are suggested and the results are discussed.

2. Subcooled boiling model of MARS code

2.1 The original model

In MARS, the subcooled boiling model involves a net vapor generation point (NVGP) model and a wall evaporation model. In a flow channel with a heated surface, bubbles can be generated at the surface although the cross-section averaged liquid is subcooled. Initially the bubbles may coalesce and condense by the subcooled liquid, thus maintaining negligible void fraction along the channel. The NVGP is generally defined as the point in the axial direction (i.e., in the direction of the flow) where the void fraction increases significantly. MARS adopts the Savannah River Laboratory (SRL) model to calculate the NVGP given by:

$$h_{cr} = \begin{cases} h_f^s - St\dfrac{C_{pf}}{(0.0055-0.0009\times F_{press})} & (for\ Pe>70{,}000) \\ h_f^s - Nu\dfrac{C_{pf}}{455} & (for\ Pe\le 70{,}000) \end{cases},\quad(1)$$

$$Nu = \frac{\ddot{q}D_h}{k_f}, \quad St = \frac{\ddot{q}}{GC_{pf}}$$

where h_{cr} is corresponding to the enthalpy at the NVGP and F_{press} is a pressure dependent multiplier:

$$F_{press} = \frac{1.0782}{1.015+\exp[(P/P_{psia}\text{-}140.75)/28.0]},$$

where

$P_{psia} = 6.894\times 10^3$ for units conversion.

Once the NVGP is determined by Eq. (1), the wall evaporation rate is calculated from the point to downstream along the heated wall. In MARS, the SRL model is also adopted for the wall evaporation. The wall evaporation is represented as:

$$\Gamma_W = \frac{q_w\cdot A_w}{V\cdot h_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\left[Mul + F_{press}\left(F_{gam} - Mul\right)\right], \quad (2)$$

where

$$Mul = \frac{h_f - h_{cr}}{h_f^s - h_{cr}},$$

$$F_{gam} = \min[1.0, 0.0022 + 0.11Mul - 0.59\times Mul^2 + 8.68\times Mul^3 - 11.29Mul^4 + 4.25Mul^5],$$

$$\varepsilon_{SRL} = \frac{\rho_f(h_f^s - h_f)\times F_{eps}}{\rho_g h_{fg}},$$

$$F_{eps} = \min\left[1.0, \frac{1.0}{0.97+38.0\times\exp[-(P/P_{psia}+60.0)/42]}\right].$$

The multiplier, F_{eps}, is applied to the pumping factor to correct the effect of the density ratio at the low pressure condition.

2.2 Deficiencies of original subcooled boiling model

The deficiencies of the original subcooled boiling model at low pressure were found through the comparison of subcooled boiling experimental data [1] with calculated results:

- The void fraction is significantly affected by an inlet subcooling temperature, when the inlet subcooling is low, as presented in Fig. 1. However, the original MARS does not consider the effect of the inlet subcooling temperature as presented in Fig. 2.
- MARS does not take into account the effect of liquid velocity. The effect of the liquid velocity is clearly shown on the experimental data under similar heat flux condition represented in Fig. 3, but the MARS code cannot consider this effect as shown in Fig. 4.
- The effect of equivalent diameter on NVGP is considered incorrectly. In MARS, the calculated void fraction is under-predicted when the equivalent diameter is small (D_h < 10 mm), as shown in Fig. 5(a). Adversely, the calculated void fraction is over-predicted in case of D_h > 10 mm, as presented in Fig. 5(b).

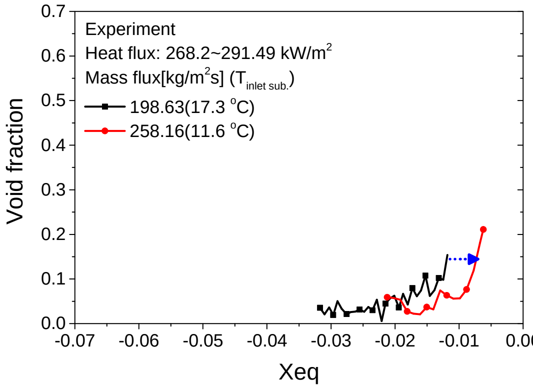


Fig.1. The effect of inlet subcooling temperature on void fraction in experimental data.

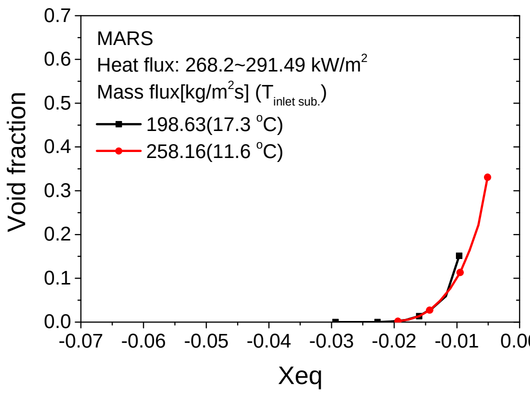


Fig. 2. The calculation results of the experiment.

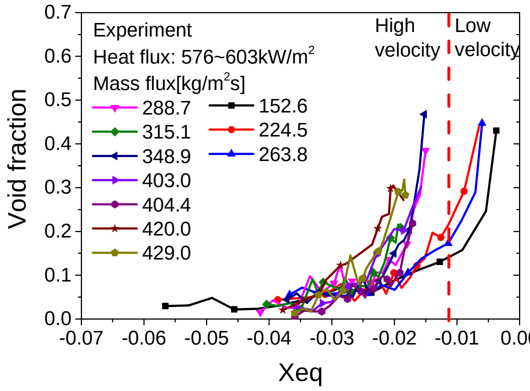


Fig. 3. The effect of liquid velocity on void fraction in experimental data.

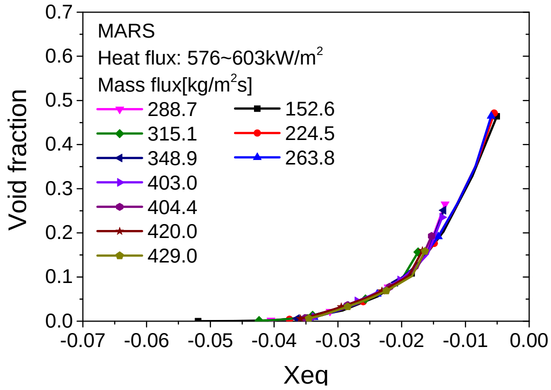
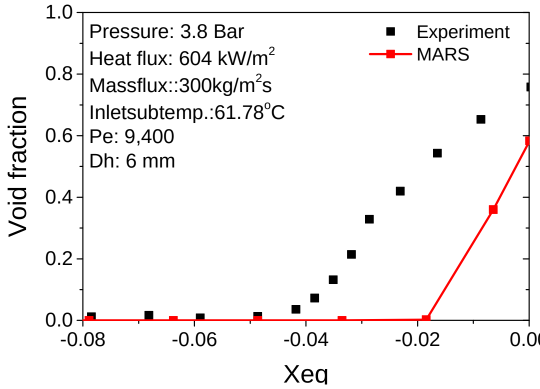
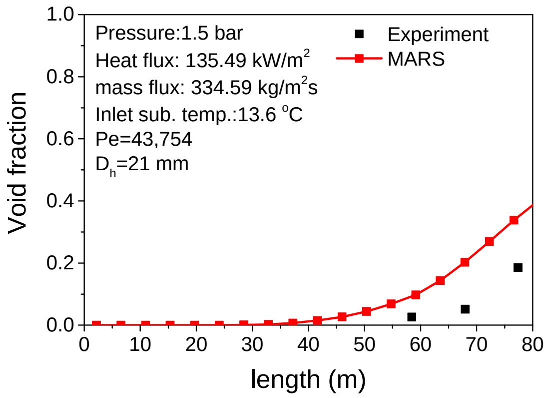


Fig. 4. The calculation results of the experiment.



(a) $D_h = 6$ mm



(b) $D_h = 21$ mm.

Fig. 5. The comparison of experimental data and calculated result.

3. Improvement and Assessment of the subcooled boiling model

To improve the problems mentioned in Section 2.2, an improved model is proposed in this section.

3.1 Improvement of the subcooled boiling model

From the collected experimental data, we observed that the void fraction versus the thermal-equilibrium quality, *Xeq*, changes quite different at around a certain liquid velocity (~ 0.3 m/s), as shown Fig. 3. Ivey [4] showed that most bubble rise velocities in boiling at low pressure have velocities within 0.3 m/s. We deduce that the void profile in low-pressure subcooled boiling is associated whether liquid velocity is greater than the bubble rise velocity or not. Therefore, a dimensionless number, u*, associated with the bubble rise velocity was introduced:

$$u^* = \frac{u_i}{1.18\times\left(\frac{g\sigma(\rho_L-\rho_v)}{\rho_L^2}\right)^{0.25}}, \quad (3)$$

where

$$u_i = \frac{\dot{m}}{\rho_f A}.$$

Then, the NVGP and wall evaporation model were respectively improved by dividing into a low velocity group and a high velocity group. The criterion between low velocity and high velocity is set to $u^* = 1.75$ (around 0.3 m/s) from the analysis of the experimental data.

At low velocity $\left(u^* \le 1.75\right)$, the NVGP was newly fitted based on the experimental data using a laminar heat transfer formulation in duct [5], to consider the effect of inlet subcooling temperature, as shown in Fig. 6.

$$h_{cr} = h_f^s - NuC_{pf}\left\{0.029 - 0.028\times\exp\left[-14.7\frac{k\left(T_{sat}-T_{in}\right)}{\ddot{q}D_h}\right]\right\} \quad (4)$$

The SRL wall evaporation model was also modified using u^* because most of the calculated void profiles were over-predicted compared to the experiment.

$$\Gamma_W = \frac{q_w \cdot A_w}{V\cdot h_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\left[Mul + F_{press}\left(F_{gam}-Mul\right)\right] \times\left(0.3556u^*\times\left(u^*-1.75\right)+1\right) \quad (5)$$

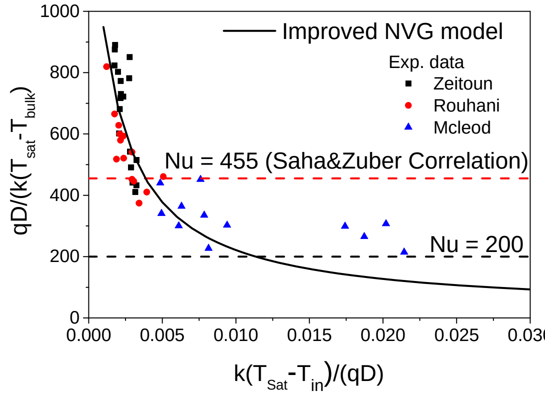


Fig. 6. Improvement of NVGP model at low velocity.

At high velocity $\left(1.75 < u^* \le 3.75\right)$, the NVGP of experimental data was also fitted using the boiling number $(Bo = \frac{\ddot{q}}{Gh_{fg}})$ to eliminate the effect of equivalent diameter, as shown in Fig. 7.

$$h_{cr} = h_f^s - 20.91\times h_{fg}Bo^{0.84} \quad (6)$$

where the data used in the correlation are within $u^* = 3.75$ m/s. The SRL wall evaporation model was also modified because the calculated void profiles are mainly under-predicted unlike in the case of low velocity.

$$\Gamma_W = \frac{q_w \cdot A_w}{V\cdot h_{fg}}\left(\frac{1}{1+\varepsilon_{SRL}}\right)\left[Mul + F_{press}\left(F_{highgam}-Mul\right)\right],$$

where

$$F_{highgam} = F_{gam} - 4\left(Mul-0.5\right)^2 + \frac{u^*-1.5}{2}. \quad (7)$$

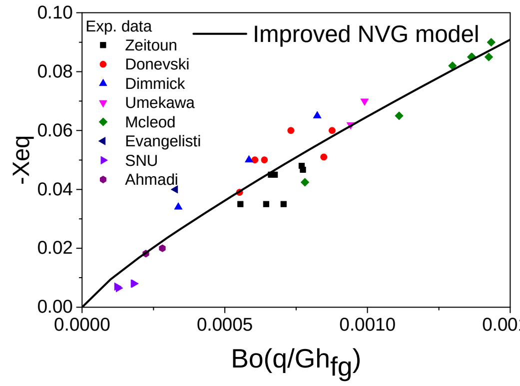
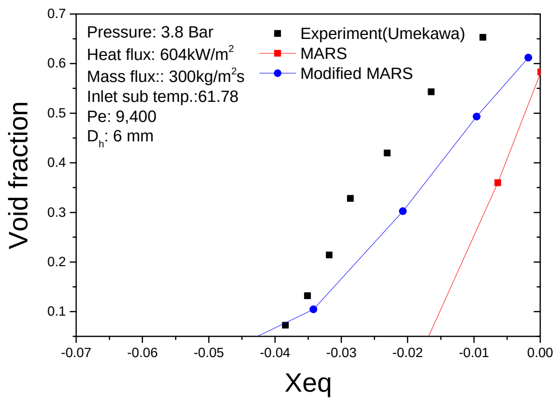


Fig. 7. Improvement of NVGP model at high velocity.

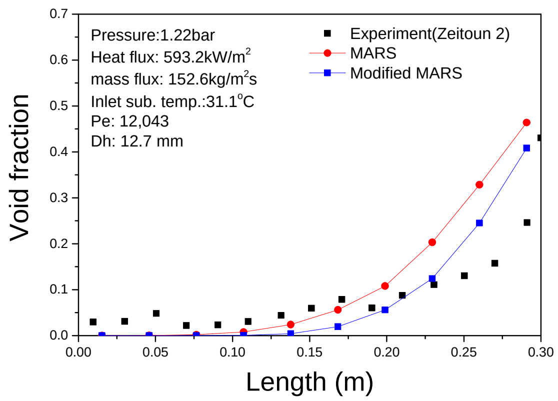
3.2 Calculation results

Figs. 8(a) and (b) show the comparisons of experiment data and the calculated results using the original and modified models at low velocity $\left(u^* \le 1.75\right)$. Fig. 8(a) shows an experiment where the inlet subcooling temperature is low and, the modified model predicts well the experimental data than the original model. Fig. 8(b) also shows the modified model predicts better.

Figs. 9(a) and (b) compare the experiment data and calculation results at high velocity $\left(1.75 < u^* \leq 3.75\right)$. As mentioned earlier, the original model under-predicts the void fraction when the equivalent diameter is small (D_h < 10 mm). Because the effect of equivalent diameter is eliminated by using the boiling number in the modified model, the modified model better predicts the experiment data than the original model. In addition, as shown in Fig. 9(b), the modified model shows a good agreement with experimental data due to the modification of the wall evaporation model.

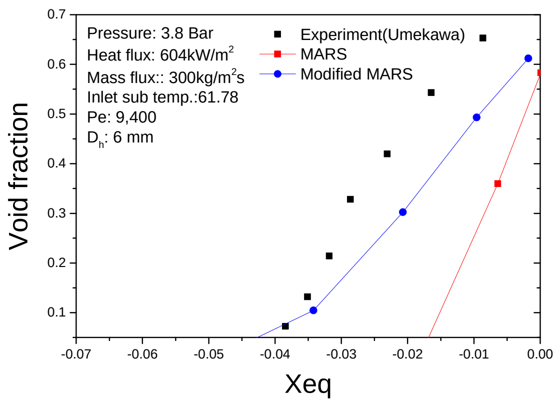


(a) The effect of inlet subcooling

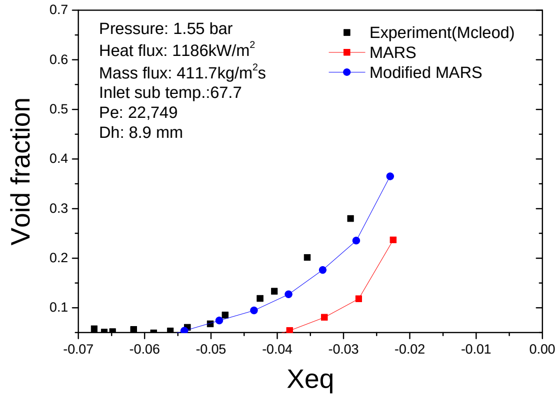


(b) The effect of the wall evaporation model

Fig. 8. Calculation results at low velocity.



(a) The effect of equivalent diameter



(b) The effect of the wall evaporation model

Fig. 9. Calculation results at high velocity.

4. Conclusions

In this work, we have assessed the subcooled boiling model of the MARS code, mainly focused on low-pressure conditions. From the results of the assessment, the following deficiencies of the MARS subcooled boiling model were found.

- It cannot consider the effects of inlet subcooling temperature and liquid velocity on axial development of void profile.
- It considers the effect of equivalent diameter incorrectly.

To solve these problems, we have modified the net vapor generation point model and the wall evaporation model of the MARS code. The results of the modified model clearly showed better agreement with experiment data than the original MARS model for low-pressure conditions.

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REFERENCES

[1] O. Zeitoun and M. Shoukri, Axial void fraction profile in low pressure subcooled flow boiling, Int. J. Heat Mass Transfer, Vol 40, pp. 869-879, 1997.
[2] B. Koncar and B. Mavko, Modelling of low-pressure subcooled flow boiling using the RELAP5 code, Nuclear Engineering and Design, Vol 220, pp. 255-273, 2003.
[3] E.L. Bibeau and M. Salcudean, Subcooled void growth mechanisms and prediction at low pressure and low velocity, Int. J. Multiphase Flow, Vol 20, pp.837-863, 1994.
[4] H.J. Ivey, Relationships between bubble frequency, departure diameter and rise velocity in nucleate boiling, Int. J. Heat Mass Transfer, Vol. 10, pp. 1023-1040, 1967.
[5] L.C. Burmeister, Convective heat transfer, John Wiley & Sons, 1993.