Application of heat transfer enhancement factors at downstream of quench front considering collapsed water level

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1. Introduction

The enhancement of the heat transfer at a downstream of a quench front was considered as the inevitable choice to well-predict the reflood experiments. However, the accessible experimental database for the quench front is currently insufficient. So the used correlations for the conventional codes were nearly empirical equations. The licensed system code, SPACE, selected the heat transfer around the quench front following the correlation used in TRAC/BF1 and RELAP5 [1]. This correlation was developed with two terms, which the first one used the extrapolation of the experimental range for the void fraction from Juhel [2] and the second term represented the empirical form from Bromley [3]. In this paper, we attempted to keep the provided experimental ranges and to add other relation of parameters found from accessible experimental data [4].

2. Applied correlation for quench front

As we mentioned, the current version of SPACE applied the same correlation used in TRAC/BF1 and RELAP5 as it follows:

$$h_{FB} = (1400 - 1880\Delta z_{QF})\max(0, \min(0.999 - \alpha_v, 0.5)) + h_{brom}\frac{{\alpha_l}^{0.5}}{{\Delta z_{QF}}^{0.25}} \quad (1)$$

where h_{FB} is the heat transfer coefficient (HTC) used for the film boiling part, Δz_{QF} is the distance of the calculation node from the quench front, α_v is the void fraction, h_{brom} is HTC from Bromley, and α_l is the liquid fraction. This h_{FB} would be used for both film boiling and transition boiling around the quench front.

The origin of the first term in the equation (1) is the work of Juhel [2]. He developed that correlation with the very limited experimental condition over the void fraction of 0.95, while the system codes applied the equation (1) with whole range of the void fraction. The maximum and minimum criteria at the first term also have no evidence. The support of the second term for the equation (2) was not found either.

With the literature survey, we found the developed form of the correlation called K2 model used in CATHARE code. This model was validated with the wide range of the quality [4]. The equation was followed as:

$$q'' = h_{FB}(T_w - T_{sat}) + K_2\frac{dT_w}{dz} \quad (2)$$

where q'' is the wall heat flux, T_w is the wall temperature, T_{sat} is the saturated water temperature, K_2 is the empirical coefficient, dT_w is the axial gradient between wall temperatures, and dz is the interval length for the dT_w.

The reference [4] did not provide the detailed form of the equation. So we digitized the graph in the reference and obtained the following model:

$$\frac{K_2(x_{th})}{z_{QF} - z_{sat}} = \begin{cases} 219.2e^{-15.6\times 0.05} + 12.83 & x_{th} \le 0.05 \\ 219.2e^{-15.6x_{th}} + 12.83 & x_{th} > 0.05 \end{cases} \quad (3)$$

where z_{QF} is the location of the quench front, z_{sat} is the location where the water became firstly saturated, and x_{th} is the thermal equilibrium quality. From the equation (3), we could notice that $K_2/(z_{QF}-z_{sat})$ became the saturated value over the quality of 0.8.

Combining the parametric effect from the equation (3) with the Juhel's correlation, we suggested the new correlation under the assumption that the high void fraction corresponds with the high quality:

$$h_{FB,SPACE} = \begin{cases} C_1 C_2\frac{K_2(x_{th})}{K_2(1)}(1400 - 1880\Delta z_{QF})(0.999 - 0.95) & \alpha_v \le 0.95 \\ (1400 - 1880\Delta z_{QF})(0.999 - \alpha_v) & \alpha_v \ge 0.95 \end{cases} \quad (4)$$

where C_1 is an empirical constant and C_2 is the relation for z_{QF}-z_{sat}.

We need C_1 and C_2 for each following reason. The first reason for C_1 is the term of dT_w/dz. As described in the equation (2), K2 model was summed with the film boiling heat flux. This approach was possible since CATHARE code is capable of calculating dz ~ 10^{-4}m. Although SPACE is available for the fine-mesh rezoning, the size of the node is too large to get the actual axial gradient of the wall temperature. So C_1 was proposed to compensate the difference between the multiplication in the equation (4) and the summation in the equation (2).

For the equation (4) of lower void fraction than 0.95 with C_2 of 1, the relative enhancement of the heat flux lead to:

$$\frac{h_{FB,SPACE}(x_1)}{h_{FB,SPACE}(\alpha_v > 0.95)} = C_1\frac{K_2(x_1)}{K_2(1)} \sim \frac{h_{FB}(T_w - T_{sat}) + K_2(x_1)\frac{dT_w}{dz}}{h_{FB}(T_w - T_{sat}) + K_2(1)\frac{dT_w}{dz}}$$

(5)

There exist two extreme situations for this equation: when the first term is negligible compared to second term or vice versa for $h_{FB}(T_w - T_{sat}) + K_2(1)\frac{dT_w}{dz}$.

For both cases, the equation (5) became as:

$$C_1 \frac{K_2(x_1)}{K_2(1)} \sim \begin{cases} K_2(x_1)/K_2(1) & h_{FB}(T_w - T_{sat}) << K_2(1)\dfrac{dT_w}{dz} \\ 1 & h_{FB}(T_w - T_{sat}) >> K_2(1)\dfrac{dT_w}{dz} \end{cases} \quad (6)$$

So C_1 could be expressed as:

$$C_1 \sim \begin{cases} 1 & h_{FB}(T_w - T_{sat}) << K_2(1)\dfrac{dT_w}{dz} \\ K_2(1)/K_2(x_1) & h_{FB}(T_w - T_{sat}) >> K_2(1)\dfrac{dT_w}{dz} \end{cases} \quad (7)$$

For this relation, we could notice that C_1 is in range of 0 and 1. Also C_1 will be decrease as h_{FB} is increased.

C_2 was suggested to count the effect of z_{QF}-z_{sat}. For SPACE, it is hard to obtain the exact beginning position of z_{sat} since the water temperature is continuously changed for n-th digit due to numerical calculation for the energy conservation. Reviewing the data of RBHT test, we found that the collapsed water level became saturated while the mass flow rate was sustained at the inlet. Even though the collapsed water level was fixed, the quench front propagated in experiments. This indicates that the water became saturated somewhere around the collapsed water level. The literature [4] showed the experimental z_{QF}-z_{sat} was in scale of 0.1 m. Based on this, we empirically proposed C_2 as it follows:

$$C_2 = \begin{cases} 1 & h_{CWL} \geq z_{QF} \\ \dfrac{z_{QF} - h_{CWL} + 0.6}{0.6} & h_{CWL} < z_{QF} \end{cases} \quad (8)$$

3. Assessment results for RBHT

We assessed and compared two RBHT cases which are described in Table I.

Table I: Assessment matrix

Parameters	RBHT-1196	RBHT-1383
Flooding rate (mm/s)	152.4	25.4
Pressure (MPa)	0.28	0.28
T_{sub} (K)	53.0	11.0
Initial rod peak power (kW/m)	2.3	1.3

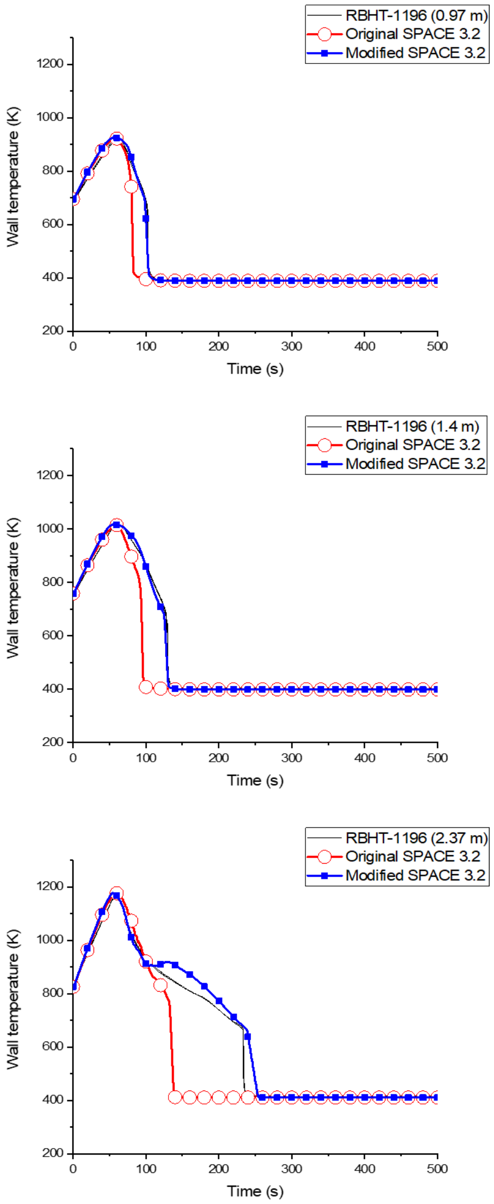

Fig. 1. Wall temperature vs. time for RBHT-1196 (at the locations of 0.97, 1.4, 2.37 m)

For RBHT-1196, we applied C_1 of 0.3. As shown in Figs. 1-2, general trends for the wall temperatures from the modified SPACE showed better agreements than those from the original SPACE.

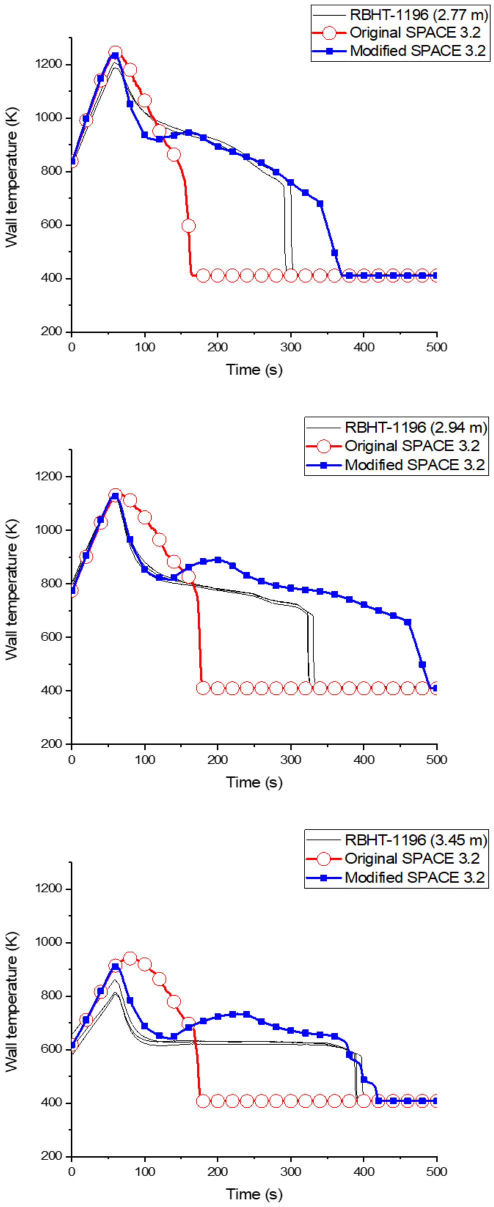

Fig. 2. Wall temperature vs. time for RBHT-1196 (at the locations of 2.77, 2.94, 3.45 m)

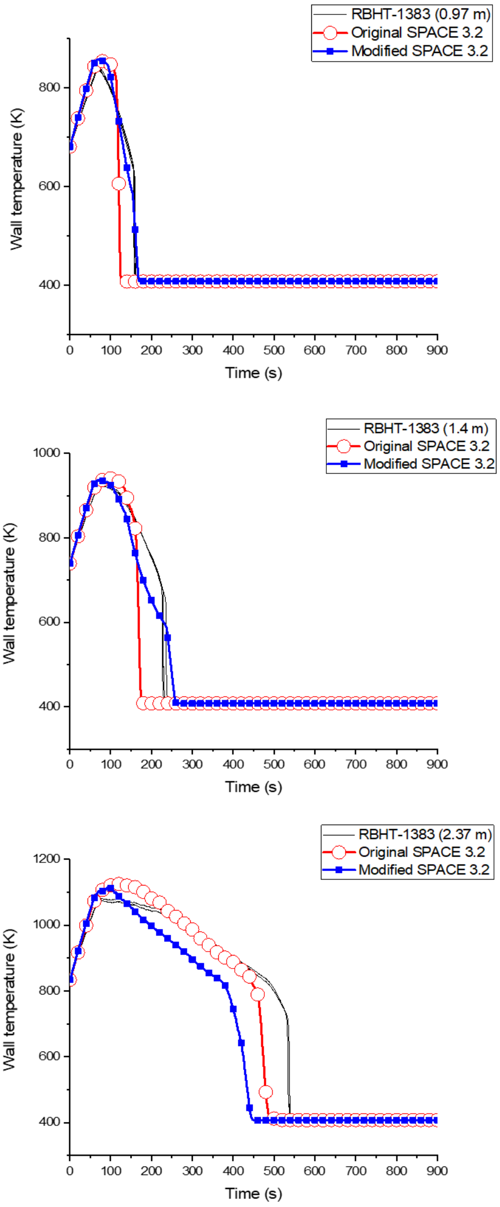

Fig. 3. Wall temperature vs. time for RBHT-1383 (at the locations of 0.97, 1.4, 2.37 m)

For RBHT-1383, we applied C_1 of 0.7. As we mentioned with the derivation of the equations (6)-(7), C1 would be increased with the decreasing h_{FB}. Since h_{FB} from RBHT-1383 should be lower than h_{FB} from RBHT-1196 for the reasons of the water subcooling and the mass flow rate, the value for C_1 (0.7) was increased compared to RBHT-1196 (0.3). Same with RBHT-1196 case, the overall trends for wall temperatures in RBHT-1383 were improved after the modification.

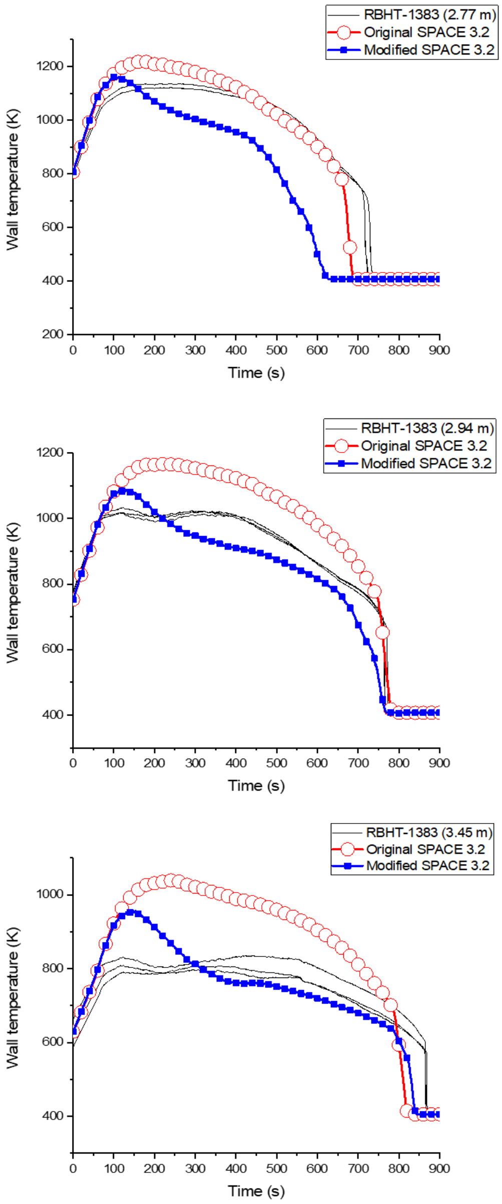

Fig. 4. Wall temperature vs. time for RBHT-1383 (at the locations of 2.77, 2.94, 3.45 m)

4. Conclusions

We attempted to apply the heat transfer enhancement factors for the downstream of the quench front, following the experimental ranges of the accessible database and correlation. As a result, the wall temperatures for RBHT-1196 and RBHT-1383 were improved. The sensitivity study and the investigation for the physical background will be continuously proceeded.

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