On the Low-Pressure Low-Flow Critical Heat Flux: Flow Instability and Spacer Grid Effects

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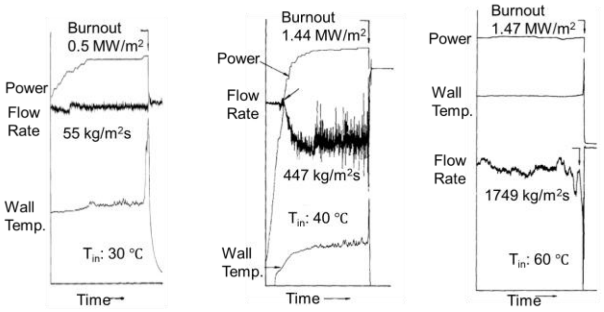
1. Introduction

The low-pressure low-flow critical heat flux (LPLF CHF) has been addressed as a key concern in the design of small modular reactors (SMRs) due to their distinctive design features, such as integrated type, small/short reactor core, long riser, and LPLF operating condition. Our previous study identified an overprediction tendency of the 2006 Groeneveld lookup table (LUT) when applied to round-tube and 2×2 rod-bundle data [1,2]. In that analysis, the inlet condition and mass flow were fixed while the power was gradually increased until CHF was detected by a sharp rise in surface temperature.

The Groeneveld LUT was evaluated against the large EPRI rod bundle database using steady CTF subchannel simulation, and it provided a good CHF prediction within an error margin of ~11% [3]. To evaluate the CHF evaluation method, the present study re-evaluates LPLF CHF data using the steady-state simulation method.

In addition, the effects of flow instability and spacer grid under the LPLF condition are investigated. Premature CHF is expected to occur by flow instability under the LPLF condition, as illustrated in Fig. 1 [4]. Spacer grids with mixing vane can enhance heat transfer. However, accurately capturing this effect remains challenging due to limitations in simulation capabilities. Phenomenologically, CHF has been interpreted globally by the similarity with hydrodynamic instabilities or locally as a result of heat flux partitioning by, for example, the dryout of liquid sublayer or the formation of irreversible dry spot/patch under a massive bubble [5]. Also, the presence of flow instability and spacer grid will introduce complex variations to CHF prediction, necessitating further investigation.



(a) Stable flow (b) Density wave oscillation (c) Flow excursion

Fig. 1. CHF under different flow mode [4]

2. Analysis Method

The CHF data for a uniformly heated round tube [6], a uniformly heated annular channel with spacer grids [7], and an non-uniformly heated 2×2 rod bundle [8] are simulated using the RELAP5 system analysis code and the CTF subchannel analysis code. Both the steady simulation using the experimental condition and the transient simulation using fixed inlet condition and power shift are performed.

3. Results and Discussion

Our previous study showed that the Groeneveld LUT overpredicted the round-tube data, 1.5 ~ 4 times for heat fluxes below ~0.7 MW/m^2 transient simulation (Fig. 2). Steady calculation was not obtained for this data due to thermodynamic property error. Two possible reasons for the overprediction are the LUT itself (i.e., its predictive capability) and the influence of flow instabilities which are dominant under the LPLF condition. The accuracy of LUT depends on its CHF tabulated data and input parameters including pressure, mass flux and quality.

Flow instabilities may not directly trigger CHF, but they will introduce uncertainties to both the CHF tabulated data and the input parameters leading to deviations between predicted and actual CHF values. As shown in Fig. 3, the predicted quality deviated to a certain extent from the measured values, and it could result in different CHF values interpolated from the CHF table and finally contribute to the CHF overprediction. Therefore, this study focuses on evaluating the effect of flow instabilities.

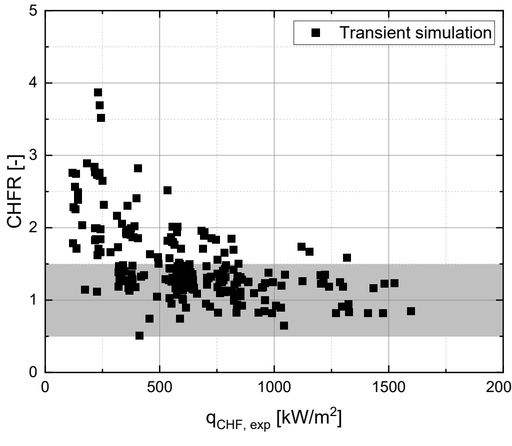


Fig. 2. Round tube: Predicted CHF [1]

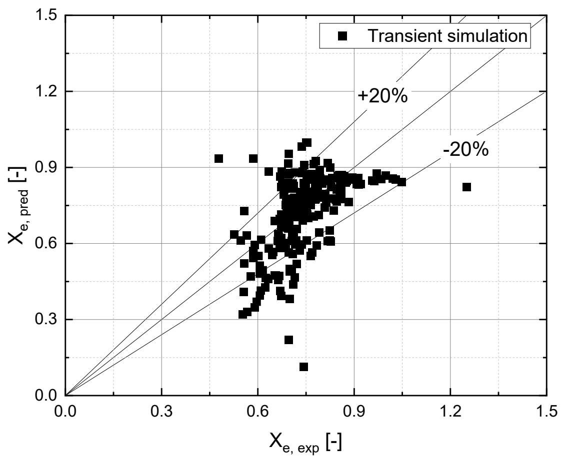


Fig. 3. Round tube: Predicted quality

Figure 4 shows the simulation results of three typical cases. Case 121 represents the high-CHF region (>1000 kW/m^2) where the LUT provided good predictions. Case 1 represents the intermediate region (500–1000 kW/m^2), while case 105 corresponds to the low-CHF region (<500 kW/m^2) where the LUT performance is poor.

These cases are consistent with the descriptions of stable flow, flow excursion, and DWO shown in Fig. 1. Case 121 exhibits relatively stable flow rate and quality with minimal fluctuation. In contrast, case 1 shows flow excursion together with a sharp change in quality at the onset of CHF. Case 105 demonstrates sustained oscillation with large amplitude, like the DWO.

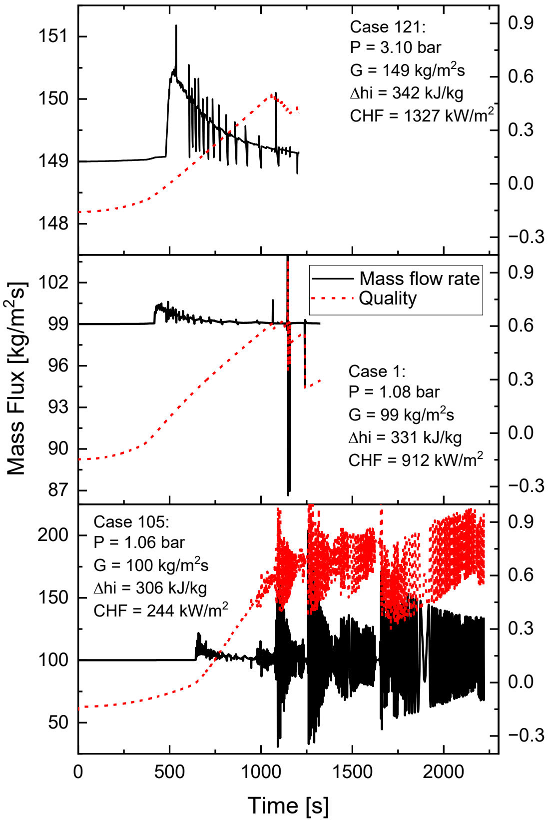


Fig. 4. Round tube: Predicted flow rate and quality

A common trend is observed in which mass flux increases once boiling begins ($X_e > 0$) and then continuously decrease toward its initial level. Fluctuations in mass flux may occur and persist. Similar flow behavior may be expected in the experiments.

This trend can be explained by pressure drop characteristics. When boiling initiates, pressure drop decreases due to reductions in the frictional factor, two-phase multiplier, and/or mixture density. As a result, mass flux must increase to keep maintain the set pressure drop between the inlet and outlet. The mass flux then decreased when the system approaches an expected state set by boundary conditions. Such fluctuations may occur in experiment at steps of power increase. Orifices are often used to mitigates the fluctuations when measuring CHF.

To determine whether the flow instabilities exist, the following criteria proposed by Guido et al. (1991) [9] were examined.

i) DWO instability: $N_{pch} < N_{sub} + N + \sqrt{N^2 + \tau}$ (1)

ii) Ledinegg instability: $N_{pch} > 2N_{sub} - \tau$ (2)

where $N_{pch} = \frac{Q}{h_{fg}W}\frac{\Delta\rho}{\rho_g}$, $N_{sub} = \frac{\Delta h_{in}}{h_{fg}}\frac{\Delta\rho}{\rho_g}$, $\tau = \frac{2(K_i+K_e)}{K_e+1}$ and $N = \frac{\tau}{2}\left(1+\frac{2}{N_{sub}}\right) - \frac{5}{2}$.

As shown in Fig. 5, most of the Kim et al. (2000) data fall within the DWO region when the inlet and outlet loss coefficients (K_i and K_e) are zero. As increasing these factors, the DWO boundary shifts upward while the Ledinegg boundary shift downward leading to a shrink of the stable region. This suggests that the DWO instability likely occurs in the Kim et al. (2000) dataset even the data are reported as steady CHF measurements.

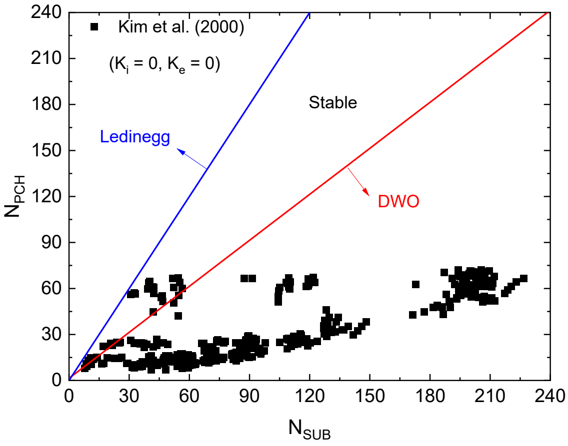


Fig. 5. Checking of flow instabilities

A key consequence of the flow instabilities is the occurrence of premature CHF which is lower than the stable CHF. Since the CHF LUT, correlation and models have been developed for stable CHF, they tend to overpredict the LPLF CHF as discussed above.

To further investigate whether the overprediction comes from unstable flow conditions, both steady-state and transient simulations were performed for LPLF CHF in annulus flow [7]. As shown in Fig. 5, no oscillations in mass flux and quality are observed in the steady-state simulations, and hence the surface temperature also remains unchanged. If flow is exactly at a CHF condition, such a steady-state simulation may not be obtainable due to very high surface temperature, as observed with Kim et al. (2000) data.

Despite reaching a steady state, the predicted CHF values are much larger than the experimental CHF values by 1.5–4 times overall, as shown in Fig. 6. This result indicates the limited applicability of the LUT table to the LPLF CHF data, rather than being an artifact of numerical analysis methods.

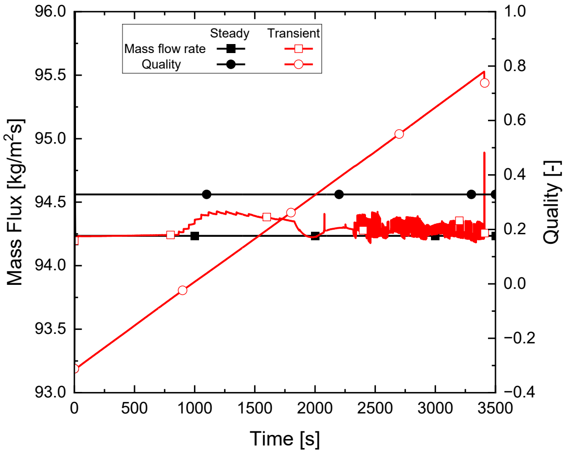


Fig. 5. Annular channel: Predicted flow rate and quality

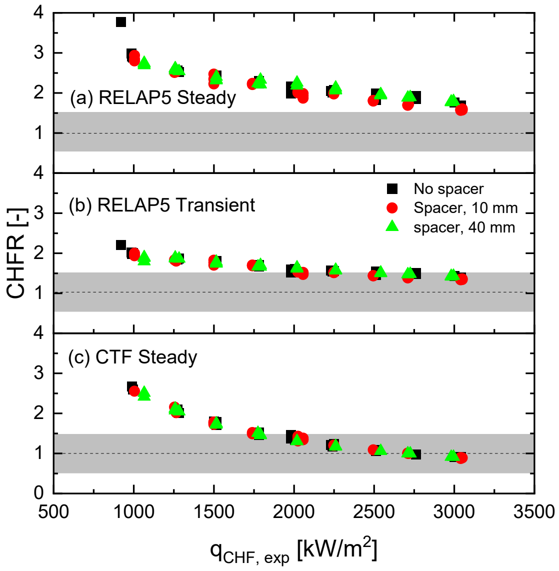


Fig. 6. Annular channel: Predicted CHF

The results show in Fig. 6 indicates insignificant effect of spacer grid on CHF. In this experiment, a spacer grid was installed 10 mm or 40 mm below the test section outlet, introducing ~10% flow blockage. The experimental results showed higher quality due to heat transfer enhancement by spacer grid. However, the spacer grid seemly has no considerable influence on CHF. It is possible that the LUT already magnified the predicted CHF so that it hindered spacer grid effects. Nevertheless, the spacer grid still left its influence on the axial CHF distribution, as shown in Fig. 7. In the vicinity of the spacer grid location, higher CHF values are observed when the spacer grid is present. In these simulations, the spacer grid was simulated in terms of blockage ratio, K factor of 0.01, and spacer grid lengths of 10 mm or 40 mm or using a simplified spacer model.

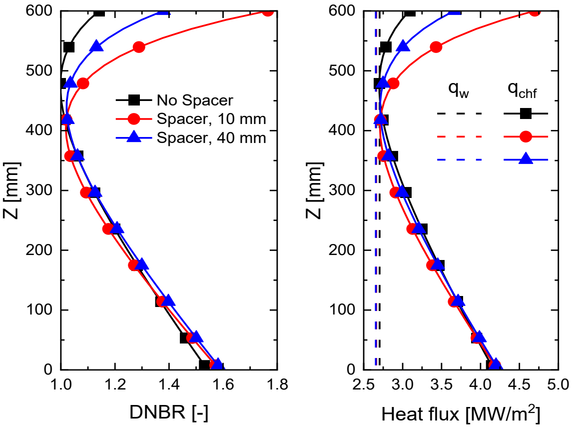


Fig. 7. Annular data: Predicted CHF (CTF)

Additional CTF steady-state simulations were performed for the 2×2 rod bundle CHF data. In this experiment, three spacer grids installed at 1.0, 1.5 and 2.0 m with a blockage ratio of ~16% [8]. The CTF simulations used a simplified spacer model to simulate these spacer grids. The W3 correlation was compared with the CHF LUT. Typical results plotted in Fig. 8 show a non-uniform flow distribution in subchannels and high heat flux as well as low MDNBR in the central region of rods. The effect of these spacer grids was not clearly captured. Both the LUT and W3 correlation were overpredicted (>1.5 times), as observed in Fig. 9. The W3 correlation provided better agreement with experimental data. This results again highlight the limited predictive capability of the LUT and correlations for LPLF CHF and the need for improved CHF prediction tailored to the LPLF region.

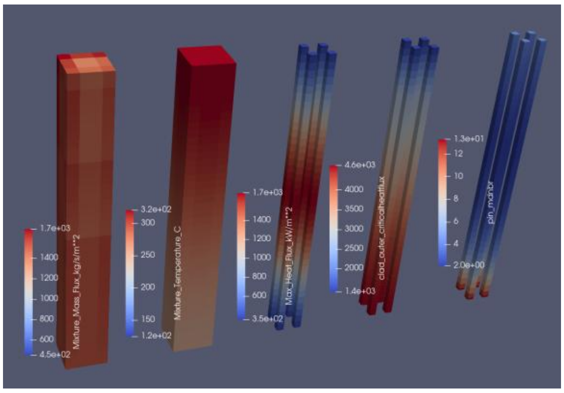


Fig. 8. Rod bundle (2×2) data: Typical results

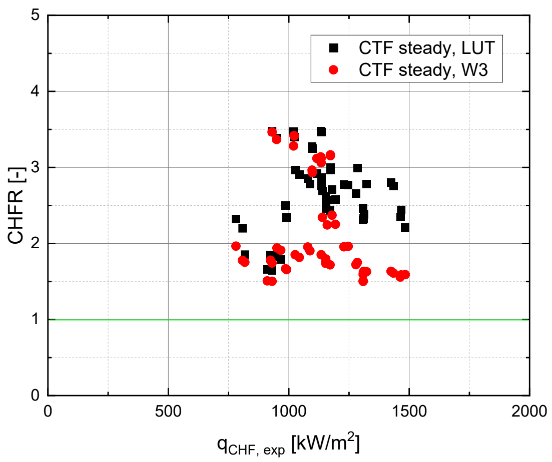


Fig. 9. Rod bundle (2×2) data: Predicted CHF

4. Conclusions

The Groeneveld lookup table (LUT) exhibits significant overprediction of low-pressure low-flow (LPLF) CHF, up to 4 times higher than the experimental results. The discrepancy was more pronounced in the low heat flux region, which typically associated with lower pressure, lower mass flux and/or lower subcooling. Since the LUT was developed based on steady CHF database, it did not adequately account for flow instabilities that are prevalent under the LPLF condition.

The simulations identified two primary types of flow instability: density wave oscillation (DWO) and flow excursion (Ledinegg instability). These instabilities can cause temporary local depletion of cooling liquid, thereby triggering CHF, which is at a lower level than the stable CHF. Consequently, the CHF LUT, correlations and models for stable CHF tend to overpredict CHF under the LPLF condition.

Although spacer grids are expected to influence flow redistribution and enhance local rod heat transfer, but the simulations did not show clear impact on CHF, except for heat transfer enhancement near the spacer grid location. This suggests that the spacer grid effects on CHF remains insufficiently captured and warrants further investigation.

Acknowledgment

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