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Invited Article

AN IMPROVED HEAT TRANSFER CORRELATION FOR DEVELOPING POST-DRYOUT REGION IN VERTICAL TUBES

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ABSTRACT

A developing post-dryout region is characterized by significant heat transfer enhancements compared with the fully developed post-dryout region. The heat transfer enhancements are mainly due to upstream disturbance and entrained droplets in the region immediately downstream of the critical heat flux location. In this paper, an improved heat transfer correlation is developed for the developing post-dryout regions in vertical tubes over a wide range of flow conditions. The correlation represents a correction factor for the fully developed film-boiling look-up table to be applied to the developing post-dryout region. The new correlation significantly improves the heat transfer prediction in the developing post-dryout regions and provides very good agreement with the experimental data.

1. Introduction

A post-dryout heat transfer region can be encountered once the local heat flux of a heated surface exceeds the critical heat flux (CHF). A steep increase of surface temperature in the post-dryout regions may lead to physical damage of the heated surface due to overheating by the poor heat transfer coefficient. Because the phenomenon is of importance under postulated accidents and transients of nuclear reactors, a large number of prediction methods for post-dryout heat transfer coefficients have been proposed over the past years. Excellent reviews of post-dryout heat transfer can be found in textbooks such as that of Hewitt and Delhaye [1] and in articles by Andreani and Yadigaroglu [2] and Chen [3]. However, most of the prediction methods for post-dryout heat transfer are either empirical or semiempirical, which are normally applicable to a limited range of flow conditions. Remarkable prediction errors and incorrect asymptotic trends should be

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considered when these prediction methods are extrapolated to conditions far beyond their database.

To overcome these deficiencies, Groeneveld et al. [4] proposed a fully developed film-boiling look-up table with great accuracy for a wide range of flow conditions. Nevertheless, post-dryout heat transfer is generally undeveloped in the region just after the CHF location due to the considerable effects of upstream history. Fig. 1 shows typical results of the wall temperature and heat transfer coefficient obtained by Becker et al. [5]. After the CHF occurrence, two distinct regions of the post-dryout heat transfer are identified, namely, developing and fully developed regions. The developing region is assumed to be the region between the CHF location and the point at which the surface temperature reaches a maximum value.

The developing post-dryout region is characterized by heat transfer enhancements due to residual disturbance caused by the CHF occurrence and entrained droplets from sputtering liquid [6]. The upstream CHF occurrence enhances the wall to vapor convective heat transfer by increasing the vapor turbulence while the entrained droplets improve the liquid–wall interaction. The heat transfer in the fully developed region is not affected by the upstream CHF history and depends solely on the local flow conditions [7]. The solid symbols in Fig. 1 represent the wall temperature and heat transfer coefficients predicted by the fully developed film-boiling look-up table developed by Groeneveld et al. [4]. The look-up table tends to underpredict the heat transfer coefficients, and hence overpredict the wall temperatures in the developing post-dryout region. This is because the look-up table was developed based on experimental data that were obtained in the fully developed region.

Isachenko et al. [8] developed an empirical relation for the heat transfer enhancements in the developing post-dryout regions up to a distance of 15 hydraulic diameters from the CHF location. The Nusselt number in the developing region was calculated by multiplying the Nusselt number in the fully developed region by a power function of the ratio of hydraulic diameter to the distance from the CHF location.

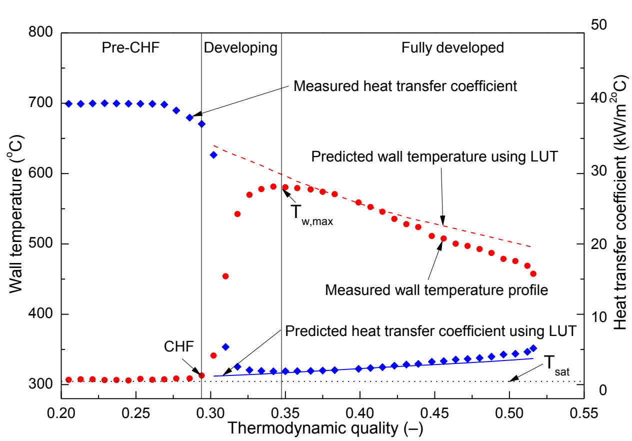

Fig. 1 – Typical surface temperature and heat transfer coefficient profile in the post-dryout region (run no.: R217, Becker et al. [5]). CHF, critical heat flux; LUT, look-up table.

In conjunction with the film-boiling look-up table [4], Guo and Leung [6] developed a generalized wall-temperature-based correlation that employs the wall temperature as an independent parameter to predict the post-dryout heat transfer coefficient in the developing region. They proposed a modification factor for the developing film-boiling effects using extensive experimental data of film-boiling heat transfer in tubes. The modification factor was represented by the exponential decay function of the local wall superheat ratio. However, constants of the correlation were not presented in their paper because of their proprietary information.

With regard to the basic assumptions and range of data assessments, the conventional wall-temperature-based correlation by Guo and Leung [6] has some disadvantages. First, the operating pressure was restricted below 17 MPa to minimize the data uncertainty. Second, the correlation cannot predict the wall temperature of the points at which local thermodynamic quality exceeds unity. The modification factor needs a local CHF value at a given post-dryout location downstream of the CHF occurrence location. However, the local CHF value becomes zero when the corresponding thermodynamic quality exceeds unity, resulting in infeasible calculation of the modification factor. Thus, the modification factor is applicable only to a limited range of post-dryout regions. Finally, the correlation by Guo and Leung [6] adjusted systematic biases introduced from the incorrect predictions of the CHF and the post-dryout heat transfer coefficients. However, from a practical point of view, the systematic biases cannot be known *a priori* without performing experiments.

Pelletier et al. [9] improved Guo and Leung's [6] correlation by adding Reynolds number of vapor to account for the effect of mass flux and thermodynamic quality on the developing post-dryout heat transfer. However, the aforementioned problems remained.

Therefore, the objective of this study is to present an improved heat transfer correlation for post-dryout heat transfer in vertical tubes. The improved correlation provides a good wall temperature prediction and eliminates the disadvantages of conventional correlations. The correlation presented was developed based on experimental data by Becker et al. [5] and validated using additional experimental data by Bennett et al. [10].

2. Derivation of the improved correlation

The improved heat transfer correlation was developed based on an analogy between the upstream history effect and the entrance length effect. The heat transfer in the developing region may be regarded as a transient, entrance-region problem with axial distance from the CHF location [3]. In fluid mechanics, the entrance length starts from the inlet of the tube. The flow structure is chaotic and unsteady leading to the enhancement of forced convection heat transfer in this entrance region. The further downstream from the entrance, the more stable the flow pattern is. In cases of post-dryout, the entrance point can be assumed to be at the CHF location where the heat transfer and the corresponding flow pattern suddenly change from pre-CHF conditions to post-CHF conditions. Therefore, the heat transfer in the post-dryout region