Prediction of Critical Heat Flux under Rolling Motion

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1. Introduction

The critical heat flux (CHF) is an essential factor in safety design and operating of marine reactor. The CHF can be influenced by rolling (kind of rotation which gives the system a time-dependent inclination together with a centrifugal and a tangential force) and heaving (time-dependent linear vertical gravity acceleration variation) motions. Compare with the effects of heaving motions, rolling motion is more complicated. The aim to this paper may be summarized as follows: (1) identify the flow regime compare with existing void-quality relationship and void fraction at OAF derived from the vapor superficial velocity obtained by the churn-to-annular flow criterion, (3) develop and evaluate the correlation for accurate prediction of CHF ratio under rolling motion.

2. Development of New Correlation

There is no previous correlation that can be applied to the present experimental condition, i.e., using a Freon R-134a working fluid in uniformly-heated tube under rolling condition. Several previous CHF correlations from Tables 1 and 2 are important to the development of correlation they are relevant to this study. To improve quantitative understanding of the rolling motion on CHF, correlations are derived in this section based on flow conditions measured in the test section inlet (i.e. single-phase region). Correlations are developed to cover the LFD and DNB regions separately, because the phenomenon is found to be quite different as explained above.

2.1 Determination of Annular Flow Regime

Hong's prediction method [1] for void fraction at onset of annular flow (OAF) is adopted because it is difficult to obtain the appropriate quality along the z-direction of heated tube. In order to define the flow regime with applying the MARMS results, phenomenological prediction of dryout is chosen as the approaching method for deciding the annular flow in each condition. This is due to fact that it is one of the successful prediction methods of the CHF in flow boiling. Quality and void fraction at OAF should be given to determine the flow pattern. The prediction method for LFD suggested by Hong et al. [24] was applied to identify the annular flow region in this study. He adopted the calculation of quality and void fraction using vapor superficial velocity suggested by Taitel et al. [26]. It could improve the accuracy of dryout prediction and extend the applicable range to low quality. The vapor superficial velocity is obtained by the churn-to-annular flow transition (CAFT) criterion proposed by Taitel et al. The void fraction at OAF is calculated by the following void-quality relation.

The values of void fraction and quality at OAF calculated are plotted against mass flux in Fig. 5. Whalley [2] assumed the quality to be 1% at the OAF location to calculate the initial film thickness at the beginning of the annular flow. Levy [3] suggests the void fraction of 80% at OAF location and Katto [4] reduced it by 60%. It is obvious that the void fraction or quality at OAF varies according to the thermal-hydraulic conditions through the flow pattern map. Fig. 1 indicates that reduction of CHF is dependent on the behavior of liquid film in annular flow under rolling motion in the low mass flux and intermediate pressure regions. However, transition region cannot be defined clearly. Low mass flux region is considered annular and the rest is defined as bubbly or bubbly-slug transition region based on general CHF mechanism. Hong's prediction method was chosen for use in this study because of its ability to better predict the void fraction as determination of annular flow regime.

2.2 Determination of Non-dimensional Numbers

The flow regime at the test section must first be classified that is representative for the flow conditions experienced. In order to correlate the present CHF data, it is important to identify an appropriate flow regime. If flow regime can be known at stationary condition, CHF mechanism under rolling condition can be predicted by suggested mechanism base on literature reviews. Void fraction at OAF can be a criterion to divide the flow regime. According to the void fraction at OAF, flow regime can be divided into two regions. LFD region is that void fraction greater than 0.6, others region can be defined as DNB region as shown in Fig.1.

Correlations for CHF ratio in current experimental conditions were developed as follows. Considering the difference for LFD-type CHF and DNB-type CHF based on void fraction at OAF as described previous section. In order to apply the above CHF mechanisms under rolling motion, non-dimensional numbers are chosen at each flow regime as follows:

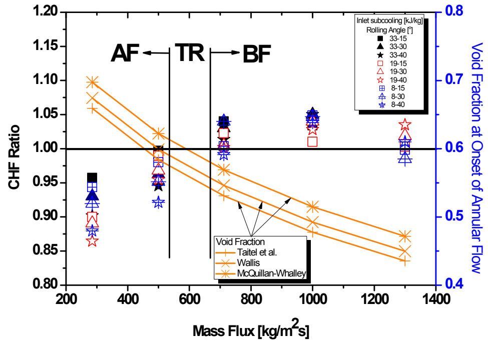

Fig 1. Flow regimes as void fraction at OAF (τ : 6 seconds)

$$C.R_{LFD} = f\left(\frac{\rho_l}{\rho_g}, Fr_R, We, \frac{\tau}{T_{tr}}, \frac{\Delta h_i}{h_{lg}}\right) \quad (1)$$

$$C.R_{DNB} = f\left(\frac{\rho_l}{\rho_g}, \frac{\mathrm{Re}}{\mathrm{Re}_R}, \frac{\Delta h_i}{h_{lg}}\right) \quad (2)$$

2.2 Determination of Functional Form

The TR between annular and bubbly flow regions has to satisfy the continuity viewed from physical. For this reason, interaction of the two regions is taken into account by means of power interpolation. To do this, function form of power is logic function form as void fraction at OAF. Also, functional form of power is logic function which is depending on void fraction at OAF. The CHF ratios of DNB and LFD regions can be predicted by keeping constant values (0 or 1) using logic function. In transition region, void fractions at OAF corresponding to 0.57 through 0.64 and slope of function have to determine to reduce the error of prediction. The CHF ratios are calculated at each regime as shown in Fig. 2. The final forms of the CHF ratio correlation is

$$C.R = \left(C.R_{LFD}\right)^{\alpha^*}\left(C.R_{DNB}\right)^{\left(1-\alpha^*\right)} \quad (3)$$

$$\alpha^* = \frac{1}{1+e^{-200(\alpha-0.52)}} \quad (4)$$

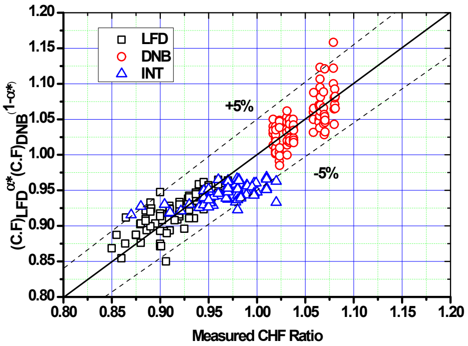

Fig 2. Evaluation of CHF Ratio correlation with all data

3. Conclusions

Experimentally measured CHF results from the previous study were not well-predicted by existing CHF correlations developed for wide range of pressure under rolling motion in vertical tube. Specifically, existing correlations do not account for the dynamic motion parameter, such as tangential and centrifugal force. This study reviewed some existing correlation and experimental studies related to reduction and enhancement of CHF and heat transfer and flow behavior under heaving and rolling motion, and developed a CHF ratio correlation for upward flow vertical tube under rolling motion. Based upon dimensionless groups, equations and interpolation factor, an empirical CHF correlation has been developed which is consistent with experimental data for uniformly heated tubes internally cooled by R-134a under rolling motion. Flow regime was determined through the prediction method for annular flow. Non-dimensional number and function were decided by CHF mechanism of each region. Interaction of LFD and DNB regions is taken into account by means of power interpolation which is reflected void fraction at OAF. The suggested correlation predicted the CHF Ratio with reasonable accuracy, showing an average error of -0.59 and 2.51% for RMS.

Rolling motion can affect bubble motion and liquid film behavior complexly by combination of tangential and centrifugal forces and mass flow than heaving motion. Through a search of literature and a comparison of previous CHF ratio results, this work can contribute to the study of boiling heat transfer and CHF for the purpose of enhancement or reduction the CHF of dynamic motion system, such as marine reactor.

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