CHAPTER 4

CORRELATION DEVELOPMENT

4.1 INTRODUCTION

In order to analyze and predict the heat transfer coefficients for the flow boiling process in tubes empirical correlations are required. Generally, the heat transfer coefficient can be easily predicted with the available correlations in the published literature. Most of the well known correlations for refrigerants, although based on analytical reasoning and rigorous experimentation, do not predict consistently within an acceptable range. These correlations cannot fully replicate the complex relationship between the variables, affecting the contribution of nucleate boiling and convective boiling on the heat transfer coefficient. Most of the correlations work well for particular test fluids, and for a range of test conditions. In most of the cases, the correlations are primarily evolved for the annular flow pattern, with high heat and mass flux conditions. However, such predictions deviate even for the annular flow condition, when used for other refrigerants. In the present work, using the experimental data base, correlations are developed for the R404A refrigerant pertaining to stratified and stratified-wavy flow patterns, occurring in low heat and mass flux conditions.

A large number of correlations have been proposed for flow boiling heat transfer. Several researchers have developed correlations that, over time, have been proven to be relatively accurate. The most recent correlations are indeed based on experimental data obtained recently, with highly sophisticated test facilities. In the present work the direct empirical method (enhancement model) has been leveraged to evolve a flow boiling correlation
for the heat transfer coefficient of R404A refrigerant. The heat transfer coefficient data base consists of 450 data points, from experiments conducted in a 7.49 mm diameter tube. Darabi et al (1995) and Webb and Gupte (1992) have done a detailed review on classification and validation of the correlations for the prediction of the flow boiling heat transfer coefficient in smooth tubes. The selection of correlation and the modification of correlations by enhancement method are discussed in this chapter.

4.2 SELECTION OF CORRELATIONS

All the existing correlations for the prediction of the heat transfer coefficient are functions of the numerous variables that influence the heat transfer process in a two-phase flow. A large number of experiments have been conducted and several correlations have been proposed by many investigators for different working fluids.

Generally, the correlations can be grouped based on three models. They are superposition, asymptotic, and enhancement models. Chen (1966) was the first to develop an additive correlation (superposition model), where both the nucleate and convective boiling heat transfer mechanisms must be taken into account, to predict the heat transfer coefficient in the flow boiling heat transfer. Forced flow creates a sharper temperature gradient at the wall, relative to that in pool boiling, which has an adverse effect on bubble nucleation. Thus, nucleation is partially suppressed which was accounted by introducing a nucleation suppression factor S, and multiplied with a standard pool boiling correlation. Chen model worked successfully for the fluid Prandtl number close to unity, and later researchers evolved modified versions to suit the fluid of different Prandtl numbers also.

Many times the direct addition of nucleate and convective components over predicts the heat transfer coefficient, with a large deviation.
Thus, an exponent ‘n’ is included to bias the individual components of the heat transfer coefficient, which resulted in an asymptotic model. The accuracy of these models depends on the pool boiling model. Even though a pool boiling correlation such as Cooper (1984) is a well-tested correlation, there is always an uncertainty in leveraging it for nucleate boiling associated with flow boiling.

On the other hand, the enhancement model or direct method correlations such as Lavin and Young (1965), Shah (1982) and Uchida-Yamaguichi (1965) are devoid of pool boiling correlations and are simple to use. In these correlations, the nucleate and convective components are correlated only with respect to dimensionless numbers. In the present work, enhancement model is used to correlate the experimental results of R404A.

### 4.3 ENHANCEMENT MODEL

Enhancement models such as Lavin-Young (1965), Uchida-Yamaguichi (1965) and Shah (1982) are chosen for the analysis. The original form of Lavin and Young (1965) is shown in Equation (4.1). For the R12/R13 mixture it fits well and around 68% of the data fall within the ±30% deviation, with suitable change in the constants and exponents, as reported in Singal et al (1984). The intercepts and exponents are modified to fit the experimental data of R404A. The multiple regression technique is used to find the exponents and intercepts in these modified forms of correlations. Using the experimental data of R404A, correlations are evolved for the 7.49 mm diameter tube.

\[
\frac{h_k}{h_L} = a Bo^b \left( \frac{1-x}{1+x} \right)^c (1-x)^d
\]  

(4.1)
The Shah correlation given in Equation (4.2) was based on the experimental data of water, cyclohexane, R11, R12, R22 and R113. The nucleate boiling component was represented by the Boiling Number while the convective number was used for the forced convection component and Froude number. In the present work this equation also has been modified to fit the data with R404A.

\[
\frac{h_k}{h_L} = a \text{Bo}^b \text{Co}^c \tag{4.2}
\]

Similarly the Uchida and Yamaguchi correlation shown in Equation (4.3), is also considered for modification. The value of the exponents and intercepts after multiple regressions for the above correlations is shown in Table 5.1.

\[
\frac{h_k}{h_L} = a \text{Bo}^b \left(\frac{1}{X''}\right)^c \tag{4.3}
\]

The value of the exponents and intercepts after multiple regressions for the above correlations is shown in Table 4.1.

<table>
<thead>
<tr>
<th>Table 4.1</th>
<th>Modified coefficients and exponents for correlations based on the direct method</th>
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<tbody>
<tr>
<td>Modified Correlation</td>
<td>a</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Lavin and Young (1965)</td>
<td>921.01</td>
</tr>
<tr>
<td>Shah correlation (1982)</td>
<td>215.94</td>
</tr>
<tr>
<td>Uchida and Yamaguchi (1966)</td>
<td>771.50</td>
</tr>
</tbody>
</table>
Thus, the experimental data extracted from the test facility are used for correlation development. Enhancement model is used to evolve the correlations. Detailed comparisons of the predicted local heat transfer coefficient with experimental results are discussed in the next chapter.