Chapter 3

An Experimental Study on Nucleate Boiling With Copper-Forane Surface-Fluid Combination.

3.1 Scope

The present experimental investigation deals with nucleate boiling studies on horizontal cylindrical heating elements made out of copper in the medium of Forane around atmospheric conditions. This study is necessitated to validate the results of chapter 2. The data could be successfully correlated with the system of criteria employed in the previous chapter. Inclusion of the data from the present experimental study on Forane and that of other investigators yielded a comprehensive correlation within reasonable limits of accuracy.

3.2 Introduction:

Studies on nucleate boiling are found to be quite extensive in the heat transfer literature. Rohsenow and his co-investigators (1952, 1969) in their pioneering studies proposed correlation in which heating surface-liquid combination is considered as dominant characterizing parameter. The constant $C_d$ in correlation is found to be different for each surface-liquid combination. Such values for $C_d$ are already are tabulated and can be found in heat transfer handbooks.
Pioro et al. \cite{Pioro04a, Pioro04b} concluded that Rohsenow's correlation is the best amongst the existing correlations. However, the constant $C_{\text{St}}$ is to be amended depending on the roughness factor and the liquid-surface combination. A modification of Rohsenow's correlation as presented by Pioro et al. \cite{Pioro04a, Pioro04b} is as follows:

$$\frac{q}{\mu_k h_s} \left[ \frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} = \left( \frac{1}{C_{\text{St}}} \right)^{1/r} Pr^{-s/r} \left\{ \frac{C_{\text{Pl}} [T_w - T_s]}{h_s} \right\}^{1/r} \quad (3.1)$$

The values of $\gamma^*$ and $m$ in the Eq. (3.2) are to be chosen based on the surface roughness factor and liquid medium-surface combination. He concluded that amongst the available correlations Rohsenow's correlation is the best.

In Russian literature there are many correlations and often several of these correlations referred in the estimation of nucleate boiling heat transfer coefficient. Among those correlations reference is made specifically to the typical investigations of Labuntsov \cite{Labuntsov72} (1972) and Kruzhilin \cite{Kruzhilin49} (1949) since a comparison of the present data is accomplished with correlations of these investigators.

Labuntsov's correlation \cite{Labuntsov72} (1972) is as follows:

$$\frac{h}{k_1} \left( \frac{\sigma}{\rho_l - \rho_v} \right)^{0.5} = C_{\text{St}}^* \left( \frac{q}{h_s \rho_v^2 \gamma^* \left[ \sigma g (\rho_l - \rho_v) \right]^{0.25}} \right)^{1/3} Pr^m \quad (3.2)$$
\[ \text{Nu} = \frac{h_{1'}}{k_i} = \frac{h}{g(T_i - T_s)} \left( \frac{\rho}{(\rho_i - \rho_s)} \right)^{0.7} \left( \frac{T_s + 273.15}{\text{Pr}^{0.45}} \right) \]

In a recent paper Sarma et al. \cite{13} (2007) employed the available data of Borishansky et al. \cite{12} (1966) for a wide range of system conditions and the correlation developed by the authors employed the following governing criteria in the regression analysis

\[ \frac{q}{\mu h_q} = F \left[ \frac{P}{P_{cr}}, \frac{6}{D}, \frac{1}{D}, \frac{\sigma}{(\rho_i - \rho_s)g} \right] \]

where \( I' = \frac{\sigma}{(\rho_i - \rho_s)g} \) and \( \delta_i = \left( \frac{(\Delta T) k_i}{q} \right) \)

Applying regression to the data of Borishansky et al. \cite{12} (1966) they proposed the following correlation with an accuracy of 16 % A.D and 20 % 3.D for cylindrical elements of diameters ranging from 5 to 7 mm. It is
inferred that the correlation is found to be dependant on a new dimensionless number known as Kakac Number, \( K_a \)

\[
\frac{q}{\mu h_{nf}} = \sqrt{\frac{\sigma}{\left(\rho_l - \rho_v\right) g}} = 3.8 \times 10^{-6} \left( \frac{D}{\delta_1} \right)^{1.33} \left( \frac{P}{P_c} \right)^{0.72} \left( \frac{PD}{\mu h_{nf}^{1/2}} \right)^{0.55} \left( \frac{\sigma}{\left(\rho_l - \rho_v\right) g D^2} \right)^{1.65}
\]

(3.6)

The present study is organized firstly to validate the system of criteria employed in previous chapter and secondly to check whether the correlations generally cited in the nucleate boiling literature can be employed in the estimation of the heat transfer coefficients for copper-Forane (R-141b) surface-liquid combination. Besides, it is found from a review of literature that nucleate boiling studies on Forane-copper combination are not available and hence the present study aims to present the experimental data related to surface-liquid combination having practical importance in chemical process industry.

3.3 Description of Experimental Setup:

The experimental investigations are conducted on a pre-fabricated nucleate boiling heat transfer test rig manufactured by M/S P.A.Hilton, U.K. A schematic diagram and photographs of the boiling heat transfer unit are shown in Figs. 3.1 through 3.4. A brief description of the same is provided with ranges and limitations in the experimental investigation.

The heat transfer unit consists of a thick walled glass chamber of 80 mm bore and 300 mm long as shown in Fig. 3.1 And Plate 3.1. The
chamber houses the heating element with a condenser coil placed above the free surface of the liquid bulk. The heating element is a 600 Watt cartridge heater swaged into the copper test surface to give a uniform heat flux.

Fig. 3.2 Schematic diagram of the Nucleate boiling test rig

The test section is a copper tube of diameter 12.7 mm and length 42 mm with an effective surface area of 0.018 m². The orientation of test section is horizontal. The test section is submerged in a pool of Forane (R-141b) liquid as shown in Plate. 3.2. Over the surface of the test section, 6 thermo-couples are preened at regular intervals and the average of these values can be read with the help of a digital temperature indicator.
The maximum permissible surface temperature is 220 °C and the test rig is automatically cut-off by a controller incorporated in the temperature indicator when the temperature exceeds the preset permissible value. A phase angle controller to give infinitely variable heat input to the test section accomplishes the heating. The heat transfer rate can be manually noted on a digital wattmeter and the heat flux is calculated using the relation $q = \frac{Q}{\pi DL}$ where $Q$ is the wattmeter reading and $D$ external diameter of the tube.

Specifications of the Experimental setup:

<table>
<thead>
<tr>
<th>Fluid</th>
<th>Forane R 141 b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material of the test surface</td>
<td>Copper</td>
</tr>
<tr>
<td>Critical pressure of fluid</td>
<td>43 bar</td>
</tr>
<tr>
<td>Diameter of the test section</td>
<td>12.7 mm</td>
</tr>
<tr>
<td>Length of the test section</td>
<td>42 mm</td>
</tr>
<tr>
<td>Effective surface area</td>
<td>0.018 m²</td>
</tr>
<tr>
<td>Maximum permissible temperature</td>
<td>220 °C</td>
</tr>
<tr>
<td>Pressure ranges</td>
<td>- 150 to 350 Kpa (gauge)</td>
</tr>
<tr>
<td>Heater capacity</td>
<td>600 W</td>
</tr>
</tbody>
</table>

The condenser situated in the free vapor space is made of 9 coils of nickel plated copper tube with a total surface area of 0.032 m². The condenser coil condenses the vapor produced by the test surface and the condensate returns to the bottom of the chamber. The pressure in the chamber is controlled by varying the cooling water flow rate to the condenser. The ranges of pressure in the chamber at which the
The experiment can be run at 150 to 350 Kpa (gauge). A glass thermometer is mounted in the bulk of the liquid to measure the liquid bulk temperature $T_B$, which happens to be the saturation temperature corresponding to the system pressure. The heat transfer coefficient of the surface is calculated according to the equation $h = \frac{q}{(T_w - T_B)}$. The unit is interfaced to a computer and parameters like heat flux $q$, temperature difference $\Delta T(=T_w-T_B)$, wall temperature $T_w$, gauge pressure $P_g$ and heat transfer coefficient $h$ are automatically registered for various heat inputs. The instrumentation used to measure temperature, power, etc., are all of class-I type and the error estimate cannot be more than $\pm 3\%$.

The test runs are taken and the data are tabulated in the Table 3.1 as entries. Different regimes of boiling observed in a test run are photographed using a high-speed digital camera and the same are shown in Photos. 3.3 Through 3.5. These figures show isolated bubble regime, slug regime, and slugs and column regime of nucleate boiling respectively.

Summary of Experimental results:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure Range</td>
<td>1.3 to 2.2 bar</td>
</tr>
<tr>
<td>Wall Temperature</td>
<td>50 to 75 °C</td>
</tr>
<tr>
<td>Wall heat flux</td>
<td>27 to 188 KW/m²</td>
</tr>
<tr>
<td>Heat transfer coefficient</td>
<td>3.2 to 15.8 KW/m² °C</td>
</tr>
<tr>
<td>Bulk temperature</td>
<td>40 to 56 °C</td>
</tr>
</tbody>
</table>
3.4 Correlation of the data

The data from the Table 1 is organized as per the system of criteria (See Eq. (3.5)) proposed in earlier chapter by and a generalized plot is drawn and it can be seen from Fig. 3.2 that all data points could be successfully represented by the correlation as follows:

$$\frac{q_w}{\mu_1 h_g} \sqrt{\frac{\sigma}{(\rho_1 - \rho_2)\delta_1}} = 9.98 \times 10^4 \left( \frac{D}{\delta_1} \right)^{0.2} \left( \frac{P}{P_r} \right)^{1.42} \left( \frac{PD}{(\mu_1 h_g)^{1/2}} \right)^{1.8} \left( \frac{\sigma}{(\rho_1 - \rho_2)\delta_1 \rho D^2} \right)^{0.08} \quad (3.7)$$

The system of criteria as suggested in chapter 2 proved to be very effective and all experimental data without exception agreed well with an average deviation of 4% and standard deviation of 6%. It can be inferred indirectly from Fig. 3.2, since all points lie with a marginal scatter, the error involved in the measurement of various parameters are minimal. In an attempt to further extend the validity of the present system of criteria, the data of Borishansky et al.\textsuperscript{12} (1966) for $5 < D < 7$ mm and for pressure varying from atmosphere to near critical values are shown plotted in Fig. 3.3. The total data comprising of 575 points could be successfully correlated by the following equation with a standard deviation of 25 % and Average deviation of 20 %. It can be seen on a relative comparison between Eqs. (3.7) and (3.8) though the criteria employed in the regression are one and the same; the indices for various $\pi$ parameters are varying.

$$\frac{q}{\mu_1 h_g} \sqrt{\frac{\sigma}{(\rho_1 - \rho_2)\delta_1}} = 5.07 \times 10^7 \left( \frac{D}{\delta_1} \right)^{1.27} \left( \frac{P}{P_r} \right)^{0.98} \left( \frac{PD}{(\mu_1 h_g)^{1/2}} \right)^{0.63} \left( \frac{\sigma}{(\rho_1 - \rho_2)\rho D^2} \right)^{1.25} \quad (3.8)$$
3.5 Comparison of data with correlations of other investigators:

The present data is shown plotted with the cited correlations on nucleate boiling. None of the correlations could satisfactorily agree with present data taken Forane-copper combination.

Rohsenow's correlation is shown plotted together with the data points in Fig. 3.4. To obtain better agreement between the correlation and data, the constants are to be changed as $C_{st}=0.0026$, $r=3$ and $s=2$

The modified form of Rohsenow's correlation as postulated by Pioro et al. $^{100, 101}$ (2004) is shown plotted in Fig. 3.5. It can be seen that the Pioro et al. correlation gave better agreement with $C_{st}^*=9.283\times10^3$ and $m=3.14$.

Similarly, Labuntsov's correlation $^{79}$ (1972) revealed substantial disagreement with the present data as shown in Fig. 3.6. A corrected value of factor of multiplication from the original value of 0.075 to 0.0215 may yield close agreement with the data.

The correlation of Kruzhilin $^{74, 75}$ (1949) as postulated by their original analysis deviates considerably from the present data. However, in Fig. 3.7 it is demonstrated that by changing the factor of multiplication in the correlation of Kruzhilin, the data could be regressed satisfactorily.
3.6 Remarks

1. The dimensionless criteria of Sarma et al. (2007) as given in Eq. (3.5) could comprehensively satisfy the data for wide range of parameters as follows. The heat transfer coefficient can be predicted from Eq. (3.8) for the experimental ranges:

   Diameter: 5 - 12.7 mm

   Fluids - water, ethyl alcohol and Forane

   Surfaces - Stainless steel and copper

   Ranges of pressure- water (1<P<200 bar), ethyl alcohol (1<P<60 bar) and Forane (1<P<2.5 bar)

2. The Kakac Number, $Ka \left[ \frac{PD}{(\mu, h_x^{1/2})} \right]$ is found to be a useful tool in effectively correlating the data for wide range of system pressures (See Fig. 3.3). Besides, the system of criteria employed in the present study proved to be successful in correlating the nucleate boiling heat transfer data on cylindrical heating elements.

3. The present experimental data of nucleate boiling with copper-Forane combination could be successfully correlated by the correlation of Pioro et al. which happens to be a modification of Rohsenow's correlation by employing the values of $C'_{\omega}=9.286 \times 10^3$ and $m=-3.12$. 