ABSTRACT

Vertical thermosiphon reboilers with boiling liquids in tubes is of common occurrence in petroleum and chemical process industry. It also finds varied application in many other allied industry due to the high rates of heat transfer and energy efficient operation.

The hydrodynamics and heat transfer in thermosiphon reboiler interact with each other making the process very complex. The prediction of rates of heat transfer and thermally induced flow is the primary requirement for the design of these units. A number of studies have been reported in literature wherein the rates of heat transfer have been measured under the conditions of uniform wall temperature/heat flux with single component liquids at their saturation temperature. Some workers have also investigated the effect of inlet liquid subcooling and liquid submergence on heat transfer, circulation rate and boiling incipience with uniform heat flux. The data on boiling of liquid mixtures seems to be scarce and most of those available give insufficient accurate information about the boiling incipience, local heat transfer coefficient and circulation rate under the influence of governing parameters. However, no systematic study seems to have been conducted to obtain the exclusive effect of important parameters on boiling incipience, heat transfer coefficient and circulation rates. Therefore, the present experimental study, was undertaken to investigate the effect of heat flux and liquid submergence on heat transfer to boiling single component liquids as well as binary liquid mixtures in a single vertical tube thermosiphon reboiler with an objective of understanding the process and developing generalized correlations for the design.

The experimental unit was made of two vertical stainless steel tubes connected to a vapor-liquid separator and condenser vessels forming a thermosiphon loop. The test section was an electrically heated S.S. tube having 25.56 mm I.D., 28.85 mm O.D.
and 1900 mm length. The stabilized power was supplied through a low voltage high current transformer. The energy input to the test section was measured by calibrated precision type voltameter and ammeter. Twenty-one copper-constantan thermocouples were spot welded on the outer surface of the tube in order to monitor the heat transfer surface temperatures. The inlet and exit liquid temperatures were measured by means of copper-constantan thermocouple probes separately. The provisions were also made to measure the flow rate and temperatures in and around the condenser and other strategic locations in the reboiler tube to ensure a reliable computation of circulation rates through the heat balance. In order to know the liquid mixture compositions of binary systems, sampling devices were provided at suitable locations. The samples were analysed by using a refractive index-composition chart.

The experimental data were generated using distilled water, methanol, benzene, toluene and ethylene glycol at atmospheric pressure covering a wide range of thermo-physical properties and boiling points. The systems used for binary mixtures were: methanol-water, benzene-toluene and water-ethylene glycol. The mixture concentrations and range of other parameters covered during experimentation are given as below:

<table>
<thead>
<tr>
<th>System</th>
<th>Heat flux $q \times 10^{-4}$ W/m²</th>
<th>Submergence $S$, %</th>
<th>$\Delta T_{sub}$ °C</th>
<th>Concentration wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.57-4.3</td>
<td>30,50,75,100</td>
<td>0.5-4.6</td>
<td>--</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.41-2.1</td>
<td>30,50,75,100</td>
<td>1.0-3.7</td>
<td>--</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.41-2.9</td>
<td>30,50,75,100</td>
<td>0.7-3.6</td>
<td>--</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.41-3.2</td>
<td>30,50,75,100</td>
<td>1.9-8.7</td>
<td>--</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>1.6-3.0</td>
<td>30,50,75,100</td>
<td>5.8-11.6</td>
<td>--</td>
</tr>
<tr>
<td>Methanol-water</td>
<td>0.57-2.9</td>
<td>30,50,75,100</td>
<td>0.5-4.6</td>
<td>5,10,18,26,30,38,58</td>
</tr>
<tr>
<td>Benzene-toluene</td>
<td>0.7-2.5</td>
<td>30,50,75,100</td>
<td>1.4-8.2</td>
<td>18,40,55,66,76</td>
</tr>
<tr>
<td>Water-ethylene glycol</td>
<td>1.6-3.3</td>
<td>30,50,75,100</td>
<td>0.7-5.1</td>
<td>5,15,25,40,57</td>
</tr>
</tbody>
</table>
The experimentally obtained wall and liquid temperature distributions along the tube length at a particular value of heat flux were utilized to compute the variation of heat transfer coefficient. These distributions clearly revealed the existence of non-boiling/subcooled boiling and saturated boiling regions with a point of incipience in between. The values of heat transfer coefficient remained to be low and changed very slowly in the non-boiling/subcooled boiling region while it increased steeply around the onset point of boiling and attains a high value in the boiling region. The relative lengths of non-boiling/subcooled boiling and boiling sections of the tube were found to be strongly influenced by heat flux and liquid submergence for all the test liquids.

The minimum degree of wall superheat required for the onset of fully developed boiling of liquids, as experimentally measured, were related to the physical properties of test liquids through the theoretically derived equation of Yin and Abdelmessih

\[(T_w-T_s)^2 = (a-bq)^2 \sigma T_s q / k_u \lambda \sqrt{\gamma}\]

The values of constants \(a\) and \(b\) were determined for various systems separately. All the data of single component liquids can also be represented by a single equation as:

\[
\sigma^* = 17.865 - 0.547 \times 10^{-4} q
\]

Similarly all the data of binary liquid mixtures can be represented by an unified equation as given below:

\[
\sigma^* = 96.04 - 0.320 \times 10^{-2} q
\]

Majority of data points for both the cases are found to be well
correlated with a maximum error of ±30 percent.

The length of heated tube required for the onset of fully
developed saturated boiling was observed to depend on wall heat
flux, inlet liquid subcooling and liquid submergence. An
empirical correlation for predicting this length has been
developed in the following form:

\[
\frac{Z_{OB}}{L} (\times 100) = C_1 (Pe_B)^{n_1} (K_{sub})^{n_2} (S)^{n_3} (---)^{n_4}
\]

The values of \(C_1, n_1, n_2, n_3\) and \(n_4\) have been determined for
various systems separately and also all the data put together
resulting in an unified equation as given below with a maximum
error of ±40 percent.

\[
\frac{Z_{OB}}{L} (\times 100) = 0.003 (Pe_B)^{0.2739} (K_{sub})^{0.39} (S)^{0.4522} (---)^{0.8656}
\]

The rate of fluid circulation through the reboiler tube was
observed to depend upon wall heat flux, liquid submergence, vapor
fraction and inlet liquid subcooling. A functional relationship
between the various parameters in their dimensionless forms has
been obtained as follows:

\[
Re = C_2 (Pe_B)^{m_1} (S)^{m_2} (X_{tt})^{m_3} (K_{sub})^{m_4}
\]

An unified correlation using the experimental data for all
the systems together has been developed.

\[
Re = 2.7494 (Pe_B)^{0.9605} (S)^{0.7235} (X_{tt})^{0.6922} (K_{sub})^{-0.3089}
\]

Almost all the data points of present study and those of similar
investigations carried out earlier have been well represented by
the above equation with a maximum error of ±20 percent.

The average value of heat transfer coefficient in the fully
developed boiling region in the tube has been found to depend
strongly on \( h_f \) in the same way as it does during nucleate pool boiling of single component liquids. The average boiling heat transfer coefficient may be correlated by a simple dimensional relationship as given below:

\[
\bar{h}_B = \Phi q^{0.713}
\]

The values of \( \Phi \) are as under:

<table>
<thead>
<tr>
<th>System</th>
<th>( \Phi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>2.800</td>
</tr>
<tr>
<td>Methanol</td>
<td>2.486</td>
</tr>
<tr>
<td>Benzene</td>
<td>1.796</td>
</tr>
<tr>
<td>Toluene</td>
<td>1.460</td>
</tr>
<tr>
<td>Ethylene glycol</td>
<td>2.088</td>
</tr>
</tbody>
</table>

Almost all the data points are found to lie within a maximum error of \( \pm 30 \) percent.

The heat transfer coefficient, \( \bar{h} \), averaged over the entire tube length also depends upon heat flux in the similar way as observed for \( \bar{h}_B \). However, the values of \( \bar{h} \) are relatively lower than \( \bar{h}_B \). The effect of liquid submergence seems to be nominal on \( \bar{h}_B \) while the values of \( \bar{h} \) get enhanced as the submergence is lowered.

The heat transfer coefficient in convection dominated single phase non-boiling/subcooled boiling section averaged over the tube length (\( Z_{OB} \)) was best correlated, with a maximum deviation of \( \pm 30 \) percent, by the following equation:

\[
Nu_C = 0.140 (Gr)^{0.268} (Pr)^{0.248} (Re)^{0.254} (Z_{OB/d})^{-0.157}
\]

A generalized correlation for boiling heat transfer coefficient has been developed in terms of suitable dimensionless groups.

\[
Nu_B = 2.8025 (Pe_L)^{0.6433} (Pr_B)^{0.685} (X_{tt})^{0.0701} \left( \frac{\sigma_{L}}{\rho_{L} c_{p,L}} \right)^{0.021} \left( \frac{\sigma_{H_2O}}{\rho_{H_2O} c_{p,H_2O}} \right)^{0.021}
\]
Almost all the experimental data of present study and those of earlier similar investigations were well represented by the above correlation with a maximum deviation of ±30 percent.

The length of the heated tube for binary liquid mixtures was correlated with a maximum deviation of ±40 by the following dimensionless equation.

\[
\frac{Z_{OB}}{L} = 0.8203 (Pe_B)^{0.6496} (K_{sub})^{0.0471} (S)^{0.043}
\]

\[

\frac{\dot{V}}{V} = 0.0393 \left[1 + \frac{(y - x)}{x}\right]^{-0.2886}
\]

The rate of liquid circulation for binaries is correlated by the same equation as developed for single component liquids with the changed constant and exponents. An unified equation correlates the data of all the systems with a maximum error of ±30 percent.

\[
Re = 1.918 (Pe_B)^{0.979} (S)^{0.637} (X_{tt})^{0.551} (K_{sub})^{-0.0884}
\]

The values of heat transfer coefficient during boiling of binary mixtures are generally lower than the weighted average of the pure component values. This reduction may be due to the expected retardation of bubble growth rate by the diffusion of more volatile component from the vapor bubble to the saturated liquid.

The heat transfer coefficient for the binary mixtures in the convection dominated section \(Z_{OB}\) was correlated with a maximum deviation of ±30 percent by the following dimensionless equation:

\[
Nu_{CM} = 0.6062 \left(Gr\right)^{0.2017} \left(Pr\right)^{0.9587} \left(Re\right)^{0.063} \left(Z_{OB}/d\right)^{0.013}
\]

The correlation developed for the boiling of single component liquids was modified to include the experimental data of binary liquid mixtures also and the following equation resulted:
\[ \text{Nu}_{BM} = 7.7297 \nu_{\infty}^{-0.433} (i_{13})^{0.1772} (X_{tt})^{0.15577} \left( \frac{\sigma_{H_2O}}{\sigma_{M}} \right)^{0.0074} (K_c)^{0.1225} \]

Almost all the data points of single component liquids and their binaries were well represented by the above equation with a maximum error of ±30 percent.