CHAPTER 6

Conclusions and Recommendations

6.1 Conclusions

The following important conclusions are drawn from the present study:

1. There exist two distinct regions over the length of a reboiler tube with different mechanisms of heat transfer up to a point where saturated boiling sets in, the heat transfer takes place by single phase convection/subcooled boiling. Saturated boiling of liquid with formation of vapor phase occupies the remaining portion of the tube.

2. The onset of fully developed boiling requires a minimum degree of wall superheat for a given liquid and heat transfer surface. Based on the analytical study of earlier workers, the following expression for wall superheat has been developed,

\[(T_w - T_s)^2 = (a-bq)^2 2\sigma T_s q / k_L \lambda_p \rho_v\]

The above equation can predict the wall superheat required for onset of boiling at a given heat flux using the physical properties of the liquids and constants \(a\) and \(b\) determined (Table 5.1).

3. The length of heated tube required for the onset of saturated boiling depends upon wall heat flux, submergence and inlet liquid subcooling for a given liquid. An empirical correlation in terms of dimensionless groups has been developed in the following form:
The values of \( C_1 \), \( n_1 \), \( n_2 \), \( n_3 \) and \( n_4 \) for single component liquids studied have been given in Table 5.2. The equation represents the experimental data with a maximum error of \( \pm 30 \) percent. The data may also be correlated by a unified equation as given below for all the liquids with a maximum error of \( \pm 40 \) percent.

\[
\frac{Z_{OB}}{100} = 4.003 (Pe_B)^{0.2739} (K_{sub})^{0.39} (S)^{0.4522} (---)^{0.8656} \frac{V_L}{V_V}
\]

4. The rate of fluid circulation through the reboiler tube has been found 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:

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

The values of constant \( C_2 \) and indices \( m_1 \), \( m_2 \), \( m_3 \) and \( m_4 \) for all the five test liquids have been evaluated and given in Table 5.3.

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

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

Almost all the data points of present study and those of similar investigations carried out earlier have been well represented by the equation with a maximum error of \( \pm 20 \) percent.
5. The heat transfer coefficient and its variation along the reboiler tube gets strongly influenced by heat flux and liquid submergence for all the systems but under identical conditions of heat flux and submergence they are different for various systems.

6. The average values of heat transfer coefficient in the fully developed boiling region in the tube has been found to depend strongly on heat flux almost in the same way as it does during nucleate pool boiling of single component liquids. The $h_B$ may be expressed as a function of $q$ in the following power law relationship.

$$h_B = \psi q^r$$

The values of $\psi$ and $r$ are listed in Table 5.4. The exponent $r$ is about 0.7 for all the test liquids while $\psi$ varies. A simplified correlation based on an average value of exponent, thus results:

$$h_B = \bar{\psi} q^{0.713}$$

Majority of data points are found to lie within a maximum deviation of ±30 present.

7. The heat transfer coefficient, $h$, averaged over the entire tube length also depends upon heat flux in the similar way. However, the values of $h$ are relatively lower than $h_B$.

8. The effect of liquid submergence seems to be nominal on $h_B$ while the values of $h$ get enhanced as the submergence is lowered.

9. The heat transfer coefficient in convection dominated single phase non-boiling/subcooled boiling section average over the tube length ($h_{Bo}$) was best correlated, with a maximum deviation of ±30 percent, by the following equation.
10. A correlation for boiling heat transfer coefficient has been developed in terms of relevant dimensionless groups as given below:

\[ \text{Nu}_B = 2.8029 (\text{Pe}_B)^{0.6433} (\text{Pr}_B)^{0.685} (X_{tt})^{0.0701} \left( \frac{\sigma_L}{\sigma_{\text{H}_2\text{O}}} \right)^{0.021} \]

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.

11. The variation of heat transfer coefficient along the heated tube length for binary liquid mixtures is essentially similar to that of pure liquids at various heat fluxes and liquid submergences. However, the relative magnitudes, positions of boiling incipience and nature of variations are affected by the mixture composition.

12. 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.

13. The minimum wall superheat required for the onset of boiling for binaries is correlated by the same equation as developed for single component liquids with the changed constants using the mixture properties (Table 5.8).

14. The length of the heated tube for binary liquid mixtures was correlated with a maximum deviation of ± 40 by the following dimensionless equation.
The rate of liquid circulation for binary mixtures is correlated by the same equation as developed for single component liquids with the changed constant and exponents (Table 5.9). An unified equation correlates the data of all the systems with a maximum error of ±30 percent.

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

16. The heat transfer coefficient for binary liquid mixtures in the convection dominated section (ZO_B) was correlated with a maximum deviation of ±30 percent by the following dimensionless equation.

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

17. 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:

\[
\frac{\sigma_M}{\sigma_{H_2O}} = 7.7297(Pe_B)^{0.4333} \ (Pr_B)^{0.1772} \ (x_{tt})^{0.15577} \ (---)^{0.0074} \ (K)^{0.1225}
\]

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.

6.2 Recommendations

1. The theoretical analysis of incipient boiling already
available in literature may be modified to fit the experimental data accurately for single component liquids as well as binary mixtures. The generalized correlations for computing wall superheats and heated lengths for onset of boiling may be developed with the help of above analysis and experimental measurements of boiling incipience.

2. The experimental study to measure the circulation rates and pressure drop may be conducted with single component liquids and binary mixtures in order to develop suitable design equations.

3. The experimental studies on single component liquid and binary liquid mixtures with widely varying physical properties may be conducted under vacuum and other important operating conditions. Further, efforts may be made to improve the proposed unified correlation for mixtures as well as for single component liquids.

4. An effort may be made to develop mathematical model to study heat transfer and circulation rate in thermosiphon reboiler and compare the results with the experimental findings.

5. All the information collected so far may be utilized to develop suitable design procedures for the thermosiphon reboilers of industrial importance.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>heat transfer area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$a$</td>
<td>cross sectional area of heated tube</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>heat capacity</td>
<td>$J/kg , ^\circ C$</td>
</tr>
<tr>
<td>$D$</td>
<td>outside diameter of heated tube</td>
<td>$m$</td>
</tr>
<tr>
<td>$D_m$</td>
<td>mass diffusivity</td>
<td>$m^2/s$</td>
</tr>
<tr>
<td>$d$</td>
<td>inside diameter of heated tube</td>
<td>$m$</td>
</tr>
<tr>
<td>$F$</td>
<td>condenser flow rate</td>
<td>$kg/s$</td>
</tr>
<tr>
<td>$h$</td>
<td>heat transfer coefficient</td>
<td>$W/m^2 , ^\circ C$</td>
</tr>
<tr>
<td>$\bar{h}$</td>
<td>average heat transfer coefficient</td>
<td>$W/m^2 , ^\circ C$</td>
</tr>
<tr>
<td>$I$</td>
<td>current</td>
<td>amperes</td>
</tr>
<tr>
<td>$k$</td>
<td>thermal conductivity</td>
<td>$W/m , ^\circ C$</td>
</tr>
<tr>
<td>$L$</td>
<td>total heated length</td>
<td>$m$</td>
</tr>
<tr>
<td>$m_f$</td>
<td>circulation rate</td>
<td>$kg/s$</td>
</tr>
<tr>
<td>$p$</td>
<td>pressure</td>
<td>$N/m^2$</td>
</tr>
<tr>
<td>$Q$</td>
<td>heat input</td>
<td>$W$</td>
</tr>
<tr>
<td>$q$</td>
<td>heat flux</td>
<td>$W/m^2$</td>
</tr>
<tr>
<td>$r_c$</td>
<td>radius of cavity, critical condition</td>
<td>$m$</td>
</tr>
<tr>
<td>$S$</td>
<td>submergence</td>
<td>percent</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>$^\circ C(K)$</td>
</tr>
<tr>
<td>$T_{c1}$</td>
<td>inlet temperature of cooling water to condenser</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$T_{c2}$</td>
<td>outlet temperature of cooling water from condenser</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$T_{L1}$</td>
<td>inlet temperature of liquid to the tube</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$T_{L2}$</td>
<td>outlet temperature of the liquid to the tube/saturation temperature of liquid in the tube</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$T_s$</td>
<td>saturation temperature of liquid</td>
<td>$^\circ C$</td>
</tr>
<tr>
<td>$T_{SL1}$</td>
<td>bubble point of the liquid corresponding to the inlet composi-</td>
<td></td>
</tr>
</tbody>
</table>
 tion-liquid saturation temperature
at Z = Z_{MB} °C

T_{s2} liquid saturation temperature
at Z = L °C

T_v condensate temperature in condenser vessel °C

ΔT temperature difference, (T_w - T_L) °C

ΔT_f temperature drop across the liquid film °C

ΔT_{sub} degree of subcooling, (T_S - T_L) °C

ΔT_{sup} degree of superheat, (T_W - T_S) °C

V voltage volts

x mass fraction of more volatile component in liquid phase

x average concentration

x^0 void fraction

y, y* mass fraction of more volatile component in vapor phase

Z distance along the test section m

Greek Letters

α thermal diffusivity, k/°C m^2/s

β coefficient of volume expansion -1/°C (∂S/∂T) °C^-1

ξ* superheated layer thickness m

ρ density kg/m^3

υ kinematic viscosity, m^2/s

μ dynamic viscosity Ns/m^2

σ surface tension N/m
Subscripts

avg average
B boiling
BM boiling for binary mixture
C convective
CB convective boiling
CM convective for binary mixture
exp experimental
i inside
in inlet liquid condition
L liquid
O outside
out outlet liquid condition
NB non boiling
Ob onset of boiling
Osb onset of surface boiling
pred predicted
s saturation
TP two-phase
v vapor
w wall
Z refers to position along the heated tube length

\( H_2O \) water

Dimensionless groups

Gr Grashof number, \( (\frac{\gamma \alpha^3 \rho \Delta T}{\nu^2}) \)

\( K_\lambda \) Relative thermal conductivity, \( (k_w/k_f) \)

\( K_C \) Criterion for concentration \[
\left[ 1 + \left( \frac{\gamma - \chi}{\gamma (1 - \gamma)} \right)^2 \right]
\]

\( K_P \) Dimensionless parameter, \( (\frac{P b}{\sigma}) \)

\( K_{\text{sub}} \) Subcooling number, \( \left(1 + \frac{\delta_L}{\delta_V} \frac{\Delta T_{\text{sub}}}{T_s} \right) \)

\( \text{Nu} \) Nusselt number, \( \left( \frac{h d}{k} \right) \)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Pr_B, Pr_*$</td>
<td>Peclet number for boiling</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number, $\left( \frac{\mu C_L}{k} \right)$</td>
</tr>
<tr>
<td>$Ra$</td>
<td>Rayleigh number, $\left( Gr \cdot Pr \right)$</td>
</tr>
<tr>
<td>$Re$</td>
<td>Reynold's number, $\left( \frac{dm}{a \mu} \right)$</td>
</tr>
<tr>
<td>$X_{tt}$</td>
<td>Lockhart-Martinelli parameter, $\left( 1 - \frac{X}{X^*} \right)^{0.9} \left( \frac{\rho_v}{\rho_L} \right)^{0.5} \left( \frac{\mu_L}{\mu_v} \right)^{0.1}$</td>
</tr>
<tr>
<td></td>
<td>concentration parameter, $\left( 1 + \frac{\gamma - x}{x} \right)$</td>
</tr>
</tbody>
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