A generalized correlation of nucleate pool boiling of liquids

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An experimental study on nucleate pool boiling of distilled water, benzene and toluene from a horizontally laid plain stainless steel heating tube at atmospheric and subatmospheric pressure has been discussed here. The main objective of the investigation is to study the variation of heat transfer coefficient around the circumference of heating tube and thereby to determine functional relationship of local and average heat transfer coefficient with heat flux and pressure. Further, a generalized correlation of boiling heat transfer coefficient of various liquids has been developed to examine the consistency of experimental data conducted on heating surfaces of different characteristics.

Keywords: Nucleate boiling, surface-liquid combination factor, heat transfer coefficient.

Boiling heat transfer takes place in industrially important systems such as evaporators, reboiler, vaporizer, etc. Accordingly, intensive research work is going on for last seventy years to understand its mechanism for high heat transfer rate. Many investigators have carried out experiments and correlated their data through various empirical correlations for predicting heat transfer coefficient. These correlations contain invariably a term, known as surface-liquid combination factor, whose value depends upon heating surface characteristics and the liquid boiling on it. The determination of surface-liquid combination factor is highly improbable. Hence, some researchers analyzed the problem of boiling of liquids and developed semi-theoretical correlations for predicting heat transfer coefficient. However, these correlations cannot be used to generalize experimental data of boiling of various liquids on heating surfaces of different characteristics, as they also contain surface-liquid combination factor. This paper is an attempt to provide a correlation free from surface-liquid combination factor.

Experimental Procedure

The experimental set-up for this study is described in Fig. 1. It consists of a cylindrical vessel, a heating tube, a heater, two knock-out condensers, a vacuum pump, wall and liquid thermocouples and an instrumentation panel board having a wattmeter, a digital multimeter, volt-and amperemeter, etc. The vessel is a stainless steel cylinder of 240 mm I.D., 470 mm height and 3 mm thickness. Top of the vessel has a cover equipped with mountings for two knockout condensers, a bubbler, a thermo-couple probe, and a vacuum/pressure gauge. The vessel is adequately insulated by wrapping it with asbestos rope and thick layers of paste of plaster of Paris and magnesia powder. The heating tube is a stainless steel cylinder having 18 mm I.D., 32 mm O.D. and 150 mm effective length. One end of the tube is open whereas the other end is closed with a 25 mm thick plug. This plug reduces the possibility of longitudinal heat flow. Four holes of 3mm diameter, each equispaced at 90° on a pitch circle diameter \( d_p \) \( = (d_i + d_o)/2 \), are made in the wall thickness of the heating tube. The outer surface of tube is made smooth by turning, rubbing and polishing by a standard 0/o grade emery paper. A home made cartridge heater is placed inside the tube for heating. The heater is prepared by winding 24 gauge nicrome wire over a porcelain tube of 16mm diameter. Thin mica sheet and glass tape are wrapped over the heater surface for providing electrical insulation between heater and tube.

Surface and liquid temperatures are measured by calibrated PTFE coated OMEGA make 30 gauge copper-constantan thermocouples. They are placed in holes made in wall thickness of the tube for measuring wall temperature at the top-, the two sides- and bottom-positions. Similarly, thermocouple probes

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are mounted in the pool of liquid corresponding to wall thermocouple positions to measure the liquid temperature. The probes are kept at sufficient distance from the tube outside the superheated boundary layer surrounding the tube for monitoring bulk temperature of the liquid. A 24 point selector switch is used to connect all thermocouples and their e.m.fs are measured by a digital multimeter of Thurlby model 1905a having a least count of 0.1 μV in 20 mV range. Reference junction is a melting ice bath at 0°C.

To conduct experiments, the heater is energized with a single phase, 220 V, 50 Hz AC stabilized supply. An autotransformer modulates input voltage to heater. The heating tube is thermally stabilized and subsequently the liquid is degasified to get reproducible data. Standard procedure is followed to obtain data for the boiling of liquids at atmospheric and sub-atmospheric pressures. Heat input is varied from 240 to 640 W in six steps and pressure from 20.01 to 97.39 KN/m² in six steps. The liquids investigated are distilled water, benzene and toluene.

Data reduction
Since thermocouples are located inside the tube wall, they do not represent the outer surface temperature of the tube. It is obtained by incorporating a correction through temperature drop from the thermocouple tip to the outer surface, δT_w. It is calculated by the following equation for thin cylinder:

\[
\delta T_w = q \left( \frac{d_o}{2k} \right) \ln \left( \frac{d_o}{d_p} \right) \quad \ldots (1)
\]

Thus, outer surface temperature at each circumferential position, \( \Psi \) on heating tube is equal to the recorded wall temperature minus temperature drop calculated by Eq. (1).

Heat flux, \( q \) is obtained from the following equation:

\[
q = \frac{Q}{(\pi d_o L)} \quad \ldots (2)
\]

Local heat transfer coefficient, \( h_{\Psi} \) is calculated by the following equation:

\[
h_{\Psi} = q / \left( T_{wy} - T_w \right) \quad \ldots (3)
\]

Average value of wall temperature, \( T_{wa} \) is calculated by taking arithmetic mean of the wall temperatures at the bottom, the two sides and the top position of the heating tube surface.

\[
T_{wa} = \frac{T_{w,b} + T_{w,s} + T_{w,t} + T_{wa}}{4} \quad \ldots (4)
\]
Similarly, liquid temperatures as monitored by liquid thermocouple probes are processed to provide the average liquid temperature, $T_{la}$.

Average heat transfer coefficient, $h$ is obtained from the following equation:

$$h = \frac{q}{(T_{wa} - T_{la})} \quad \ldots (5)$$

Each data is processed to determine the extent of error, which is crept in due to inherent limitations of measuring instruments and the method of measurement. The maximum error in the value of average heat transfer coefficient is found to be $\pm 3.08 \%$ only.

**Results and Discussion**

Figure 2 is a plot to demonstrate the variation of wall and liquid temperature along the circumference of a plain heating tube for the boiling of distilled water at atmospheric pressure. In this plot, heat flux is a parameter. An inspection of this plot reveals the following silent features:

(i) At a given heat flux, wall temperature increases from bottom to side to top position of heating tube.
(ii) For a given circumferential position, an increase in heat flux increases wall temperature.
(iii) Liquid temperature remains uniformly constant irrespective of heat flux and circumferential position.

Above features are consistent and can be explained as follows:

Initiation of vapour bubble occurs at preferred sites randomly distributed on heating surface. The vapour-bubbles grow in size and depart from the surface to travel in the pool of liquid. However, in case of tube surface, the growth of vapour bubble and its movement is not uniform throughout its circumference. As a matter of fact, bubbles generated at top position have free access to travel upward, whereas those formed at bottom position do not have so. Bubbles generated at bottom position slide upward along the wall surface as their movement gets continuously accelerated due to increase in buoyancy force. In doing so, they push the bubbles formed at adjoining circumferential positions on their way and carry them along the wall surface to reach to top position. Thus, population and volume of vapour bubbles continuously increases as one moves from bottom to side to top position. Coalescence of bubbles leading to form agglomerates and vapour cloud occur in this thick layer of vapour bubbles engulfing the tube circumference. The thickness of this layer increases along the circumference from bottom to side to top position. Since this layer obstructs the passage of heat from tube surface to liquid, heat removal rate decreases from bottom to side to top position. As a consequence, wall temperature is found to increase continuously from bottom to side to top position. The above phenomenon has also been witnessed by Kang\(^1\) and Gupta et al.\(^2\).

At a given circumferential position, increase in wall temperature due to increase in heat flux is obvious. An increase in heat flux leads to higher heat transfer rate which in turn, is accompanied with higher wall superheat and so the wall temperature.

Similar features have also been observed for the boiling of benzene and toluene at atmospheric and subatmospheric pressures too.

Figure 3 depicts the variation of local heat transfer coefficient with heat flux for boiling of distilled water at atmospheric pressure. Circumferential position is a parameter in this plot. From this plot following features emerges out,

(i) At a given heat flux, the value of local heat transfer coefficient increases from top to side to bottom position on heating tube.
(ii) For a given circumferential position, an increase in heat flux increases local heat transfer coefficient and variation between the two is governed by the power law, $h_\phi \propto q^{0.7}$.

Above features can be explained as follows: As discussed, wall temperature increases from bottom to side to top position so wall superheat also increases in the same order. As a result, local heat transfer coefficient is found to increase from top to side to bottom position on the tube. As regards the variation of local heat transfer coefficient with heat flux, an increase in heat flux increases the wall temperature and thereby the value of local wall superheat. This, according to following equation, activates small sized nucleation sites on heating tube surface to form vapour-bubbles:

$$r_m = \frac{2\sigma}{(dp/dT)\Delta T_w} \ldots (6)$$

As the population of small sized nucleation sites on a heating tube surface is more than that of large sized ones, higher number of vapour bubbles form, grow and detach from the surface. All these increase the intensity of turbulence and thereby the higher value of local heat transfer coefficient. Above features have also been observed during the boiling of benzene and toluene at all the pressures of this study.

As local heat transfer coefficient is found to be a function of heat flux and pressure, following correlation is developed by the use of least squares method within a maximum error of $\pm 10\%$:

$$h_\phi = C_1 q^{0.7} p^{0.32} \ldots (7)$$

The value of constant, $C_1$ depends upon circumferential position and the boiling of liquid. They are given in Table 1.

Figure 4 shows a plot between average heat transfer coefficient (hereafter referred as heat transfer coefficient) and heat flux for the boiling of distilled water at atmospheric pressure. This plot also contains the experimental data of earlier investigators, namely Kang, Gupta & Varshney, Wang & Dhir, Borishanskii et al., Cryder & Finalborgo, Vittala et al., and Jamialahmadi et al. for the purpose of comparison. As seen, the data of this investigation do not agree with those of earlier investigators. Further, there is no agreement even amongst the data of earlier investigators. In fact, the data of an investigation form a separate distinct group. These features are quite natural as boiling is a surface phenomenon and the heating surface employed in each investigation is of different characteristics. Another worth-noting point is that data points of an investigation follow the boiling power law, $h \propto q^{0.7}$.

Figure 5 represents a plot to demonstrate the variation of heat transfer coefficient with heat flux for the boiling of distilled water. Pressure is a parameter in this plot. Following salient features are obtained from this plot,

(i) At a given pressure, heat transfer coefficient varies with heat flux according to power law, $h \propto q^{0.7}$. 

### Table 1—Values of constant, $C_1$ for various circumferential positions on the tube

<table>
<thead>
<tr>
<th>Circumferential positions</th>
<th>Bottom</th>
<th>Side</th>
<th>Top</th>
<th>Side</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distilled water</td>
<td>0.537</td>
<td>0.478</td>
<td>0.427</td>
<td>0.480</td>
</tr>
<tr>
<td>Benzene</td>
<td>0.407</td>
<td>0.386</td>
<td>0.358</td>
<td>0.389</td>
</tr>
<tr>
<td>Toluene</td>
<td>0.426</td>
<td>0.391</td>
<td>0.351</td>
<td>0.392</td>
</tr>
</tbody>
</table>
At a given value of heat flux, an increase in pressure increases the value of heat transfer coefficient.

Possible explanations for these features are as follows: An increase in pressure alters physico-thermal properties of the liquid but the most significant effect appears in surface tension. In fact, raising pressure reduces the value of surface tension, which according to Eq. (6) decreases the value of minimum radius of curvature of nucleation sites to activate. This causes large number of bubbles to form, grow and detach. As a result, the intensity of turbulence increases and thereby, higher heat transfer coefficients are observed at elevated pressures.

Similarly, an increase in heat flux causes average wall superheat of the tube to rise. This also as per Eq. (6) leads to higher population of the vapour bubbles and thereby higher heat transfer coefficient.

Similar features have also been observed for the boiling of benzene and toluene as shown in Figs 6 and 7, respectively. Following functional relationship between heat transfer coefficient and heat flux and pressure is developed by the method of least squares within a maximum error of ±10%:

$$h = C_2 q^{0.7} p^{0.32} \quad \ldots \quad (8)$$

where constant, $C_2$ depends upon heating surface characteristics and boiling liquid. The values of $C_2$, as obtained, are 0.477, 0.384 and 0.388 for distilled water, benzene and toluene, respectively.

Since Eq. (8) contains constant, $C_2$ whose determination is highly improbable, it cannot be
employed in its present form to compare experimental data of boiling heat transfer conducted on various heating surfaces. Therefore, it is reduced to the following dimensionless form:

\[
\frac{h^*}{h_1^*} = \left(\frac{p}{p_1}\right)^{0.32}
\]

... (9)

where \(h^*\) stands for \((h/q_0.7)\) and subscript 1 refers to reference state which in the present case corresponds to one atmosphere pressure.

Experimental data of this investigation as well as of Cryder & Finalborgo\(^6\) for the boiling of distilled water, methanol, carbon-tetrachloride and \(n\)-butanol on copper surface for pressures ranging from 16.72 to 100 kN/m\(^2\); Agarwal & Gupta\(^9\) for the boiling of distilled water, benzene and toluene on stainless steel tube for pressures from 29.86 to 98 kN/m\(^2\) and Bansal\(^10\) for the boiling of water on stainless steel surface for pressures ranging from 31.53 to 98.06 kN/m\(^2\) are plotted against the values predicted from Eq. (9) in Fig. 8. As a result, the predicted values are found to match with the experimental values within a maximum error of \(\pm\)10\%. This proves the validity of Eq. (9) for boiling of liquids at atmospheric and subatmospheric pressures. As Eq. (9) is free from surface-liquid combination factor, it can be used to generalize the experimental data for boiling of various liquids on heating surfaces of differing characteristics. Further, it can also be employed for the calculation of heat transfer coefficient of boiling liquids at various subatmospheric pressures from the knowledge of heat transfer coefficient at atmospheric pressure without resorting to experimentation.

**Conclusions**

The following conclusions may be drawn from the results of present study:

(i) For a given value of heat flux, wall temperature increases circumferentially from bottom to side to top position of the heating tube during nucleate pool boiling of distilled water, benzene and toluene at atmospheric and subatmospheric pressures.

(ii) Local heat transfer coefficient, at a given circumferential position of the heating tube has been found to vary with heat flux according to relationship: \(h \alpha q^{0.7}\).

(iii) An equation has been developed by regression analysis to relate heat transfer coefficient with heat flux and pressure: \(h = C_2 q^{0.7} p^{0.32}\), where \(C_2\) is a constant whose value depends upon boiling liquid and heating surface characteristics.

(iv) A correlation has been developed for the generalization of experimental data for the boiling of various liquids on heating surfaces.
of different surface characteristics at atmospheric and subatmospheric pressures.

**Nomenclature**
- \( d \) = diameter, m
- \( k \) = thermal conductivity of heating tube material, W/ m \( ^\circ \)C
- \( L \) = effective length of heating tube, m
- \( q \) = heat flux, W/ m\(^2\)
- \( Q \) = heat input, W
- \( T \) = temperature, \( ^\circ \)C
- \( \Delta T \) = wall superheat, \((T_w - T_l), ^\circ \)C
- \( h \) = heat transfer coefficient, W/ m\(^2\) \( ^\circ \)C
- \( \rho \) = pressure, N/ m\(^2\)
- \( \sigma \) = surface tension, N/m
- \( \psi \) = circumferential position on heating tube

**Subscripts**
- \( a \) = average
- \( b \) = bottom
- \( l \) = liquid
- \( m \) = minimum
- \( o \) = outer
- \( p \) = thermocouple pitch circle
- \( s \) = side, saturation
- \( t \) = top
- \( w \) = wall

**References**