Pool boiling: pool boiling
heat transfer from a
stationary and a vibrating
wire to pure liquids and to
binary mixtures

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POOL BOILING

by

PETER RICE
POOL BOILING.

(Pool boiling heat transfer from a stationary and a vibrating wire to pure liquids and to binary mixtures.)

by

Peter Rice

A Thesis
Submitted for the Degree of
Doctor of Philosophy.

Loughborough University of Technology.

Supervisor W.F. Calus

Department of Chemical Engineering. September 1970
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1. ABSTRACT
1. ABSTRACT.

Pool boiling heat transfer data from a 0.0315 cm diameter 'Alumel' wire 15.2 cm long of which the middle 8.9 cm was used as the heat transfer surface to water, toluene, methanol, carbon tetrachloride, normal propyl alcohol and to binary mixtures of isopropyl alcohol/water are reported. Experiments were carried out on a stationary and on a vibrating wire. The ranges of vibrational parameters were frequencies up to 124 Hz and amplitudes up to 0.203 cm i.e. approximately seven times the wire diameter.

Heat transfer to water was increased when the wire was vibrated and the correlation of the experimental data proposed is:-

\[
\frac{\sqrt{A}}{h_{fg} \mu} \left( \frac{\sigma}{g_{m}'} \left( \rho_{L} - \rho_{v} \right) \right)^{\frac{1}{2}} \left( \frac{g_{m}'}{g} + 2 af/(gd)^{\frac{1}{2}} \right)^{\frac{1}{4}} = \frac{1}{0.0227} \left( C_{p} \Delta t/h_{fg} \text{Pr} \right)
\]

for the partial nucleate boiling region and

\[
\frac{\sqrt{A}}{h_{fg} \mu} \left( \frac{\sigma}{g_{m}'} \left( \rho_{L} - \rho_{v} \right) \right)^{\frac{1}{2}} \left( \frac{g_{m}'}{g} + 2 af/(gd)^{\frac{1}{2}} \right)^{\frac{1}{4}} = \frac{1}{(0.0184)^{\frac{3}{2}}} \left( C_{p} \Delta t/h_{fg} \text{Pr} \right)^{\frac{3}{2}}
\]

for the fully developed nucleate boiling region where

\[ g_{m}' = \left| \frac{g'}{2} + \frac{g - g'}{2} \right| \text{and} \quad g' = 2 \pi af^2 \]

Heat transfer to the pure organic liquids was unaffected by vibration of the wire, in fact under certain conditions a slight reduction in heat transfer was found.

A correlation is proposed for the heat transfer to the pure liquids from the stationary wire:-

\[
\left( \frac{Nu}{K_{p}^{0.7}} \right)^{T_{s}/T_{sw}} = \text{constant} \left( \text{Pe} \right)^{N}
\]

where \( T_{s} \) is the boiling point of the liquid and \( T_{sw} \) is the boiling point of water.

This is then extended to produce a correlation for binary mixtures:-
\[ \left( \frac{\text{Nu}}{k^{0.7}} \right) \left( \frac{T_g - T_{sw}}{T_{sw}} \right)^4 = \text{constant} \left( \frac{Pe}{t} + \frac{|y^+ - x|}{(\alpha_d')^2} \right)^n \]

where the constant and \( n \) depend on the heat transfer material and its surface.

Finally a simple graphical correlation is proposed for the effect of vibration in the convective region where all liquids showed improvements in heat transfer:

\[ \frac{\text{Nu}}{(Gr Pr)^{0.25}} \text{ versus } (Re^2 / Gr)^{0.25} \]

where \( Re = 2afd\rho / \mu \)

All correlations have been further tested using experimental data from the published literature and found to be satisfactory.
2. INTRODUCTION
2. INTRODUCTION.

Investigation into pool boiling heat transfer is a favourite research subject with chemical, mechanical and other engineers and scientists. The wide interests in this subject of research has produced a large volume of literature covering some of the practical aspects of boiling liquids and a smaller number of reports covering some fundamental aspects of boiling and of bubble dynamics in particular. Practical knowledge of boiling is limited, however, to pure liquids and is far from being of help to designers.

In this work an effort is being made to concentrate on two aspects of boiling which are of value to process industries and yet are poorly covered by the existing research literature. These are:

(1) the effect of vibration on pool boiling heat transfer, and (2) heat transfer to boiling binary liquid mixtures. In the processing of experimental data an extensive use is made of the available fundamental knowledge of boiling.

The effect of vibration on single phase heat transfer is fairly well known. The information available in literature on the effect of vibration on boiling processes is very scarce and confusing. It has been shown in this report that the effect of vibration is complicated depending on transport properties and operating variables, vibration may increase transfer rates or have no effect at all. So far in this investigation, it has been possible to define quantitatively the effect of vibration on boiling pure water only.

Experimental results from boiling several pure liquids allowed the development of a correlation which also agrees very well with the data of other workers. It was possible to adapt this correlation to results from experiments with binary mixtures obtained both in this investigation and by other workers.
3. LITERATURE SURVEY
3.1. **Stationary Wire.**

3.1.1. **Convective Region.**

Most data for laminar flow over the wire appears to be well correlated by:

\[ \text{Nu} = K (Gr \text{ Pr})^{0.25} \]  

(1)

where \( K \) has values of 0.53, 1.75 and 1.98 depending on the \( Gr \text{ Pr} \) range.

This flow is set up by the buoyancy caused by the reduction in density as the liquid adjacent to the surface becomes superheated.

For high surface superheats the flow will become turbulent, when the above correlation is altered to:

\[ \text{Nu} = K (Gr \text{ Pr})^{0.33} \]  

(2)

where \( K \) now has the value 0.1 for air and 0.17 for water, see ref. (1).

It is worth mentioning that if the Grashof number is interpreted as a Reynolds number squared, see ref. (78) for instance, then:

\[ \text{Nu} = K \text{ Re}^{0.66} \text{ Pr}^{0.33} \]  

(3)

where the exponents are similar to those in forced convection correlations.

3.1.2. **Nucleate Boiling Region.**

Most correlations which have been most successful in correlating nucleate boiling heat transfer are based on extensions of correlations used in forced convection heat transfer. They take the form:

\[ \text{Nu} = f(\text{ Re}, \text{ Pr}) \]  

(4)

i.e. for correlating the heat transfer for the flow over a cylinder McAdams ref. (2) recommends:

\[ \frac{\text{Nu}}{\text{Pr}^{0.3}} = 0.35 + 0.56 \text{ Re}^{0.52} \text{ for single phase flow.} \]  

(5)

What occurs in saturated pool boiling is that as the wall superheat is increased the adjacent layer of liquid also becomes superheated.
until at a discrete point on the surface called a nucleus, formed by
a scratch or blemish, a bubble of vapour starts to grow. The bubble
pushes the superheated layer of liquid away from the surface as it
continues to grow until it becomes so large that it detaches from the
surface. It then rises through the liquid dragging further areas of the
superheated liquid layer away from the surface due to a vortex ring set
up in its wake. Bulk liquid then rushes in to become superheated and the
process is repeated. Also as the wall superheat is further increased so
more nuclei become active. Finally so many sites are activated that
bubbles interfere with each other and the start of film boiling occurs.
It is possible therefore to treat the agitation caused by the bubble in
the manner of forced convection.

With boiling therefore it is necessary to produce a Nusselt
number and a Reynolds number which are characteristic of nucleate
boiling and then relate them in the above equation i.e.

\[ Nu = f(Re, Pr) \]

(6)

Perhaps the most well known correlation is that due to Rohsenow
ref. (3), He used the bubble diameter at breakaway as the characteristic
dimension.

\[ D_b \propto \beta (\sigma/\rho)(\rho_L - \rho_v)^{1/2} \]

(7)

where \( \beta \) is the angle of contact in degrees. This diameter is obtained
by a force balance on the bubble such that the surface tension force is
equated to the buoyancy force and was proposed by Fritz ref. (4).
It is also referred to as the Laplace length.

Rohsenow then proposed that the heat flow into producing a
bubble was proportional to the total heat flow from the surface. We
have:
\[ Q_b = m \ h_{fg} = \text{heat in forming bubble} \]
\[ = \rho_v A V h_{fg} \]  
\[ \text{i.e.} \quad \frac{(Q/A)_b}{h_{fg}} = \rho_v V h_{fg} = \left(\frac{Q}{A}\right)_{\text{overall}} \]  
\[ \text{i.e.} \quad G = \rho_v V = \left(\frac{Q}{A}\right)/h_{fg} \]  
\[ \text{i.e.} \quad \text{Reynolds number} = G \ \frac{d_v}{\mu} \]
\[ = \frac{Q/A}{h_{fg}} \left(\sigma / g (\rho_L - \rho_v)\right)^{1/2} \]  
and \[ \text{Nusselt number} = h \ \frac{d_v}{k} \]
\[ = \frac{Q/A}{\Delta t} \left(\sigma / g (\rho_L - \rho_v)\right)^{1/2} \]  

Since plotting Nusselt number against Reynolds number involves plotting \( (Q/A)/\Delta t \) versus \( Q/A \), Rohsenow plotted Reynolds number versus the reciprocal of Stanton number:—
\[ \text{i.e.} \quad \text{Re} \ \text{versus} \ \text{Re} \ \text{Pr}/\text{Nu} \]
\[ \text{i.e.} \quad \frac{Q/A}{h_{fg}} \left(\sigma / g (\rho_L - \rho_v)\right)^{1/2} \ \text{versus} \ \text{Cp} \ \Delta t/h_{fg} \]  

His final correlation was:—
\[ \text{Cp} \ \Delta t/h_{fg} = C_{sf} \ \text{Re}^{0.33} \ \text{Pr}^{1.7} \]  

Later in ref. (5) he proposed that for water the exponent on the Prandtl number should be 1. The value of the constant \( C_{sf} \) depends on the surface liquid combination. Vachon et al ref. (5) have reported an investigation into the value of the constant \( C_{sf} \) and also of the indices of the Reynolds number and Prandtl number. They showed that the constant was very much affected not only by the surface liquid combination but also by the surface treatment and finish. They found that the index of the Reynolds number was also affected by surface treatment and finish.
Nagarajan and Adelman ref. (11) also report an investigation into the effect of surface conditions. They measured the metal surface grain size and produced a correlation in which this quantity was introduced into the exponent and into the value of $C_{sf}$ as a modification of the correlation.

Science et al. ref. (10) correlated their data for boiling methane from 1 atmosphere to 0.9 of the critical pressure using a modified Rohsenow correlation. They found it necessary to introduce a temperature correction term $T_g/T_c$ so that the correlation became:

$$\frac{Q/A}{h_{fg}} \left( \frac{\sigma}{\rho L - \rho_v} \right)^{\frac{1}{2}} = 3.25 \left( 10^5 \right) \left[ \frac{C_P \Delta T}{h_{fg}} \left( \frac{T_g}{T_c} \right)^{0.18} \right]^{2.89}$$

Rohsenow's correlation has the drawback that the Prandtl number index, when the equation is rearranged to the more standard form $Nu = f(Re, Pr)$, is negative contrary to convective heat transfer theory. The other important point to note is that the characteristic mass velocity is that of the vapour leaving the surface.

Kutateladze ref. (6) proposed that the characteristic mass velocity should be that of the liquid leaving the surface i.e. the liquid carried away by the vapour bubbles. For the Reynolds number we then have:

$$Re = \frac{Q/A \rho_L}{\mu h_{fg} \rho_v} \left( \frac{\sigma}{\rho L - \rho_v} \right)^{\frac{1}{2}}$$

The Nusselt number is the same as that of Rohsenow. Kutateladze's final correlation is:

$$Nu = C Re^{0.7} Pr^{0.35}$$

With both Rohsenow and Kutateladze the characteristic velocity is that of the bubbles leaving the surface. It is also important to note that both the Rohsenow and Kutateladze correlations do not include the absolute boiling temperature. Since a change of state occurs (liquid
to vapour) it is reasonable to assume that the boiling temperature should appear in the correlation. The modification introduced by Sciance et al. ref. (10) satisfies this requirement.

Forster and Zuber ref. (7) proposed that the important velocity was that of the growing bubble while still adhering to the wire. From a study of bubble dynamics they obtained:

\[ 2 \dot{R} = \left( \frac{\rho_L}{\rho_v} \cdot \Delta t \frac{\pi \alpha'}{h_{fg}} \right)^2 \]

\[ R = \rho_L \cdot \Delta t \sqrt{\frac{\pi \alpha'}{\rho_L \Delta p}} \left( \frac{2 \sigma / \Delta p}{\rho_L / \Delta p} \right)^{\frac{1}{2}} \frac{1}{\rho_v h_{fg}} \]

hence their correlation:

\[ \frac{Q/A}{\rho_v h_{fg}} \left( \frac{\rho_L}{\rho_v} \cdot \Delta t \sqrt{\frac{\pi \alpha'}{\rho_L \Delta p}} \right)^{\frac{3}{2}} = 0.0015 \left( \frac{\rho_L}{\rho_v h_{fg}} \right)^{\frac{1}{2}} \frac{\Delta_p}{\rho_L / \mu}^{0.62} Pr_{0.33} \]

where \( \Delta p \) is the vapour pressure difference corresponding to the superheat \( \Delta t \).

Forster and Greif ref. (8) used the same concept but solved the simplified differential equations for bubble growth and obtained:

\[ \frac{Q/A}{\rho_v h_{fg}} \left( 2 \sigma / \alpha' \Delta p \right)^{\frac{3}{2}} \left( \frac{\rho_L}{\rho_v} \Delta p \right)^{\frac{1}{2}} = 0.0012 \left( \frac{\Delta t}{\rho_L / \mu} \right)^{\frac{3}{2}} Pr_{0.33} \]

where \( A_t = \frac{C_p \rho_L T_s \pi \alpha' \Delta p / \left( h_{fg} \rho_v \right)^{\frac{3}{2}}} \]

Again \( \Delta p \) is the vapour pressure difference corresponding to the superheat \( \Delta t \).

These two correlations have not been as extensively tested and proved as the Rohsenow and Kutateladze equations.

A more extensively tabulated list of nucleate boiling heat transfer correlations can be found in ref. (9). They appear to be modifications of the above correlations. A review of earlier empirical correlations such as that of Insinger and Bliss is given in ref. (79).
3.1.2a. Bubble Nucleation and Growth.

Nucleation of a bubble site will occur if there is residue vapour or inert gas trapped in the site. It is also necessary, and can be shown from thermodynamic reasoning, that the wire superheat temperature should be greater than a certain minimum value which permits the excess pressure in the embryo bubble to overcome the surface tension forces. With these requirements fulfilled the bubble starts to grow and finally to expand out from the nucleation site.

There are now considered to be two possible modes for further bubble growth. For bubbles at higher pressures, which are heat diffusion controlled, the superheated layer of liquid formed around the wire is pushed away by the bubble and there is an exchange of the superheat in this thermal boundary layer for latent heat of the vapour formed in the growing bubble. In the second mechanism, more applicable at lower pressures where the bubbles tend to be hemispherical rather than the spherical shape obtained at higher pressures, there is trapped between the bubble and the surface a microlayer of liquid and the high temperature of the heat transfer surface causes direct evaporation of this layer into the bubble, heat diffusion through the thicker sections of the microlayer being only a smaller contribution. The existence of this microlayer has been demonstrated by the direct photography of it using a technique in which transparent heat transfer surfaces were used.

Obviously there are both mechanisms present but it is thought that under suitable conditions either mechanism will dominate the vapour production contribution to the bubble growth rate.
3.1.3. **Binary Mixtures.**

Very little research appears to have been carried out on binary mixtures. One of the earliest was that of Bonilla and Perry ref. (14) where a whole range of binary mixtures consisting of permutations of water, ethanol, butanol and acetone were tested. The data was poorly correlated using the pure liquid correlations then existing, that of Insigner and Bliss ref. (12) and Jakob and Linke ref. (13). These correlations, both empirical, do not contain any factor which describes a binary liquid such as mass diffusivity or driving force such as \((y^*-x)\).

More recently Scriven ref. (15) has studied the growth of vapour bubbles in binary mixtures with the condition of spherical symmetry i.e. bubbles in a uniformly superheated liquid mixture. His equation, for high superheats, is:

\[
R(t_1) = C (\Delta t)^{(\alpha' t_1)^{1/2}} \quad (t_1 = \text{time})
\]  

where

\[
C = \left[ \frac{3}{4\pi} \right]^{1/2} \left\{ 1 - \rho_L \frac{h_f e}{\rho_p} - \left( \frac{\alpha}{D} \right)^{1/2} \left( m \rho_L - \rho_p \frac{\partial \rho}{\partial \rho} \right) \right\}^{1/2}
\]

is the growth constant.

A similar equation has been developed by Van Stralen ref. (16) where:

\[
C = \left[ \frac{12}{\pi} \right]^{1/2} \left\{ 1 - \rho_L \frac{h_f e}{\rho_p} \left[ \frac{\Delta e}{\rho_p} + \left( \frac{\alpha}{D} \right)^{1/2} \frac{\Delta \rho}{\rho_p} \right] \right\}
\]

This indicates that there not only exists a temperature gradient from the bulk liquid to the bubble boundary but also a concentration gradient. This concentration gradient is the driving force which allows for the vapour composition to be different to the bulk liquid composition i.e. it 'drives' the more volatile component through the bulk liquid to the
Van Stralen also argues that if the concentration at the bubble surface is $x'$ (say) due to the concentration gradient this, in effect, raises the boiling point at the surface by an amount $\Delta \Theta$ so that the original superheat $\Delta t$ is reduced to $(\Delta t - \Delta \Theta)$. He also assumes that the vapour in the bubble is in equilibrium with the surface composition (say $y''$) and then defines a vaporised mass fraction:

$$G_d = (x - x')(y'' - x')$$

(26)

With these two conditions he modified Scriven's equation as previously noted. He does not state when the vapour composition $y'''$ changes to $y''$ as it must to be in equilibrium with $x$. Although he develops his theory further Van Stralen does not produce a correlation for binary mixtures.

Stephan and Korner ref. (17) from thermodynamic reasoning evaluated the excess enthalpy required to produce bubbles in pure liquid and binary mixtures. These are:

$$\Delta G_p = \left( 16\pi \sigma^3 / 9 \right) \left( V^2 / \Delta t (\Delta H/T)^2 \right)$$

(27)

and

$$\Delta G_b = \left( 16\pi \sigma^3 / 9 \right) \left( V^2 / \Delta t (\Delta H/T + ((y'' - x)(5G/6x^2)(\Delta x/\Delta T)))^2 \right)$$

(28)

It shows that, for binary mixtures, additional terms must be included to any pure liquid correlation which describes the mass transfer which occurs in heat transfer to binary liquid mixtures.

They then proceed to develop an empirical correlation in the following manner. For constant heat flux they showed that the heat transfer coefficient $h_{\text{exp}}$ for a particular composition was always less than an ideal value $h_{\text{id}}$ lying on a straight line drawn between the values for the two pure components.

i.e. $h_{\text{exp}} < h_{\text{id}}$  

(29)

i.e. $\Delta t_{\text{exp}} > \Delta t_{\text{id}}$ since $Q/A = h \Delta t$

(30)
They divided the wall superheat $\Delta t$ into two parts $\Delta t_{id}$ and $\Delta t_{exc}$

\[ \Delta t_{exp} = \Delta t_{id} + \Delta t_{exc} \]

i.e.

\[ \frac{\Delta t_{exp}}{\Delta t_{id}} = 1 + \frac{\Delta t_{exc}}{\Delta t_{id}} = 1 + \theta \]

where $\Delta t_{id}$ is the wall superheat corresponding to $h_{id}$. They then formed $\Delta t_{id}$ as:

\[ \Delta t_{id} = [x_1 \Delta t_1] + [x_2 \Delta t_2] \]

where $\Delta t_1$ and $\Delta t_2$ are the wall superheats of the two pure components in the liquid. Further, they said that:

\[ \theta = A[y^* - x] \]

where $A$ is a constant which has to be determined experimentally. They found it tended to be independent of concentration. The obvious drawback of this scheme, since it is for constant heat flux, is that it is limited to the maximum heat flux of the more volatile component. This can be overcome by extrapolation of the nucleate boiling region of the boiling curve into a fictitious region using a logarithmic plot of heat flux versus wall superheat or one of the well known pure liquid correlations.

### 3.2 Vibrating Wire.

A critical review of methods of improving heat transfer has been given by Bergles ref. (18) as late as 1969. In it he gives a critical survey of the effects of vibration on convective and nucleate
boiling and the associated published literature.

3.2.1. Convective Region.

An extensive investigation of the effects of vibration on convective heat transfer has been made over the past decade. In all the investigations a forced convection type correlation is developed of the form:

\[ \text{Nu} = f(\text{Re}, \text{Pr}) \] 

or of the mixed convection type:

\[ \text{Nu} = f(\text{Re}, \text{Gr}, \text{Pr}) \] 

An example of this type is that of Pei ref. (19):

\[ \text{Nu} / (\text{Gr} \text{Pr})^{0.25} = c_1 + c_2 (\text{Re}^2 / \text{Gr})^{0.25} \] 

The characteristic velocity for the Reynolds number is then obtained as a function of amplitude times frequency:

\[ v = f(\alpha f) \] 

If the oscillations are simple harmonic, three velocities are possible:

i. \[ v = \sqrt{2} \pi \alpha f \] root mean square velocity

ii. \[ v = 2 \alpha f \] mean velocity

iii. \[ v = 2 \pi \alpha f \] maximum velocity

ii. has the advantage of simplicity since it is the amplitude of one complete vibration divided by the time to complete the vibration.

iii. has the merit that in association with the maximum acceleration \( 2\pi^2 \alpha f^2 \) a Froude number can be formed of the ratio of the maximum inertia force to the maximum acceleration force i.e.

\[ \text{Fr} = 4\pi^2 \alpha f^2 / 2\pi^2 \alpha^2 f^2 d \]

\[ = 2\alpha / d \] 

All the relevant investigations are shown in table (1) with all the pertinent details.
## Table 1: Convective heat transfer from a vibrating surface, literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Wire Diameter</th>
<th>Amplitude</th>
<th>Frequency</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>(20)</td>
<td>0.0253''</td>
<td>0 - 0.231''</td>
<td>0 - 122 Hz</td>
<td>Nichrome/Air</td>
</tr>
<tr>
<td></td>
<td>0.0396''</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0810''</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = \left( 0.75 + \left( (0.0022 \text{ Re}^{2.05} \Delta t^{0.33})/(\text{Pr}^{4.54} \text{ Gr}^{0.41}) \right) \right) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Or less accurately</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( h = 1/h' = 0.00265 \text{ Re}^{2.13} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(21)</td>
<td>0.7 - 1.99 mm</td>
<td>0 - 7.66 mm</td>
<td>0 - 118 Hz</td>
<td>Naphthalene &amp; D-Camphor/Air</td>
</tr>
<tr>
<td></td>
<td>( h/h' = 0.038 \text{ Re}^{0.85} \text{ Pr}^{1.13} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(22)</td>
<td>0.049''</td>
<td>0 - 0.086''</td>
<td>0 - 37 Hz</td>
<td>S.S./Water &amp; Aq. Glycerine</td>
</tr>
<tr>
<td></td>
<td>( h/h' = \text{func:} \left( \text{Re Pr}^{0.6} (a/d)^{0.4}/(\text{Gr Pr})^{0.26} \right) )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(23)</td>
<td>0.875''</td>
<td>0 - 0.16''</td>
<td>0 - 225 Hz</td>
<td>Aluminium/Air</td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = 0.495 (\text{ Gr Pr})^{0.25} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = C (\text{ Gr Pr})^{0.2} \text{ Re where C = 8.5 x 10^{-4}} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(25)</td>
<td>1.98 cm</td>
<td>1 - 4 cm</td>
<td>1.6 - 27 Hz</td>
<td>not given/Oils</td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = 0.146 \text{ Pr}^{0.67} \text{ Pr}^{0.16} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(26)</td>
<td>0.005''</td>
<td>0 - 2.76''</td>
<td>0 - 4.25 Hz</td>
<td>Platinum/Water</td>
</tr>
<tr>
<td></td>
<td>( \text{Nu/Pr}^{0.3} = 0.35 + 0.48 \text{ Re}^{0.52} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = 0.44 (\text{ Gr Pr})^{0.5} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = 1.15 (\text{ Gr Pr})^{0.15} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(27)</td>
<td>1.1 cm</td>
<td>( a/d = 0.102'' )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( = 0.198'' )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( = 0.298'' )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \text{Nu} = 0.746 \text{ Re}^{0.5} \text{ Pr}^{0.33}(a/d)^{0.167} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Benzoic Acid/Aq. Glycerine &amp; Water</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table (†) continued.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Wire Diameter</th>
<th>Amplitude</th>
<th>Frequency</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>(23)</td>
<td>0.75'' &amp; 1''</td>
<td>0 - 25.5 mm</td>
<td>0 - 930 Hz</td>
<td>Copper/Air</td>
</tr>
<tr>
<td>Spheres</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h'/h = 0.83</td>
<td>(Re(^{0.5}(a/d)^{0.1})/(Gr)^{0.25})^{1.28}</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
One of the earliest reported investigations was that of Lemlich ref. (20). In his correlation he introduced the concept of a 'stretched' Reynolds number which was obtained by using as the characteristic dimension a value equal to the amplitude plus the wire diameter. This because from smoke visualisation tests the vibrating wire appeared as an extended surface of dimension equal to the characteristic dimension just given. His investigation was carried out using air and he added an additional factor to allow for different liquids. $2\pi a_f$ was used in the correlation for velocity.

Lemlich ref. (21) again used a concept of the 'stretched' Reynolds number in correlating data obtained in an investigation of the effect of vibration on mass transfer using the evaporation of naphthalene and d-camphor to air.

In ref. (22) Lemlich reverted to the accepted definition of characteristic dimension (wire diameter) in an investigation of heat transfer to water and to aqueous glycerine solutions. He used the method of indices to obtain his correlation using factors $Re$, $Pr$ etc., which he considered should have an effect. One of these factors was amplitude to wire diameter.

Fend and Kaye in ref. (23) developed two correlations to represent their data. For the lower range data, vibration appeared to have no effect and the normal $(Gr Pr)^{0.25}$ for free convection reduced the data to a single line. For the upper range of their data, a mixed correlation of $(Gr Pr)$ and $Re$ was used. The velocity term used was $2\pi a_f$ i.e. maximum velocity.

In a later paper ref. (24) Fand and Peebles compared the effect of acoustical vibrations with mechanically produced vibrations. These showed that for low amplitude to wire diameter ratio and high
frequencies for the mechanically produced vibrations the two effects were similar. In both cases acoustic streaming was produced which could account for the similarity of results.

Kalashnikov and Chernikin ref. (25) used a range of viscous oils and using the root mean squared velocity obtained a correlation of the standard forced convection type.

Deaver et al ref. (26) simply divided their data into three ranges. For the upper range they used the McAdams ref. (2) type forced convection correlation:

\[
\frac{Nu}{Pr^{0.3}} = 0.35 + 0.48 \text{Re}^{0.52}_v \quad (\text{Re}_v = 2af \rho \nu / \mu)
\]  

(43)

While for the two lower ranges they used:

\[
Nu = K (GrPr)^n
\]  

(44)

with the constant K and the exponent n having two appropriate values.

In a more theoretical approach Jameson ref. (27) used simplified boundary layer equations to develop a mass transfer correlation for the dissolving of benzoic acid cylinders in aqueous glycerol solutions. The factor amplitude to wire diameter appears in the correlation, also the maximum velocity appeared in Reynolds number.

Finally Baxi and Ramachandran ref. (28) studied the effect of combined vibration and forced convection on heat transfer from a wire to air flowing over it. Air velocities up to 84 ft/sec. were used. Vibration appeared to have no effect until the vibrational velocity was of the order of 20 percent of the forced convection velocity. The root mean squared velocity was used to characterise the vibration.

3.2.2. Nucleate Boiling Region.

In table (2) all pertinent details are shown for all the investigations found in the published literature.
Table (2) Nucleate boiling heat transfer from a vibrating surface, literature.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Wire Diameter</th>
<th>Amplitude</th>
<th>Frequency</th>
<th>Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>(29)</td>
<td>0.01&quot;</td>
<td>0 - 0.0701&quot;</td>
<td>0 - 115 Hz</td>
<td>Pt/Water</td>
</tr>
<tr>
<td>(30)</td>
<td>38 mm</td>
<td>0 - 0.35 mm</td>
<td>0 - 50 Hz</td>
<td>Cu/Water</td>
</tr>
<tr>
<td>(34)</td>
<td>0.123&quot;</td>
<td>0 - 0.15&quot;</td>
<td>0 - 2000 Hz</td>
<td>S.S./Water</td>
</tr>
<tr>
<td>(35)</td>
<td>1&quot;</td>
<td>0 - 0.058&quot;</td>
<td>0 - 120 Hz</td>
<td>Cu/Water</td>
</tr>
<tr>
<td>(33)</td>
<td>0.12&quot;</td>
<td>0 - 0.125&quot;</td>
<td>0 - 80 Hz</td>
<td>S.S./Water</td>
</tr>
<tr>
<td>(32)</td>
<td>2.25&quot; Sphere</td>
<td>0 - 2&quot;</td>
<td>0 - 7 Hz</td>
<td>Al/LN₂</td>
</tr>
</tbody>
</table>

Pt - Platinum  
Cu - Copper  
S.S. - Stainless Steel  
Al - Aluminium  
LN₂ - Liquid Nitrogen
One of the most interesting is that of Nangia and Chon ref. (29) because included in the range of parameters investigated were amplitude to wire diameter ratios up to seven. They stretched a platinum wire and used a bell mechanism to cause the wire to execute sinusoidal vibrations along its length. By altering the power to the bell mechanism and the wire tension they were able to control the frequency and amplitude. No correlation was proposed and water was the only liquid used.

Kovalenko ref. (30) reported a reduction in heat transfer with vibration although the maximum amplitude to wire diameter ratio was only 0.092. Water was again the heat transfer liquid. Subsequently in a report Nevill et al ref. (31) describe a reduction in heat transfer for low values of 'average vibrational velocity' for convective heat transfer from a laterally oscillating tube to flowing water in a surrounding annulus.

McQuiston and Parker ref. (34) plotted curves of wall superheat versus vibrational acceleration for constant frequencies. They drew the conclusion that vibration had negligible effect. However if a computation is made, it is shown that the amplitudes covered are very small so that in terms of amplitude to diameter values much less than one are obtained. For instance with the 0.123 inches diameter tube the maximum amplitude reported at 200 Hz is 0.008" i.e. amplitude to diameter ratio of 0.065. Their results also indicate that the little improvement which occurred at low heat flux disappeared as film boiling was approached.

In ref. (35) Price and Parker present results of a visual study of the effect of vibration. Again only low values are covered of amplitude to diameter i.e. 0.058 maximum. They do state in their
conclusion that bubbles leave the surface at a smaller diameter and higher frequency than those from a stationary surface.

In their paper ref. (32) Rhea and Nevins used liquid nitrogen and although no correlation was produced for their data, note the importance of Froude number in the discussion.

Finally in ref. (33) Bergles, although not correlating his data indicates that the improvement at low heat flux is not maintained at higher heat flux for vibration.

3.2.3. Film Boiling Region.

Although not directly applicable to the present work, the effect of vibration on film boiling has been included for completeness. Only one article was found ref. (80). Rhea and Nevins used liquid nitrogen and a metal sphere as the heat transfer surface. They found that heat transfer was improved with vibration and correlated their data using additional terms, which describe vibration, on the Frederking and Clarke correlation ref. (83) for film boiling on a stationary wire as follows:

$$\text{Nu} = 0.14 \left( \frac{\rho_v}{\rho_L} - \frac{\mu_v}{\mu_L} \right) \left( \frac{h_{fg}}{C_p \Delta T} + 0.5 \right) \left( \frac{d}{g} + \frac{(af)^2}{gd} \right)$$

(45)

The term which describes vibration and takes account of velocity and acceleration is:

$$\left( \frac{d}{g} + \frac{(af)^2}{gd} \right)$$

where $a'$ is the wire acceleration and $a$ is the vibrational amplitude.

3.2.4. Acoustic Streaming.

In a series of papers ref. (36) to (39) the fluid dynamics associated with an oscillating cylinder in an infinite fluid have been studied. Both experimental and theoretical treatment
show that for small amplitudes, less than the cylinder diameter, and high frequencies a steady streaming flow is set up called acoustic streaming. A similar flow is produced when a cylinder is subjected to sound (pressure) vibrations. Associated with the steady flow is a recirculating boundary layer adjacent to the cylinder.

The flow is towards the cylinder at right angles to the direction of vibration and away from the cylinder along the line of vibration.

In a paper Richardson ref. (40) studied theoretically the heat transfer associated with acoustic streaming. In particular three modes which were prominent:

1. convection by outer streaming at small streaming Reynolds numbers.
2. convection by inner streaming.
3. convection by outer streaming at large streaming Reynolds numbers.

His final results were:

1. \( \frac{Nu}{Re} = 0.718 \frac{Pr^{0.5}(3\psi/\omega)^{0.5}}{R_s} \)  

2. \( Nu = 1.36 \frac{Re^{0.5}Pr^{0.5}(a/R_s)^{0.167H^{0.5}}} \)  

3. \( Nu R_s(1 + 0.95(a/d)) = 0.484 Re Pr^{0.5}(3\psi/\omega)^{0.5} \)

where Reynolds number has the characteristic velocity:

\[ v = \sqrt{\frac{2}{\pi}} \alpha \]

and \( H \) is a correction term which governs the thickness of the boundary layer. The important facts are that if the inner boundary layer is thick then this governs the heat transfer while if it is thin the outer streaming flow controls the heat transfer.

Intuitively, one would think that although applicable to convective heat transfer; under the strong effect of turbulence caused by departing bubbles in the nucleate boiling region this type of flow would break down i.e. the bubble turbulence would dominate the flow pattern.
4. EXPERIMENTAL APPARATUS
4. DESCRIPTION OF EXPERIMENTAL APPARATUS.

4.1. Description of Experimental Apparatus.

The general layout of the test rig is shown in fig. (1). The vibrations were generated by a 'Derritron' vibrator VP25 mounted on a 0.533 m x 0.763 m x 0.305 m deep concrete block to give rigidity. The vibrator was controlled by a 'Siemens' type R2125 oscillator through a 'Derritron' type 1 KW. LF amplifier, see fig. (10). Also mounted to the concrete base was a 3.18 cm diameter tubular structure which supported the fulcrum transferring the vibrations down through the top cover of the pool. This structure was also used to support the pool. The pivot of the fulcrum was actually mounted on a 2.54 cm section angle iron frame which in turn was supported on the tubular structure.

The pool consisted of a 0.228 m diameter by 0.305 m deep 'Quickfit' glass cylinder closed at each end by 0.955 cm thick brass plates. The upper plate was also used to support the pool in the tubular structure. The glass was sealed by rubber and cloth rings with P.T.F.E. envelopes. The two plates were pulled together by eight 2.22 cm diameter by 0.381 m long studs.

Through the bottom plate a 3 KW. bulk liquid heater was fixed, connected to an autotransformer so that its output could be varied. Mounted above the heater was an inclined 0.178 m diameter by 0.158 cm brass deflector plate, which shielded the test wire from the convection currents of the bulk liquid heater.

A total reflux condenser was mounted to the top plate of the pool by means of a 0.381 m long by 1.9 cm brass tube using 'Prestex' fittings. Also through the top plate a calibrated mercury in glass thermometer reading to 0.1°C was mounted.

The drive from the vibrator was connected to a length of 1.9 cm diameter aluminium tube through a universal joint. The other end of the aluminium tube was connected by a hinge, made from stainless steel, see
Fig. (1.) Sketch of apparatus.
Fig. (3.) Test wire electrical circuit.

Fig. (10.) Vibrator electrical circuits.
fig. (5.), to a horizontal 0.955 cm diameter stainless tube. This tube passed through the pivot to another similar hinge, this arrangement forming the fulcrum.

The pivot see fig. (5.) consisted of a 2.54 cm cube block of stainless steel with a 0.955 cm diameter hole through 1 pair of faces for the 0.955 cm diameter tube. From two faces at 90° to these, two projections 0.955 cm diameter x 3.81 cm long were supported in two Plummer bearing blocks mounted to the 2.54 cm angle iron frame.

The test surface, which consisted of a 15.2 cm length of 0.0315 cm diameter 'Alumel' wire, was supported in a yoke made from 0.955 cm stainless tube. The ends of the test wire had 1.9 cm long by 0.318 cm diameter ferrules soldered to them. The soldering was accomplished using 'Eutectic' solder with 'Castolin Eutectic' flux. The choice of the alumel wire was decided upon because, with the power available, its resistance and size permitted surface heat fluxes up to the onset of film boiling with water and did not fail under the 'G' loading when vibrated. A pure platinum wire 0.0127 cm diameter to give equivalent surface heat fluxes, failed when vibrated. Two 0.0178 cm diameter tapping wires were soldered to the test wire so that only the middle 7 cm approximately was used as the test surface. These were connected to two small rings around the P.T.F.E. blocks. P.T.F.E. coated wire then continued up through two P.T.F.E. inserts in the upper plate to a terminal block. They were then connected, as were the wires for measuring the standard resistance voltage drop, to a 'Digital Measurements' digital voltmeter DM 2001 with typewriter output. The method of support of the wire so that power could be supplied to and yet insulated from the yoke is described later.

The arms of the yoke supporting the test wire were submerged 0.102 m when the liquid level was maintained just below the position of
Fig. 4. Details of yoke.
Fig. 5. Details of vibrator pivot arm and bearings.
the yoke cross member.

The middle of the yoke cross member was welded to a 8.9 cm length of 1.9 cm diameter stainless steel tube which passed through the upper plate. A sliding seal was obtained by means of a 'Prestex' fitting with a P.T.F.E. olive. The tube was then reduced to 0.955 cm diameter stainless tube and connected to the second hinge; see fig. (4.).

Mounted to the second hinge, and therefore directly to the test surface, was a 'G.E.C.' type E (Barium Titanate) accelerometer pick up. The output from this was read on a 'Derritron' type A1 'G' meter. This meter was calibrated such that 1 on its scale represent 9.812 m/sec$^2$ i.e. in unit gravitational increments, see fig. (2.).

The two P.T.F.E. coated power leads passed into the 1.9 cm tube at the point where it was reduced to 0.955 cm diameter and then continued to the ends of the yoke. At the ends of the power leads were soldered brass nipples. Each nipple was held away from the yoke by means of a P.T.F.E. block. Through this block and the nipple passed the ferrule on the end of the test wire which was locked to the nipple by means of a screw in the nipple end, see fig. (6.).

Power to the test wire supplied from two 'Solartron' D.C. power packs AS 1218 connected in parallel to give 20 amps maximum. Connected in series with the test wire was standard 'Zenith' type TNE 0.784 ohm resistance. The voltage drop across the standard resistance and the test wire were used to compute the wire temperature using its change in resistance; also together with the wire dimensions, to calculate the surface heat flux.

4.2. **Calibration of Experimental Apparatus.**

To obtain the correct 'G' meter calibration, a frequency of 44 cps. was selected on the oscillator and the amplitude increased by
increasing the amplifier output until the amplitude was 0.254 cm. This amplitude was measured on an optical wedge.

Now,
\[ \frac{d^2x}{dt^2} = -n^2x \quad \text{for S.H.M.} \] \hspace{1cm} (50)

For maximum acceleration, \( x \) must be maximum that is:
\[ x = a' = \frac{\text{amplitude (peak to peak)}}{2} \] \hspace{1cm} (51)

Therefore
\[ \left[ \frac{d^2x}{dt^2} \right]_{\text{max}} = -n^2a' = n^2a' \quad \text{numerically} \] \hspace{1cm} (52)

but \( n = 2\pi \sqrt{f} \)

therefore
\[ \left[ \frac{d^2x}{dt^2} \right]_{\text{max}} = 4n^2a'f^2 \quad \text{numerically} \] \hspace{1cm} (54)

The 'G' meter is calibrated to indicate acceleration in units of earth gravitational acceleration (9.812 m/s²). Putting \( a = 2a' = \text{amplitude (peak to peak)} \):
\[ \text{Instrument 'G'} = \frac{2\pi^2af^2}{9.812} \] \hspace{1cm} (55)

with \( a \) in metres and \( f \) in cps. (Hz)

Therefore
\[ \text{'G'} = \frac{2\pi^2 \times 0.00254 \times 44^2}{9.812} = 0.988 \] \hspace{1cm} (56)

This value of 'G' was then set on the instrument dial using the adjusting screw.

The above procedure in reverse was used for selecting the required amplitude i.e. selecting a frequency and then adjusting the amplifier to give a selected 'G' meter reading equivalent to the required amplitude.

The test wire dimensions i.e. wire diameter and length between tapping wires, were measured before assembly.

The wire temperature (mean temperature) was determined from
\[ R_{tw} = R_o \left(1 + \alpha T_m \right) \] \hspace{1cm} (57)
### Standard Resistance Test Wire

<table>
<thead>
<tr>
<th>V1 Volts</th>
<th>V2 Volts</th>
<th>Temp. ºC</th>
<th>Test Wire Resistance OHMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2025</td>
<td>0.09915</td>
<td>100</td>
<td>0.3643</td>
</tr>
<tr>
<td>0.2050</td>
<td>0.09780</td>
<td>90</td>
<td>0.3549</td>
</tr>
<tr>
<td>0.2070</td>
<td>0.09640</td>
<td>80</td>
<td>0.3465</td>
</tr>
<tr>
<td>0.2091</td>
<td>0.09435</td>
<td>70</td>
<td>0.3357</td>
</tr>
<tr>
<td>0.2126</td>
<td>0.09345</td>
<td>60</td>
<td>0.3270</td>
</tr>
<tr>
<td>0.2140</td>
<td>0.09300</td>
<td>55.5</td>
<td>0.3224</td>
</tr>
<tr>
<td>0.2167</td>
<td>0.09265</td>
<td>50</td>
<td>0.3190</td>
</tr>
<tr>
<td>0.2180</td>
<td>0.09035</td>
<td>45</td>
<td>0.3083</td>
</tr>
<tr>
<td>0.2210</td>
<td>0.08875</td>
<td>40</td>
<td>0.2988</td>
</tr>
</tbody>
</table>

(\( R_s = 0.744 \) OHMS.)

**Fig. (7. ) Determination of temperature coefficient of ALUMEL wire and \( R_o \).**
where \( R_{tw} \) was wire resistance at temperature \( T_m \) \(^{\circ}\text{C}\).

\( R_0 \) was wire resistance at temperature 0 \(^{\circ}\text{C}\).

\( \alpha \) was temperature coefficient.

The temperature coefficient was determined by passing a small current (to give negligible heating) with the wire immersed in the pool filled with water at ambient temperature and then at temperatures up to the boiling point and measuring the change in resistance. The water temperature was measured using the calibrated mercury in glass thermometer. From plotting resistance against temperature the value of resistance at 0\(^{\circ}\text{C}, \ R_0, \) and at 100\(^{\circ}\text{C}, \ R_{100}, \) were found, hence from fig. (7):-

\[ R_{100} = 0.363 \text{ ohms and } R_0 = 0.2884 \text{ ohms.} \]

Substituting in:-

\[ R_{100} = R_0 \left(1 + \alpha T_m\right) \]

\[ 0.363 = 0.2884 \left(1 + 100 \alpha\right) \]

\[ \alpha = 0.002586 \]

\[ = 0.00259 \]

When other wires were fitted only one temperature/resistance calibration point was required since \( R_0 \) was given by:

\[ R_0 = \frac{R_t}{1 + \alpha T_m} \]  \hspace{1cm} (59)

To measure the wire resistance we have, see fig. (3.) for circuit diagram,

\[ \frac{V_t}{R_s} = \frac{V_2}{R_{tw}} \] \hspace{1cm} (60)

therefore:-

\[ R_{tw} = \frac{V_2}{V_1} R_s \text{ ohms} \] \hspace{1cm} (61)

The surface temperature \( T_s \) was calculated from:-

\[ T_s = T_m + \frac{Q}{A} \frac{R_4}{4} \frac{1}{k} \] \hspace{1cm} (62)

See appendix (A.) for derivation of this expression.
Surface heat flux was calculated by dividing the wire power consumption by the wire surface area between tapping wires i.e.

\[
\text{energy generated in wire} = \frac{V^2}{R_{tw}} = \frac{V_{tw} \cdot V^2}{R_s} \text{ watts}
\]

Therefore surface heat flux = \( \frac{V_{tw} \cdot V^2}{R_s} \times \frac{1}{\text{surface area of wire}} \)

\[
= \frac{V_{tw} \cdot V^2}{R_s} \times \frac{1}{\pi d l}
\]

4.3. **Repeatability of Test Results.**

MacAdams ref. (2) stresses the importance of the repeatability of tests in boiling heat transfer so that results will be accurately comparable. For this reason a great deal of attention was given initially to this aspect of the work.

The wire was prepared using the method recommended by Vos and Van Stralen ref. (46). This consisted of first annealing the wire and then keeping submerged in the pool at room temperature for at least 24 hours.

Any extraneous agitations due to the yoke ends were investigated by enclosing the test wire in a glass cylinder 9.2 cm diameter and 15 cm deep in which slots 0.2 cm wide had been cut 7.5 cm along two diametrical generators to allow the wire to pass through it. No effect was found, see fig. (8.) which shows results for water with a stationary wire and a vibration of 94 Hz and 0.0508 cm amplitude with and without the glass cylinder fitted. It appears that the flow pattern set up by the nucleate boiling completely dominates any other effects. Fig. (60.) shows the results for 42.5 wt. percent isopropyl alcohol/water using two different wires. Repeatability was considered acceptable.
4.4. Accuracy of Test Readings.

This, of course, is intimately connected with repeatability since accuracy of results can be the dominant effect in repeatability.

The mercury in glass thermometer was calibrated against a standard N.P.L. thermometer and since it was calibrated in 0.1°C intervals this was the accuracy with which the pool temperature could be read.

The length between tapping points was measured using a travelling telescope which read to 0.1 mm. However, due to the spot of solder used to retain the tapping wires, this accuracy could not be used. The length between tapping wires was 7 cm approximately and the accuracy was judged at 0.5 mm i.e. approximately 0.5 percent.

The diameter of the wire was measured using a micrometer. This measured the diameter to an accuracy of 0.00005 cm i.e. in 0.00315 cm is 2 percent approximately.

The standard resistance was measured using a commercial A.C. bridge which measured to 0.001 ohms; for the 0.784 ohms an accuracy of 0.02 percent approximately.

The measurement of voltage drop, across the standard resistance and across the test wire, was to an accuracy of 0.002 volts. This represents different accuracies at each end of the wall superheat range. It represents an error of approximately 0.8°C when the wall superheat is 5°C and 0.3°C when the wall superheat is 15°C.

4.5. Accuracy of Physical Properties.

It is very difficult to ascribe values of accuracy to the physical properties. As will be seen, the diverse range of techniques used to obtain the physical properties at the boiling points of the liquids makes estimates of accuracy impossible. It may be however that in
FIG. (9.) Response of voltage drop across test wire to step change in power output.
the correlation of the data, the inaccuracy of the physical properties completely dominates the accuracy of the factors of the correlations.

4.6. **Test Procedure.**

The liquid was brought to the boil using the three kilowatts heater. When this was reached the output of the heater was reduced using the autotransformer until the boiling temperature was just maintained. Boiling was allowed to continue for 9 hours if the liquid had just been placed in the pool, 2 hours otherwise, before testing was begun.

The test procedure proper consisted of selecting a fixed frequency and obtaining a series of boiling curves for different amplitudes set as previously indicated or by using a fixed amplitude and obtaining a series of boiling curves for various frequencies. The boiling curves were obtained by increasing and then decreasing, in small step increments of voltage, the power output from the power packs allowing the pool conditions to reach equilibrium and then taking voltage readings of the test wire and standard resistance using the digital voltmeter. It was found that the time lapse to steady readings after selecting a voltage was negligible since the wire responded instantly to the voltage change due to its small thermal inertia. See fig. (9. ) for trace of voltage drop across test wire for step change in voltage setting.

The pool temperature was taken with the mercury in glass thermometer and this thermometer was also used to monitor the pool conditions.

The barometer was also read and from this the boiling point of the liquid could be found. The difference between this calculated temperature and the measured pool temperature was the pool superheat (from 0.1 to 0.5°C).
5. PHYSICAL PROPERTIES
5. PHYSICAL PROPERTY DATA.

5.1 WATER.

All properties of water are well documented.

The sources of the data were as follows:

- liquid density: ref. (47)
- latent heat: ref. (48)
- thermal conductivity: ref. (49)
- surface tension: ref. (50)
- vapour density: ref. (48)
- specific heat: ref. (51)
- viscosity: ref. (52)

These are shown in graphical form in figs. (11) to (17).

5.2 ORGANICS.

The organics used in the tests were: methanol, toluene, carbon tetrachloride, isopropyl alcohol, normal propyl alcohol and the azeotrope of water/isopropyl alcohol. All the property data is shown in the table (13) tabulated together for easy reference.

The source of the property data is as follows:

Boiling point.

All boiling points were obtained from ref. (53) except that for isopropyl alcohol which was found in ref. (54).

Density liquid.

For methanol the expression:

\[
density = 0.80999 - 0.0009253 t + 0.00000041 t^2\]

(65)
given in ref. (55) was used.
Similarly for toluene:
\[
\text{density} = 0.88412 - 0.00092248 t + 0.0000000152 t^2
\]  \quad (66)

from ref. (55) was used.

The liquid density for isopropyl alcohol was taken from ref. (54).

For carbon tetrachloride the liquid density was calculated from:
\[
\text{density} = 1.63255 - 0.00191 t - 0.00000069 t^2
\]  \quad (67)

found in ref. (55).

Similarly for normal propyl alcohol the expression:
\[
\text{density} = 0.8201 - 0.0008183 t + 0.00000108 t^2
\]  \quad (68)
given in ref. (55) was used.

Latent heat.

The latent heats for the organics were taken from the references as follows:

methanol \quad \text{ref. (56)}
toluene \quad \text{ref. (56)}
carbon tetrachloride \quad \text{ref. (56)}
isopropyl alcohol \quad \text{ref. (56)}
normal propyl alcohol \quad \text{ref. (56)}

Thermal conductivity.

The thermal conductivity for methanol was evaluated using the expression from ref. (57):
\[
k_t = 209 \times 10^{-5} (1 - 0.00053(t - 20)).
\]  \quad (69)

Similarly for toluene from the same reference:
\[
k_t = 160 \times 10^{-5} (1 - 0.00144(t - 20)).
\]  \quad (70)

The thermal conductivity of carbon tetrachloride was obtained by linear extrapolation of two values at 20°C and 50°C obtained from ref. (49)
The thermal conductivity for isopropyl alcohol was calculated using the expression:

\[ k_t = 153 \times 10^{-5} (t - 0.00024(t - 20)) \]  

For normal propyl alcohol the data from ref. (58) was extrapolated to the boiling point.

**Surface tension.**

From data in ref. (50) the surface tension of methanol was obtained by interpolation.

Similarly the surface tension for toluene was obtained by interpolation of data from ref. (59).

Also by interpolation of data from ref. (59) the surface tension of carbon tetrachloride was obtained.

The data in ref. (60) was extrapolated to the boiling point to obtain the surface tension of isopropyl alcohol.

The value of surface tension given in ref. (50) was used for normal propyl alcohol.

**Viscosity.**

The data of ref. (62) was extrapolated to the boiling point to obtain the viscosity of methanol.

The viscosity of toluene was taken from ref. (63), as was the value for carbon tetrachloride and normal propyl alcohol.

The viscosity of isopropyl alcohol was found in ref. (64).

**Specific heat.**

The specific heat for methanol was obtained by extrapolation of three data points at 0, 20 and 40°C given in ref. (51).
Similarly three data points at 0, 50 and 100°C for toluene given in ref. (66) were extrapolated to the boiling point.

The data for the specific heat given in ref. (59) for carbon tetrachloride were extrapolated to obtain the value at the boiling point.

The specific heat for isopropyl alcohol and normal propyl alcohol were taken from ref. (67).

**Vapour density.**

All vapour densities were calculated using the perfect gas law i.e.

$$\text{vapour density} = \frac{\text{Mole. wt.}}{359} \left(\frac{273}{\text{Dew temp.}}\right)$$

The properties for ethanol, n-heptane and benzene were taken from ref. (41).

5.3. **BINARY MIXTURES.**

5.3.1. **ISOPROPYL ALCOHOL/WATER**

Properties at the boiling point versus liquid composition are shown in fig. (18.) to (26.).

**Boiling point and dew point.**

These were obtained from ref. (60).

**Liquid density.**

These were obtained from ref. (69).
Latent heat.

Latent heat of binary mixture was calculated from the following relationship:

\[(h_{fg})_m = (h_{fg})_w(y_w) + (h_{fg})_i(y_i)\]  

(73)

\((h_{fg})_m\) is latent heat of mixture at its boiling point.
\((h_{fg})_w\) is latent heat of water at mixture boiling point.
\((h_{fg})_i\) is latent heat of IPA at mixture boiling point.
\(y_w\) is weight fraction of water in the vapour mixture.
\(y_i\) is weight fraction of IPA in the vapour mixture.

TABLE. (3) Latent heat of isopropyl alcohol/water versus liquid composition.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % IPA</th>
<th>VAPOUR COMPOSITION WT. % IPA</th>
<th>LATENT HEAT Btu/lb. J/kg (\times 10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>972</td>
</tr>
<tr>
<td>10</td>
<td>70</td>
<td>500</td>
</tr>
<tr>
<td>20</td>
<td>76</td>
<td>459</td>
</tr>
<tr>
<td>30</td>
<td>78</td>
<td>446</td>
</tr>
<tr>
<td>40</td>
<td>79</td>
<td>439</td>
</tr>
<tr>
<td>50</td>
<td>79.5</td>
<td>435</td>
</tr>
<tr>
<td>60</td>
<td>80.5</td>
<td>428</td>
</tr>
<tr>
<td>70</td>
<td>82</td>
<td>417</td>
</tr>
<tr>
<td>80</td>
<td>84</td>
<td>403</td>
</tr>
<tr>
<td>90</td>
<td>89</td>
<td>368</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>294</td>
</tr>
</tbody>
</table>

Subsequently results were found in the literature ref. (72). They agreed with these calculations within acceptable limits.

Thermal conductivity.

This was obtained by extrapolation of the data of ref. (58) from 0 to 80°C to the boiling point.

Surface tension.

These were taken from ref. (70).

Viscosity.

These set of data were taken from ref. (69).
Specific heat.

This was taken from ref. (71) where the temperature range 18 – 100°C is stated. The results are shown in table (4).

TABLE (4) Specific heat versus composition for isopropyl alcohol/water.

<table>
<thead>
<tr>
<th>COMPOSITION</th>
<th>SPECIFIC HEAT</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT. % IPA</td>
<td>BTU/lb.°F</td>
</tr>
<tr>
<td>100</td>
<td>0.7233</td>
</tr>
<tr>
<td>89.66</td>
<td>0.7749</td>
</tr>
<tr>
<td>80.01</td>
<td>0.8184</td>
</tr>
<tr>
<td>70.08</td>
<td>0.8695</td>
</tr>
<tr>
<td>59.94</td>
<td>0.9189</td>
</tr>
<tr>
<td>49.97</td>
<td>0.9594</td>
</tr>
<tr>
<td>39.95</td>
<td>0.9996</td>
</tr>
<tr>
<td>30.00</td>
<td>1.0278</td>
</tr>
<tr>
<td>19.99</td>
<td>1.0525</td>
</tr>
<tr>
<td>10.00</td>
<td>1.0325</td>
</tr>
<tr>
<td>0</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Vapour density.

This was calculated using the perfect gas law by first estimating a mean molecular weight using the expression:

\[
\text{Mole. wt. mean} = \frac{x}{60.09} + \frac{100 - x}{18}
\]

where \( x \) is the weight percent composition of liquid hence:

\[
\text{vapour density} = \frac{\text{M.W}}{359} \times \frac{273}{\text{dew temp.}°K}
\]

where the dew temperature is that of the vapour in equilibrium with liquid mixture.

The results are shown in table (5).
TABLE (5) Vapour density versus liquid composition for isopropyl alcohol/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % IPA</th>
<th>VAPOUR COMPOSITION WT. % IPA</th>
<th>VAPOUR DENSITY lb/ft³ Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0366 0.586</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>0.0395 0.633</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>0.0429 0.688</td>
</tr>
<tr>
<td>5</td>
<td>42.5</td>
<td>0.0530 0.850</td>
</tr>
<tr>
<td>7</td>
<td>54</td>
<td>0.0602 0.965</td>
</tr>
<tr>
<td>11</td>
<td>65</td>
<td>0.0696 1.115</td>
</tr>
<tr>
<td>25</td>
<td>74</td>
<td>0.0795 1.265</td>
</tr>
<tr>
<td>54</td>
<td>78</td>
<td>0.0853 1.366</td>
</tr>
<tr>
<td>80</td>
<td>82</td>
<td>0.0910 1.455</td>
</tr>
<tr>
<td>87.7</td>
<td>87.7</td>
<td>0.1005 1.605</td>
</tr>
<tr>
<td>90</td>
<td>89</td>
<td>0.1030 1.650</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0.1285 2.060</td>
</tr>
</tbody>
</table>

Mass diffusivity.

This was taken from ref. (69) at 25°C and then calculated at the boiling point using the Stokes – Einstein equation:

$$\frac{D \mu}{T} = \text{const.}$$

The results are shown in table (6).

TABLE (6) Mass diffusivity versus composition for isopropyl alcohol/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % IPA</th>
<th>MASS DIFFUSIVITY cm²/sec x 10⁵</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4.645</td>
</tr>
<tr>
<td>7.29</td>
<td>4.475</td>
</tr>
<tr>
<td>16.25</td>
<td>3.419</td>
</tr>
<tr>
<td>28.20</td>
<td>2.450</td>
</tr>
<tr>
<td>44.10</td>
<td>1.368</td>
</tr>
<tr>
<td>61.15</td>
<td>1.263</td>
</tr>
<tr>
<td>73.40</td>
<td>1.625</td>
</tr>
<tr>
<td>82.35</td>
<td>2.052</td>
</tr>
<tr>
<td>100</td>
<td>3.058</td>
</tr>
</tbody>
</table>

5.3.2 WATER/GLYCEROL

Properties versus liquid composition at the boiling point are shown in figs. (27.) to (35.).
All properties were found in ref. (73) such that extrapolation to the boiling point was the only technique required. The exceptions were vapour density, mass diffusivity and latent heat.

Vapour density.

This was calculated in a like manner to isopropyl alcohol/water. The results are shown in table (7).

**TABLE. (7) Vapour density versus liquid composition for glycerol/water.**

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION</th>
<th>VAPOUR COMPOSITION</th>
<th>VAPOUR DENSITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT. % GLYCEROL</td>
<td>WT. % GLYCEROL</td>
<td>lb/ft.³</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0.0367</td>
</tr>
<tr>
<td>92.5</td>
<td>2</td>
<td>0.0332</td>
</tr>
<tr>
<td>95.0</td>
<td>5</td>
<td>0.0328</td>
</tr>
<tr>
<td>96.0</td>
<td>10</td>
<td>0.0329</td>
</tr>
<tr>
<td>96.3</td>
<td>20</td>
<td>0.0348</td>
</tr>
<tr>
<td>96.8</td>
<td>30</td>
<td>0.0378</td>
</tr>
<tr>
<td>97.1</td>
<td>40</td>
<td>0.0410</td>
</tr>
<tr>
<td>97.5</td>
<td>50</td>
<td>0.0453</td>
</tr>
<tr>
<td>98.0</td>
<td>60</td>
<td>0.0511</td>
</tr>
<tr>
<td>98.2</td>
<td>70</td>
<td>0.0594</td>
</tr>
<tr>
<td>98.7</td>
<td>80</td>
<td>0.0711</td>
</tr>
<tr>
<td>99.2</td>
<td>90</td>
<td>0.0895</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0.1241</td>
</tr>
</tbody>
</table>

Mass diffusivity.

The values at 20°C were found in ref. (74). The values at the boiling point were calculated using the Stokes - Einstein equation similarly to isopropyl alcohol/water. The results are shown in table (8).

**TABLE. (8) Mass diffusivity versus liquid composition for glycerol/water.**

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION</th>
<th>MASS DIFFUSIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT. % GLYCEROL</td>
<td>cm²/sec x 10⁶</td>
</tr>
<tr>
<td>0</td>
<td>36.6</td>
</tr>
<tr>
<td>20</td>
<td>32.0</td>
</tr>
<tr>
<td>40</td>
<td>30.3</td>
</tr>
<tr>
<td>60</td>
<td>29.8</td>
</tr>
<tr>
<td>80</td>
<td>39.2</td>
</tr>
<tr>
<td>100</td>
<td>83.2</td>
</tr>
</tbody>
</table>
Latent heat.

This was calculated in a similar way to IPA/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION</th>
<th>VAPOUR COMPOSITION</th>
<th>LATENT HEAT J/Kg x 10^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT. % GLYCOL</td>
<td>WT. % GLYCOL</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>2257</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>2250</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>2244</td>
</tr>
<tr>
<td>60</td>
<td>0.05</td>
<td>2228</td>
</tr>
<tr>
<td>80</td>
<td>0.05</td>
<td>2195</td>
</tr>
<tr>
<td>90</td>
<td>1.20</td>
<td>2121</td>
</tr>
<tr>
<td>95</td>
<td>8.00</td>
<td>1933</td>
</tr>
<tr>
<td>100</td>
<td>100.00</td>
<td>390</td>
</tr>
</tbody>
</table>

5.3.3. WATER/ETHYLENE GLYCOL.

Properties at the boiling point versus liquid composition are shown in figs. (36.) to (44.). Most properties were found in ref. (75) such that extrapolation to the boiling point was the only technique required. The exceptions were boiling and dew temperatures, liquid density, mass diffusivity, latent heat, surface tension and vapour density.

Boiling and dew temperatures.

These were taken from ref. (76).

Liquid density.

This was taken from ref. (76).

Mass diffusivity.

The values at 20°C were found in ref. (74) and extended to the boiling point using the Stokes - Einstein equation. The results are shown in table (9).

TABLE. (9) Mass diffusivity versus liquid composition for ethylene glycol/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION</th>
<th>MASS DIFFUSIVITY cm^2/sec x 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT. % GLYCOL</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>48.2</td>
</tr>
<tr>
<td>20</td>
<td>43.8</td>
</tr>
<tr>
<td>40</td>
<td>39.4</td>
</tr>
<tr>
<td>60</td>
<td>36.0</td>
</tr>
<tr>
<td>80</td>
<td>41.7</td>
</tr>
<tr>
<td>100</td>
<td>101.0</td>
</tr>
</tbody>
</table>
Latent heat.

This was calculated in a similar manner to isopropyl alcohol/water, the results are shown in table (10).

TABLE. (10) Latent heat versus liquid composition for ethylene glycol/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % GLYCOL</th>
<th>VAPOUR COMPOSITION WT. % GLYCOL</th>
<th>LATENT HEAT calories/gm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>540.0</td>
</tr>
<tr>
<td>70.5</td>
<td>5</td>
<td>516.8</td>
</tr>
<tr>
<td>80.0</td>
<td>10</td>
<td>469.0</td>
</tr>
<tr>
<td>88.5</td>
<td>20</td>
<td>467.8</td>
</tr>
<tr>
<td>94.3</td>
<td>40</td>
<td>420.6</td>
</tr>
<tr>
<td>97.0</td>
<td>60</td>
<td>330.2</td>
</tr>
<tr>
<td>99.0</td>
<td>80</td>
<td>257.4</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>191.0</td>
</tr>
</tbody>
</table>

Vapour density.

This was calculated using the same method as for isopropyl alcohol/water. The results are shown in table (11).

TABLE. (11) Vapour density versus liquid composition for ethylene glycol/water.

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % GLYCOL</th>
<th>VAPOUR COMPOSITION WT. % GLYCOL</th>
<th>VAPOUR DENSITY lb/ft.² Kg/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0367 0.588</td>
</tr>
<tr>
<td>80</td>
<td>10</td>
<td>0.0370 0.593</td>
</tr>
<tr>
<td>88.5</td>
<td>20</td>
<td>0.0391 0.626</td>
</tr>
<tr>
<td>92</td>
<td>30</td>
<td>0.0414 0.663</td>
</tr>
<tr>
<td>94.2</td>
<td>40</td>
<td>0.0452 0.725</td>
</tr>
<tr>
<td>96</td>
<td>50</td>
<td>0.0490 0.785</td>
</tr>
<tr>
<td>97.4</td>
<td>60</td>
<td>0.0540 0.855</td>
</tr>
<tr>
<td>98.4</td>
<td>70</td>
<td>0.0607 0.972</td>
</tr>
<tr>
<td>99</td>
<td>80</td>
<td>0.0696 1.115</td>
</tr>
<tr>
<td>99.5</td>
<td>90</td>
<td>0.0820 1.315</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0.1001 1.610</td>
</tr>
</tbody>
</table>

Surface tension.

The values at the boiling point were measured using the method of ref. (77). This consists of measuring the excess pressure difference, when nitrogen is bubbled through the boiling liquid mixture, as bubbles
detach from the end of a fine tube (diameter 0.1306 cm) and a capillary tube immersed in the liquid and comparing the excess pressure difference with a standard liquid whose surface tension is known. The empirical equation used is:

$$\frac{A\rho g (h_1 - h_2)}{1 + 0.69 \frac{r_2 D}{h_1 - h_2}}$$

(77)

where A is constant determined using standard liquid

- $h_1 - h_2$ is excess pressure difference
- $r_2$ is radius of fine tube
- $\rho$ is density of manometer liquid
- $D$ is density of liquid under test.

The results are shown in table (12).

**TABLE. (12) Surface tension versus liquid composition for ethylene glycol/water.**

<table>
<thead>
<tr>
<th>LIQUID COMPOSITION WT. % GLYCOL</th>
<th>SURFACE TENSION dynes/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>58.5</td>
</tr>
<tr>
<td>26</td>
<td>47.7</td>
</tr>
<tr>
<td>51</td>
<td>44.6</td>
</tr>
<tr>
<td>76</td>
<td>40.4</td>
</tr>
<tr>
<td>100</td>
<td>35.0</td>
</tr>
<tr>
<td></td>
<td>SPECIFIC HEAT</td>
</tr>
<tr>
<td>------------------</td>
<td>---------------</td>
</tr>
<tr>
<td></td>
<td>J/Kg (^o)C</td>
</tr>
<tr>
<td>TOLUENE</td>
<td>2.011</td>
</tr>
<tr>
<td>CARBON TETRACHLORIDE</td>
<td>0.934</td>
</tr>
<tr>
<td>METHYL ALCOHOL</td>
<td>2.694</td>
</tr>
<tr>
<td>N PROPYL ALCOHOL</td>
<td>3.193</td>
</tr>
<tr>
<td>I PROPYL ALCOHOL</td>
<td>3.038</td>
</tr>
<tr>
<td>IPA/WATER AZEBOTROPE</td>
<td>3.268</td>
</tr>
<tr>
<td>WATER</td>
<td>4.190</td>
</tr>
<tr>
<td>ETHYL ALCOHOL</td>
<td>3.063</td>
</tr>
<tr>
<td>N HEPTANE</td>
<td>2.619</td>
</tr>
<tr>
<td>BENZENE</td>
<td>1.944</td>
</tr>
</tbody>
</table>

Table (13) Physical properties of liquids at their respective boiling points.
FIG. (11.)

WATER VISCOSITY

REF. (52)
FIG. (12.)

WATER

LATENT HEAT

REF. (48)
FIG. (13.)
WATER
SURFACE TENSION
REF. (50)
FIG. (14a)

WATER

LIQUID DENSITY

REF. (47)
FIG. (15.)
WATER
SPECIFIC HEAT
REF. (51)
FIG. (16.)
WATER
THERMAL CONDUCTIVITY
REF. (49)
FIG. (17)

WATER

VAPOUR DENSITY

REF. (48)
FIG. (18.)
IPA/WATER
THERMAL CONDUCTIVITY
REF. (49)
FIG. (19.)
IPA/WATER
SPECIFIC HEAT
REF. (71)
The latent heat shown on the ordinate is that of the mixture of the composition which is in equilibrium with liquid shown on the abscissa.

Figure (20)
IPA/WATER
LATENT HEAT
CALCULATED
FIG. (24.)

IPA/WATER

SURFACE TENSION

REF. (70)
**FIG. (25.)**

IPA/WATER

MASS DIFFUSIVITY

REF. (69)
FIG. (26.)

IPA/WATER

BOILING POINT TEMPERATURE
CONDENSATION (DEW) TEMPERATURE

REF. (60)
The latent heat shown on the ordinate is that of the mixture of the composition which is in equilibrium with liquid shown on the abscissa.

FIG. (27.)

GLYCEROL/WATER
LATENT HEAT
CALCULATED
FIG. (28.)

GLYCEROL/WATER

BOILING POINT TEMPERATURE
CONDENSATION (Dew) TEMPERATURE

REF. (73)
FIG. (29)
GLYCEROL/WATER
MASS DIFFUSIVITY
REF. (74)
FIG. (30.)
GLYCEROL/WATER
SURFACE TENSION
REF. (73)
FIG. (31.)
GLYCEROL/WATER
VISCOITY
REF. (73)
FIG. (32.)

GLYCEROL/WATER

DENSITY OF VAPOUR IN EQUILIBRIUM WITH LIQUID CALCULATED

The vapour density shown on the ordinate is that of the mixture of the composition which is in equilibrium with liquid shown on the abscissa.
FIG. (33.)
GLYCEROL/WATER
LIQUID DENSITY
REF. (73)
FIG. (34.)
GLYCEROL/WATER
THERMAL CONDUCTIVITY
REF. (73)
FIG. (35)
GLYCEROL/WATER
SPECIFIC HEAT
REF. (73)
FIG. (36.)
GLYCOL/WATER
MASS DIFFUSIVITY
CALCULATED
FIG. (37.)

GLYCOL/WATER

VISCOITY

REF. (75)
FIG. (38.)
GLYCOL/WATER
LIQUID DENSITY
REF. (76)
FIG. (39.)
GLYCOL/WATER
SURFACE TENSION
EXPERIMENTAL
FIG. (40.)

GLYCOL/WATER

BOILING POINT TEMPERATURE

CONDENSATION (DEF) TEMPERATURE

REF. (76)
FIG. (41.)

GLYCOL/WATER

DENSITY OF VAPOUR IN EQUILIBRIUM WITH LIQUID CALCULATED

The vapour density shown on the ordinate is that of the mixture of the composition which is in equilibrium with liquid shown on the abscissa.
FIG. (42.)
GLYCOL/WATER
THERMAL CONDUCTIVITY
REF. (75)
The latent heat shown on the ordinate is that of the mixture of the composition which is in equilibrium with liquid shown on the abscissa.

FIG. (43.)
GLYCOL/WATER
LATENT HEAT
CALCULATED
FIG. (44.)
GLYCOL/WATER
SPECIFIC HEAT
REF. (75)
6. EXPERIMENTAL RESULTS
6. **EXPERIMENTAL RESULTS.**

6.1. **Experimental Programme.**

Because of the lack of data in the published literature covering amplitudes which gave large amplitude to wire diameter ratios, it was decided that the amplitudes used in the present investigation should cover this range. Since the test wire diameter was 0.0315 cm, amplitudes up to 0.203 cm were used which gave a maximum amplitude to wire diameter ratio of seven approximately. The power output from the vibrator used to produce the vibrations was limited to 1 kilowatt, this together with the maximum amplitude fixed the maximum frequency which could be obtained at 124 Hz. Table (14) shows the range of amplitude and frequencies used in the testing, it also lists the wire acceleration associated with them in terms of earth gravitational acceleration i.e. 'G' values.

Table (14) Range of vibrational parameters.

<table>
<thead>
<tr>
<th>Amplitude cm</th>
<th>0.0127</th>
<th>0.0254</th>
<th>0.0508</th>
<th>0.1016</th>
<th>0.1524</th>
<th>0.2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Hz</td>
<td>24</td>
<td>0.147</td>
<td>0.295</td>
<td>0.589</td>
<td>1.034</td>
<td>1.768</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>0.495</td>
<td>0.990</td>
<td>1.980</td>
<td>3.965</td>
<td>5.942</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>1.047</td>
<td>2.095</td>
<td>4.190</td>
<td>7.333</td>
<td>12.571</td>
</tr>
<tr>
<td></td>
<td>84</td>
<td>1.804</td>
<td>3.609</td>
<td>7.218</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>94</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>104</td>
<td>2.766</td>
<td>5.532</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>114</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>124</td>
<td>3.930</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Initially water was used as the test liquid. The tests were then extended to pure organic liquids and finally to binary mixtures. The pure organic liquids were: toluene, methanol, carbon tetrachloride, normal propanol, isopropanol, and the azeotrope of isopropanol/water. The binary mixtures were of isopropanol/water.
As the test programme progressed the number of vibration tests were reduced since it was found that vibration appeared to have little effect on heat transfer in the nucleate boiling region. In fact for the binary mixtures only tests with the stationary wire and one with vibrating wire at 0.203 cm amplitude and 64 Hz frequency to give maximum 'G' value of the test programme, were carried out.

The boiling curves obtained were stopped at the onset of film boiling. Physical wire burnout would have resulted if continued since there was no safety switch available to prevent it. The test wire diameter was decided by the D.C. power available so as to reach the onset of film boiling for all the liquids tested.

A limited number of high speed photographs was taken to help explain the results obtained.

6.2 Some Visual Observations.

Water.

The onset of nucleation occurred when one or two sites for bubble production became active. As the heat flux increased the number of nucleating sites increased. These sites were randomly scattered over the surface of the wire, see fig. (47). With further increase in heat flux the number of sites still further increased until the whole of the surface was covered with bubble producing nuclei. The distribution of the nucleating sites became fairly uniformly spread over the surface. Finally any further increase in heat flux caused adjoining bubbles to coalesce indicating the onset of film boiling, when the wire became incandescent and finally melted.

If the heat flux was not increased to burnout stage then it was possible to reduce it back to the convective region. As the heat flux was reduced the number of active sites was reduced, again in a random
manner, over the wire surface. The behaviour of the nucleating sites was roughly the same as in the case of increasing heat flux but in the reversed order. When the heat flux was further reduced the number of sites for bubble production became even less until there were only two or three sites on the wire producing bubbles and these finally stopped. It was seen that occasionally small diameter bubbles were ejected downwards, see fig. (50).

With vibration of the wire, the distribution of nuclei followed a similar pattern to the stationary wire, see fig. (48), except that a much higher heat flux was necessary before the first sites became active. Also the rate at which sites became active for a constant increase in heat flux was greater so that the heat flux at which the first bubbles began to coalesce was of the same value as the stationary wire. The bubbles leaving the vibrating surface rose through the water so that the vibrating wire at its highest frequency and largest amplitude recaptured a bubble only occasionally. A similar pattern occurred in reverse when the heat flux was reduced. However with the vibrating wire the bubble diameter was slightly smaller also the frequency of bubble emission slightly increased. The exception to this was when a bubble was recaptured by the vibrating wire and continued to grow becoming even larger than the bubble leaving the stationary wire.

**Pure Organic Liquids.**

For pure organic liquids with a stationary surface large temperature excursions into the convective region were obtained before the onset of nucleation. However, when nucleation did occur, unlike water where just one or two sites appeared, the whole of the wire gradually became covered with sites producing bubbles. This spread of bubbles took a finite time, as much as five minutes occurred before the wire was
completely covered, without altering the heat flux to accomplish it. The density of sites increased with increasing heat flux until the onset of film boiling occurred. If the heat flux was then reduced the density of sites reduced in a similar manner to water until finally nucleation stopped. This was at a much lower value of heat flux than with the onset of nucleation.

The visual picture was the same when the wire was vibrated. It was observed that the rise velocity of organic bubbles, which were much smaller in diameter than water bubbles (due to their lower surface tension?) by a factor 4 to 5, was also very slow to rise away from the wire so that the wire appeared to vibrate in an 'atmosphere' of vapour bubbles. It was observed on high speed photographs, see figs. (45, ) and (46,) that the wire starting from the line of its lowest position had risen to its highest position and had returned some 3/4 of its amplitude before it met the line of bubbles, left at its lowest position, rising through the liquid i.e. for some 7/8 of its vibration, it was in an 'atmosphere' of vapour bubbles. It was also seen from the photography that a large number of bubbles were 'recaptured' and continued to grow so that the bubbles above the wire were on average larger than those below. This 'recapturing' of bubbles led to coalescence with bubbles forming on the wire and partial vapour blanketing of the heat transfer surface. This could account for the fact that no increase and in some cases a decrease in heat transfer occurred when the wire was vibrated in pure organic liquids.

**Isopropyl Alcohol/water Mixtures.**

It was observed with the IPA/water binary mixtures that the bubble formation changed from the picture given for water to that for organics as the concentration of IPA was increased. This is also seen
in the heat transfer curves where there is a steady loss of the increase due to vibration in water as a concentration of IPA is increased.

6.3. Brief Description of Results.

Basic results for all the experimental runs listed in tables (15) to (164).

Water.

The effect of vibration was such that heat transfer was improved, both with increasing amplitude and increasing frequency but only over a particular range of heat flux, see figs. (51.) and (52.). The maximum increase was at the end of the convective region / beginning of the nucleate boiling region; with further increase in heat flux up to the onset of film boiling the improvement diminished. This is shown in fig. (52.).

With small amplitudes only small improvements occurred even for large changes in frequency, see fig. (53.). However the reverse was not the case, with a large amplitude the increase in heat transfer was quite substantial even with low frequencies, see fig. (54.). This indicated that amplitude (relative to wire diameter?) was the more important variable in vibration.

The increase in heat transfer appears to be in the convective region and that vibration delays the onset of nucleation which does not start until a certain temperature difference (5.5°C approximately) is reached and that once nucleation starts the improvement diminishes with increasing heat flux. That is, as the number of nucleation sites increase the effect of vibration in removing heat by improving convection is completely obliterated by the agitation of bubbles leaving the surface. The turbulence caused by the departing bubbles completely dominates heat transfer! It also appears that while the bubbles are spaced widely apart
on the wire, the drag forces on them caused by the vibration makes the bubble leave the surface earlier i.e. at a smaller diameter and therefore at a higher frequency but once the bubbles begin to touch each other, they shield one another and then vibration has not the same effect, see fig. (50).

The onset of nucleation, as previously noted, was at a wall superheat of 5.5°C approximately and appeared independent of vibration. This would appear to substantiate the fact that the start of nucleation is temperature controlled and independent of heat flux.

Pure Organic Liquids.

The organics tested all behaved in a similar manner but differently to water. No improvement in heat transfer occurred due to vibration except in the convective region which was considerably extended with increasing heat flux compared with decreasing heat flux, see fig. (55). In fact for some conditions there appears to be a slight decrease in heat transfer in the nucleate boiling region. An explanation for this strange phenomenon has been given already. Another point worth mentioning is that if there is a boundary layer formed around the wire when it vibrates, then for the organics the drag force on a bubble will be considerably less than that on a water bubble under similar conditions because a greater percentage of the organic bubble will lie within the boundary layer due to its smaller diameter.

Isopropyl Alcohol/Water Mixtures.

With vibration similar results to the pure organics were obtained at high concentrations of isopropyl alcohol; that is vibration did not improve heat transfer. As the percentage of IPA decreased the effect of vibration increased until the result for water was reached, see figs. (57) to (65).
Some limited data for maximum heat flux was obtained for the stationary wire. This is shown in fig. (66.) plotted against concentration. It will be seen that at low concentrations of IPA the onset of film boiling was delayed such that the maximum heat flux at these low concentrations (10 to 40 wt. percent IPA range) was two to three times the maximum heat flux for pure water. This is similar to the results reported by Van Stralen ref. (16). With the onset of film boiling much larger bubbles appeared, see fig. (49.). These were typical of all organics tested.
Fig. (45.) IPA, 0.203 cm amplitude, 64 Hz frequency, heat flux 345,000 W/m². Descending wire meeting lowest line of rising bubbles. Lines A and B highest and lowest position respectively of vibration.

Fig. (46.) IPA/water azeotrope, 0.203 cm amplitude, 64 Hz frequency, heat flux 116,000 W/m². Descending wire meeting lowest line of rising bubbles. Lines A and B highest and lowest position respectively of vibration.
Fig. (47.) Water, stationary wire, heat flux 113,000 W/m²

Fig. (48.) Water, 0.203 cm amplitude, 44 Hz frequency, heat flux 113,000 W/m²
Fig. (50.) Water, stationary wire, 
heat flux 515,000 W/m$^2$

Fig. (49.) IPA/water azeotrope, stationary 
wire, heat flux 345,000 W/m$^2$, 
showing partial film boiling.
FIG. 51(1)
WATER
FREQUENCY 64 Hz.
AMPLITUDE

- O cm
- 0.0127 ▽
- 0.0254 ×
- 0.0503 ●
- 0.1016 △
- 0.1524 +
- 0.2032 □

WALL SUPERHEAT ΔT °K
0 5.0 10.0 15.0 20.0 25.0

Heat Flux Q/A
- 0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0

$\frac{w^2}{2} \times 10^{-5}$
FIG. (52.)
WATER
AMPLITUDE 0.0508 cm
FREQUENCY 0 Hz
24  o  
44  x  
64  o  
84  △  
94  +  

\[ \frac{Q/A}{n_h x 10^{-5}} \]

HEAT FLUX

WALL SUPERHEAT \( \Delta T \)

0 5.0 10.0 15.0 20.0 25.0
FIG. (54)
WATER
FREQUENCY 24 Hz.
AMPLITUDE
0 cm. 0
0.0254 ▼
0.0508 X
0.1016 ●
0.1524 △
0.2032 +
Fig. (55.)

METHANOL

- NO VIBRATION
- Δ 64 Hz 0.103 cm.
- × 64 Hz 0.206 cm.

--- Excursion into convective region.
Fig. (56.)

TOLUENE

- NO VIBRATION
- 94 Hz. 0.0503 cm.
+ 64 Hz. 0.0503 cm.
Fig. (57.)

IPA/WATER 0 WT. PERCENT

- NO VIBRATION

- 64 Hz, 0.205 cm.
Fig. (58.)

IPA/WATER 10 WT. PERCENT

× NO VIBRATION
○ 64 Hz. 0.205 cm.

\[ \frac{Q}{A} = \frac{W}{A} \times 10^{-5} \]

WALL SUPERHEAT \( \Delta T \)

\[ 0 \quad 10 \quad 20 \quad 30 \quad 40 \quad 50 \]

108
Fig. (59.)
IPA/WATER 20 WT. PERCENT

× NO VIBRATION

○ 64 Hz, 0.205 cm.
Fig. (61,)

IPA/WATER 54 WT. PERCENT

× NO VIBRATION
○ 64 Hz. 0.205 cm.
Fig. (62.)
IPA/WATER 65 WT. PERCENT
× NO VIBRATION
○ 64 Hz. 0.205 cm.

HEAT FLUX $Q/A \times 10^{-5}$

WALL SUPERHEAT $\Delta T$ °K

0 10 20 30 40 50
Fig. (64.)

IPA/WATER 87.7 WT. PERCENT

* NO VIBRATION
  - 64 Hz. 0.205 cm.

Heat Flux $q/A$ vs. Wall Superheat $\Delta T$
Fig. (65.)

IPA/WATER 100 WT. PERCENT

x NO VIBRATION

○ 64 Hrs. 0.205 cm.
Fig. (66). IPA/WATER SYSTEM.

MAX. HEAT FLUX AS FUNCTION OF COMPOSITION.
BASIC DATA.

IPA/WATER MIXTURES.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Units</th>
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<tbody>
<tr>
<td>G</td>
<td>Ratio of Wire to Gravitational Acceleration</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Amplitude</td>
<td>m</td>
</tr>
<tr>
<td>F</td>
<td>Frequency</td>
<td>Hz</td>
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<tr>
<td>AF</td>
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<tr>
<td>GM</td>
<td>Acceleration of Wire</td>
<td>m/s²</td>
</tr>
<tr>
<td>V1</td>
<td>Volts Standard Resistance</td>
<td>volts</td>
</tr>
<tr>
<td>V2</td>
<td>Volts Test Wire</td>
<td>volts</td>
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<tr>
<td>Δt</td>
<td>Surface Superheat</td>
<td>°C</td>
</tr>
<tr>
<td>Q/A</td>
<td>Heat Flux</td>
<td>W/m²</td>
</tr>
</tbody>
</table>

Table(15) to (20) First wire length
- Diameter: 0.0715 m
- Resistance: 0.000315 m
- Heat Flux: 0.2618 ohms.

Table(21) to (28) Second wire length
- Diameter: 0.0722 m
- Resistance: 0.000315 m
- Heat Flux: 0.256 ohms.

Table(29) to (164) First wire length
- Diameter: 0.0715 m
- Resistance: 0.000315 m
- Heat Flux: 0.2618 ohms.
### TABLE C

<table>
<thead>
<tr>
<th>GTA/WATER</th>
<th>WT. PERCENT</th>
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</thead>
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<td>0.00</td>
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<td>V1</td>
<td>V2</td>
</tr>
<tr>
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<td>0.249</td>
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<tr>
<td>0.605</td>
<td>0.249</td>
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<td>0.704</td>
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<td>3.076</td>
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ISO PROPYL ALCOHOL

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**Note:**

- G, A, F, AF, GM denote the respective values.
- V1, V2, DT, Q/A represent other parameters.

**Legend:**

- IPA: Isopropyl Alcohol
- WATER: Water
- AZEOTROPE: Azeotrope
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IPA/WATER AZEOTROPE
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CARBON TETRACHLORIDE

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BASIC DATA.

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WATER.
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B.P.A.  BOILING POINT FROM VAPOUR PRESSURE  °C
B.P.M.  BOILING POINT MEASURED  $T_s$  °C
G.  RATIO OF WIRE TO GRAVITATIONAL ACCELERATION
F  FREQUENCY  $f$  Hz
A  AMPLITUDE  $a$  cm
AF  FREQUENCY X AMPLITUDE  $af$  cm/sec
GM  ACCELERATION OF WIRE  $g_m$  m/sec$^2$
FR  FROUDE NUMBER  $2af/\sqrt{g_m}$
Z  $(g_m/g + 2af/\sqrt{g_m})^{1/2}$
V1  VOLTS STANDARD RESISTANCE  volts
V2  VOLTS TEST WIRE  volts
TF  MEAN FILM TEMPERATURE  $(T_w + T_s)/2$  °C
DT  SURFACE SUPERHEAT  $\Delta t = T_w - T_s$  °C
Q/A  HEAT FLUX  $w/m^2$
FR  FRIEDEL NUMBER  $C_p h/k$
DB  $(\sigma/g_m(\rho_L - \rho_v))^{1/2}$
X  $C_p \Delta t/h_{fg}Pr$
Y  $\frac{Q/A}{\rho_A(\sigma/g_m(\rho_L - \rho_v))^{1/2}} (g_m/g + 2af/\sqrt{g_m})^{1/2}$
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NANGIA AND CHON  FIG. 3

REF. (29)

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7. CORRELATION AND DISCUSSION OF RESULTS
7. **CORRELATION AND DISCUSSION OF RESULTS.**

All processed results are listed in tables (131) to (246).

7.1. **Correlation of vibration results for water.**

Since the properties of water are well documented, it was possible to evaluate them at a mean film temperature defined as:

\[ \text{Mean film temperature } = \frac{(T_w + T_s)}{2} \quad (78) \]

It was thought intuitively that the correlation of the results would be possible using a modification, to include the effects of vibration, of one of the well known correlations used for a stationary wire. Rohsenow's correlation ref. (3) was chosen for this purpose.

Using the physical picture as a guide, the data was correlated in the following manner.

The bubble diameter at breakaway \( d_b \) used by Rohsenow is given as:

\[ d_b = C \left( \frac{\sigma}{g(\rho_L - \rho_v)} \right)^{1/2} \quad (79) \]

This expression, developed by Fritz ref. (4) was modified to:

\[ d_b = C \left( \frac{\sigma}{g'_m(\rho_L - \rho_v)} \right)^{1/2} \quad (80) \]

so as to represent the smaller diameter bubbles observed leaving the surface. \( g'_m \) is defined as:

\[ g'_m = \frac{(|g'| + g' - |g'| - g)}/2 \]

\[ = g' \text{ for } g' > g \]
\[ = g \text{ for } g' < g \quad (81) \]

where \( g' \) is the wire vibrational acceleration given by:

\[ g' = 2\pi^2 a f^2 \quad (82) \]

To describe the increased frequency of bubble emission and other hydrodynamic effects a term was appended to the Reynolds number which was appropriate to vibration, to include \( g'_m/g \) and \( \sqrt{(g'd)^3} \) where
v is the vibrational velocity defined as:
\[ v = 2 \alpha f \]
so that the Reynolds number becomes:
\[ \text{Re} = \frac{Q/\dot{A}}{h_{fg} / \mu} \left( \sigma / \gamma_m (\rho_L - \rho_v) \right)^{\frac{1}{2}} \left( g''_m / g + 2\alpha f / (g d)^{\frac{1}{2}} \right)^{\frac{1}{4}} \]

With this modification it will be appreciated that for the stationary wire the correlation assumes Rohsenow's original form. The exponent \( \frac{1}{4} \) was obtained as the best fit to the data.

A plot of:
\[ C_p \Delta T / h_{fg} Pr \text{ versus } \frac{Q/\dot{A}}{h_{fg} / \mu} \left( \sigma / \gamma_m (\rho_L - \rho_v) \right)^{\frac{1}{2}} \left( g''_m / g + 2\alpha f / (g d)^{\frac{1}{2}} \right)^{\frac{1}{4}} \]

is shown in fig. (67.). The exponent of 1 for the Prandtl number is that recommended by Vachon et al. ref. (5) for water; for organics the value 1.7 is recommended. Also included in fig. (67.) is the data of Nangia and Chon ref. (29) who used a 0.0103 cm diameter platinum wire.

For the sake of clarity not all the data is shown plotted. However 90 percent of all experimental points are within the ± 20 percent accuracy lines for the fully developed nucleate boiling region and within ± 15 percent accuracy lines for the partial nucleate boiling region.

As just mentioned there are two lines for the nucleate boiling region, one for the low heat flux range (partial nucleate boiling) and one for the high heat flux range (fully developed nucleate boiling). This is similar to the results reported by Heled et al. ref. (81). One possible explanation for the two ranges is that the lower range represents the region of separated bubbles while the upper range is that represented by interfering bubbles prior to their coalescing at the onset of film boiling, see fig. (50.) which shows this region.
The reason for the different line for the data of Nangia and Chon is because of their different heat transfer surface.

Because of the two parts to the correlating line, two constants \((C_{af})\) and exponent values will be necessary. The two values of \(C_{af}\) are 0.0184 for the fully developed nucleate boiling and 0.0227 for the partial nucleate boiling. The corresponding values for the data of Nangia and Chon are 0.0134 and 0.0175 respectively. The value of 0.0134 compares with Rohsenow's recommended value of 0.013 for the platinum/water combination. The values of \(C_{af}\) were obtained from fig. (67.), also from this figure the values of the exponent for the partial and the fully developed nucleate boiling regions were 1 and 3 respectively for the present experimental data and for the data of Nangia and Chon.

The full equations for the experimental data of this work are:

\[
\frac{Q/A}{h_{fg} \mu} \left( \sigma \gamma_m (\rho_L - \rho_v) \right)^{1/2} \left( \gamma_m / \xi + 2af/(gd)^{1/2} \right)^{1/2} = \frac{1}{0.0227} \left( C_P \Delta t / h_{fg} \text{Pr} \right) \tag{86}
\]

for the partial nucleate boiling region and:

\[
\frac{Q/A}{h_{fg} \mu} \left( \sigma \gamma_m (\rho_L - \rho_v) \right)^{1/2} \left( \gamma_m / \xi + 2af/(gd)^{1/2} \right)^{1/2} = \frac{1}{0.0134} \left( C_P \Delta t / h_{fg} \text{Pr} \right)^3 \tag{87}
\]

for the fully developed nucleate boiling region.

### 7.2. Correlation of Pure Liquid Data for the Stationary Wire

Prior to attempting the correlation of the data for the vibrating wire, the correlation of all liquids for the stationary wire was necessary. It is desirable that for one particular heat transfer surface, the correlation of all liquids relative to that surface should be accomplished with only one constant, particular to that surface.

Because of the scarcity of reliable physical property data for the liquids, the properties were evaluated at the respective
boiling points of the liquids and not at the mean film temperature. For comparison with the organics the properties of water at its boiling point were also used. The errors in using properties at the boiling point and not at the mean film temperature were considered to be small compared with the accuracy of properties at the boiling point and that the inclusion of a temperature ratio of the type \((T_b/T_s)^n\) could be used at a later time to account for this.

Initially Rohsenow's correlation ref. (3) was used to correlate the data. A plot of this correlation is shown in fig. (68.). It will be seen that the experimental points of every pure liquid lie on separate lines. There is no obvious systematic variation such that the inclusion of some simple term would bring these lines together. Apparently the correlation requires a constant \(Q_{sf}\) for each liquid relative to the 'Alumel' surface.

Because of the previous remarks concerning the use of only a single constant and because it was hoped to extend the single correlation to include binary mixtures by the use of a suitable factor characteristic of binary mixtures, a search of the literature suggested the following correlation of Minchenko and Firsova ref. (43) used to correlate data for water/lithium salts systems:

\[
\frac{\text{Nu}}{k_p^{0.7}} = 0.55 \text{Pe}^{0.7}
\]

(88)
i.e.

\[
\frac{\text{Nu}}{k_p^{0.7}} \text{ versus Pe}
\]

(89)
where

\[
\text{Nu} = \frac{Q/A}{\Delta t_k} \left( \sigma/\varepsilon (\rho_L - \rho_v) \right)^{1/2}
\]

(90)
\[
X_p = \frac{P/(\sigma/\varepsilon (\rho_L - \rho_v))^{1/2}}
\]

(91)
\[
\text{Pe} = \text{Re} \text{ Pr}
\]

(92)
\[ Pe = \frac{Q/A \rho_L}{h_f g k \rho_v} \left( \sigma/\rho_v (\rho_L - \rho_v) \right)^{1/2} \]  

(93)

and

\[ Re = \frac{Q/A \rho_L}{\mu h_f g \rho_v} \left( \sigma/\rho_v (\rho_L - \rho_v) \right)^{1/2} \]  

(94)

A plot of the data according to this correlation is shown in fig. 69. Again the experimental points of every pure liquid lie on four separate lines but it was noticed that the displacements were proportional to the boiling points of the liquids which are:

- Methanol 339°K
- Carbon Tetrachloride 350
- IPA/Water Azeotrope 354
- Isopropyl Alcohol 356
- Normal Propyl Alcohol 370
- Water 373
- Toluene 384

To keep the nondimensionality of the correlation the boiling points were divided by the boiling point of water i.e. \( T/T_{sw} \). This was interpreted as a 'reduced' temperature ratio. Intuitively, the inclusion of the boiling temperature would appear to be a most important variable in boiling heat transfer. In the correlations where bubble growth is considered to be the important physical phenomenon, the boiling temperature does appear. Also in the literature survey it was noted that Sciame et al. ref. (10) introduced a reduced temperature ratio \( T/T_{crit} \) into Rohsenow's correlation with their data for methane. Since the boiling point of water at the pressure of the operation is used, this correlation should be valid for any pressure. Actually several other temperatures were tried such as the critical temperatures of the respective liquids but it was found that they were neither constant nor varied as the boiling points.
A cross plot of $\frac{\text{Nu}}{K_0^{0.7}}$ against $\frac{T_S}{T_{sw}}$ at a constant Peclet number gave the index of 4 to the temperature ratio i.e. $(\frac{T_S}{T_{sw}})^4$, see fig. (70).

A plot of:

$$(\frac{\text{Nu}}{K_0^{0.7}})(\frac{T_S}{T_{sw}})^4$$

versus Peclet number

is shown in fig. (71.). The correlation appears satisfactory with scatter becoming appreciable only as the convective region is neared.

The equation of the line is:

$$(\frac{\text{Nu}}{K_0^{0.7}})(\frac{T_S}{T_{sw}})^4 = 0.000645 \text{ Pe}^{0.7}$$

As further confirmation, the data of Cichelli and Bonilla ref. (41) for ethanol, n-heptane and benzene at atmospheric pressure is shown plotted in fig. (72.). Again the scatter is acceptable. The equation of the line is:

$$(\frac{\text{Nu}}{K_0^{0.7}})(\frac{T_S}{T_{sw}})^4 = 0.000435 \text{ Pe}^{0.68}$$

The pressure data of Cichelli and Bonilla ref. (41). is shown plotted in fig. (73.). Although the present work had not included tests at pressure conditions, it was considered advisable that the correlation should be tested using data covering a range of pressures. The correlation was evaluated using $T_{sw}$ as the boiling point of water at the same pressure as that of the liquid considered. The scatter was again acceptable. However using this bigger range of data the slope of the line was found to be 0.62 i.e. the equation of the line was:

$$(\frac{\text{Nu}}{K_0^{0.7}})(\frac{T_S}{T_{sw}})^4 = 0.000854 \text{ Pe}^{0.62}$$

All their experiments were carried out using a stainless steel flat plate.

7.3. Correlation of Binary Mixture Data for Stationary Wire.

Isopropyl alcohol/water mixtures were used to obtain data for the purpose of studying binary systems. Including the data for the pure
components water and isopropyl alcohol as the two extremes of the system
nine mixtures were used. These were 100, 87.7, 74, 65, 54, 42.5, 20, 10
and 0 wt. percent isopropyl alcohol; the azeotrope is the 87.7 wt. percent
isopropyl alcohol mixture. The data, using the pure liquid correlation, is
shown plotted in fig. (74.). Only six ratios are plotted for clarity
although the remaining three are suitably positioned if plotted e.g.
65 wt. percent lies between the 74 and 54 wt. percent.

It will be noticed that the 0, 87.7 and 100 wt. percent lie on
a single line as is to be expected for the correlation and that the rest
of the mixtures are displaced to the right with 20 wt. percent having
the greatest displacement.

Assuming that with the binary system bubble growth i.e.
vapour production is controlled by mass diffusion and not heat diffusion
as in a pure liquid since the former is smaller by several orders of
magnitude, see fig. (75.), then the growth will depend on:-

\[ |y^* - x| \left( \alpha' / D \right)^{0.5} \]

where \( \text{mod. } (y^* - x) \) is the 'driving force'. This factor was earlier
considered by Scriven ref. (15) without a practical working correlation
being produced. To retain the Peclet number in the case of pure liquids,
the modification assumes the form:-

\[ 1 + |y^* - x| \left( \alpha' / D \right)^{0.5} \]

i.e. \( \text{Pe}/(1 + |y^* - x| \left( \alpha' / D \right)^{0.5}) \)

The choice of \( \text{mod. } (y^* - x) \) is important because as this passes through
the azeotrope its sign would change.

A plot of data including the modified Peclet number is shown
in fig. (76.). The correlation was considered satisfactory. The equation
of the line is, as expected from the results for pure liquids:-

\[ (\text{Nu}/K_p^{0.7}) (T_s / T_{sw})^{0.4} = 0.000645 \left( \text{Pe}/(1 + |y^* - x| \left( \alpha' / D \right)^{0.5}) \right)^{0.7} \]  (99)
The data of Sternling and Tichacek ref. (42) obtained using a stainless steel tube with the systems glycerol/water and ethylene glycol/water were also plotted using this correlation. These are shown in figs. (78.) and (77.). Again a satisfactory correlation of the data is obtained. The equation of the line for both systems is:

\[
\left(\frac{\text{Nu}}{K_P^{0.7}}\right)\left(\frac{T_s}{T_{SW}}\right)^{1.4} = 0.0156 \left(\frac{\text{Pe}/(t + |y^* - x| (\alpha'/D)^{1/2})}{100}\right)^{0.79}
\]

(100)

It will be noted that the two systems are correlated onto a single line requiring only one constant because they were obtained on the same surface. Also the correlation for the isopropyl alcohol/water system is the same as for the pure organics requiring only one constant.

The index for the data of Sternling and Tichacek is somewhat higher than expected although as previously stated Minchenko and Firsova in ref. (43.) recommended 0.7 but the best fit line to their data has slope 0.79.

In the bubble growth theory developed by Scriven ref. (15) the growth constant C for binary mixtures has the form:

\[
C = \left(\frac{1}{\pi} \right)^{1/2} \left(\frac{\rho}{\rho_L} \right) \left(\frac{h_{fg}}{C_P} - (\alpha'/D)^{1/2} (\rho_L - C\infty) (\partial T/ \partial C)\right)
\]

(101)

using his notation; this can be written, ignoring the constant, as (in our notation):

\[
C = \frac{1}{\left(\rho_{fg}^{h_{fg}/C_P} \right)} \left(1 - (\alpha'/D)^{1/2} (y^* - x) (C_P/h_{fg}) (\partial T/ \partial x)\right)
\]

(102)

The most important point to note is that the sign of the terms \((y^* - x)\) and \((\partial T/ \partial x)\) are always opposite so that the factor:

\[
((\alpha'/D)^{1/2} (y^* - x) (C_P/h_{fg}) (\partial T/ \partial x))
\]

is always added to the one. By using \(\text{Mod}.(y^* - x)\) we have an equivalent effect. Also from the correlation of the data it would appear that the term \((C_P/h_{fg}) (\partial T/ \partial x)\) must vary only slightly with concentration since
our modification of the Peclet number should be:

\[ 1 - (\alpha' / D)^{1/2}(y^* - x)(C_P/h_f)( \Delta T / \partial x) \]

if Scriven's growth constant had been used.

If we rearrange the Peclet number as:

\[ \frac{\varphi_A}{k} \left( \sigma / g (\rho_L - \rho_v) \right)^{1/2} \left( 1 / \rho_v h_f / \rho_L C_P \right) \]

it will be seen that by the use of the term \((1 + |y^* - x| (\alpha' / D)^{1/2})\) we get:

\[ \frac{\varphi_A}{k} \left( \sigma / g (\rho_L - \rho_v) \right)^{1/2} \left( 1 / \left( ( \rho_v h_f / \rho_L C_P ) (1 + |y^* - x| (\alpha' / D)^{1/2}) \right) \right) \]

so that the similarity with Scriven's growth constant is obvious.

Korner ref. (17) also used \(\varphi_A\) \((y^* - x)\) in the empirical correlation he developed (see also literature survey).

Although with the isopropyl alcohol/water system no mixtures above the azeotrope were tested, some data obtained in this laboratory for the whole range of normal propyl alcohol/water mixtures were tested and proved the correlation to be correct.

Finally a comment should be made that in the correlation viscosity is absent. In the case of binary mixtures this ranged from 0.285 Kg/ms x 10^{-3} for water to 2.2 Kg/ms x 10^{-3} for glycerol i.e. a nine fold range. In the case of pure liquids the range is approximately the same with 0.05 Kg/ms x 10^{-3} for carbon tetrachloride and 0.47 Kg/ms x 10^{-3} for normal propyl alcohol. This suggests that viscosity is not a very important property in pool boiling heat transfer.

7.4. Correlation of Convective Region Data for Vibrating Wire.

Although the range of data is limited, by the temperature range given by the onset of nucleate boiling, the results for the convective region were correlated as follows. It was thought, intuitively,
that the effect of vibration was to produce a mixed region of free and forced convection.

The correlations used for free convection have the form:

$$\text{Nu} = K(Gr \ Pr)^{0.25}$$

while for forced convection they have the form:

$$\text{Nu}/Fr^a = K_1 + K_2 \ Re^b$$

It is natural to assume that as Reynolds number tends to zero the correlation for forced convection should approximate to that for free convection so that $K_1$ was replaced by $K Gr^{0.25}$

i.e. $$\text{Nu}/Fr^a = K Gr^{0.25} + K_2 \ Re^b$$

The exponents were then found as a best fit to the data to give:

$$\text{Nu}/(Gr \ Pr)^{0.25} = K + K_2 (Re^2/Gr)^{0.25}$$

i.e. an exponent of 0.5 for the Reynolds number.

A plot of data for the stationary wire and for two different amplitudes, 0.1015 cm and 0.203 cm, and for two different frequencies, 64 Hz and 94 Hz, is shown in fig. (79.) for all the liquids tested. The large scatter is attributed, in part, to the greater inaccuracy in temperature measurement at the lower temperatures for convective heat transfer. The interrupted line is that obtained by Pe: ref. (19) for an investigation using air and a sphere as the heat transfer surface.

It will be noticed that the change from free to predominantly forced convection is gradual. Also that the effects of vibration are negligible until the value of $(Re^2/Gr)^{0.25}$ becomes greater than approximately 2, but above this value the forced convection effect of vibration dominates free convection.
A mean value for the constant $K$ is:

$$\text{Nu} = K(\text{Gr Pr})^{0.25}$$

(107)

for all liquids tested is 1.1 and thus compares with the value 0.75 recommended by McAdams ref. (2) and 1.75 recommended by Soehngen ref. (82).

A final point, which is worth noting, is the large increase in $(\text{Nu / Gr Pr})^{0.25}$ at high values of $(\text{Re}^2 / \text{Gr})^{0.25}$ compared with its value at a zero value for $(\text{Re}^2 / \text{Gr})^{0.25}$ i.e. vibration has a large effect in the convective heat transfer region.

7.5. Other Methods of Correlation.

With nucleate boiling, in the region of low heat flux, where the bubble producing sites are widely spaced there is obviously still a large proportion of the heat transfer occurring due to natural convection. That is, the total heat flux is made up of contributions due to natural convection, bubble enhanced natural convection (a type of forced convection) and the latent heat transfer of the bubble vapour. It should be possible to evaluate each contribution and to then obtain the total heat flux by the simple addition of each contribution. The boundary conditions will be that the free convective heat transfer contribution to the total heat flux will be 100% at the start of nucleation and 0% at the onset of fully developed nucleate boiling.

Another possibility is to use the usual correlation for the convective heat transfer region:

$$\text{Nu} = f(\text{Gr Pr})$$

and Rohsenow's correlation for the fully developed nucleate boiling region; a correlation for the region of low heat flux nucleate boiling could be developed using the enhanced natural convection proposal, to link these two regions, see ref. (84).
Fig. (67.)

○ Vibrating wire
+
Stationary wire
× Nangia and Chen ref. (29)

Fig. (67.) Correlation of vibration data for water.
Fig. (68.) Plot of pure liquid data according to Rohsenow ref. (3).
Fig. (69.) Plot of pure liquid data according to ref. (43).
Fig. (70.) Cross plot of \( (\text{Nu}/k_p^{0.7}) \) against \( T_S/T_{SW} \) at a constant Peclet number of 3000.
Fig. (71.) Correlation of pure liquid data.
Fig. (72.) Correlation of pure liquid data of Cichelli & Bonilla ref. (41) atmospheric pressure.
Fig. (73.) Correlation of pure liquid data of Cichelli and Bonilla ref. (41) covering range of pressures.
Fig. (74.) Plot of data for IPA/water system.
Fig. (75.) Variation of ratio of heat to mass diffusivities with composition.
Fig. (76.) Correlation of data for IPA/water system.
Composition wt. percent water.

Δ 95.5 †   ▼ 47.6   ◇ 2.64
× 90.5 †   △ 19.3   ★ 0.28
○ 73.3   ■ 10.1

† It is not quite clear from the original paper ref. (42) whether these two mixtures belong to the system ethylene glycol/water or to the proceeding one in the same table.

Fig. (77.) Correlation of data of Sternling & Tichacek ref. (42) for ethylene glycol/water.
Composition wt. percent water.

△ 0.33 ▼ 4.28 □ 25.5 ▲ 49.8
+ 1.69 × 9.09 □ 28.9 ● 67.4
＋ 1.73 × 9.64 ▽ 40.8 △ 74.7
▼ 4.05 ● 18.6

Fig. (78.) Correlation of data of Sternling & Tichacek ref. (42) for glycerol / water.
Fig. (79.) Correlation of pure liquid data for convective region.
PROCESSED DATA.

ROSENOW'S CORRELATION
DT  SURFACE SUPERHEAT  \( \Delta t = T_w - T_s \)  \(^\circ\text{C}\)

Q/A  HEAT FLUX  \( \text{W/m}^2 \)

ST  \( C_p \Delta t / h_f \text{Pr}^{1.7} \)

RE  \( Q/A \frac{c_f}{h_f} \left( \frac{\sigma}{8 \rho_L (\rho_L - \rho_v)} \right)^{1/2} \)

PR  FRANDTL NUMBER  \( C_p \mu / k \)
### Table 165

**Toluene**

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ATMOSPHERIC PRESSURE RESULTS.

TOLUENE
CARBON TETRACHLORIDE
METHANOL
NORMAL PROPA Bol
ISOPROPANOL
IPA/WATER AZEOTROPE
WATER
ETHANOL
N HEPTANE
BENZENE
DT  SURFACE SUPERHEAT  \( \Delta t = T_w - T_s \)  °C

Q/A  HEAT FLUX  \( \frac{Q/A}{\Delta t} k \frac{\sigma}{g(\rho_L - \rho_v)^{\frac{5}{2}}} \)  w/m²

NU  NUSSELT NUMBER  \( \frac{Q/A}{\Delta t} k \frac{\sigma}{g(\rho_L - \rho_v)^{\frac{5}{2}}} \)

KP  PRESSURE TERM  \( \frac{P}{\sigma g(\rho_L - \rho_v)^{\frac{1}{2}}} \)

X  \( \frac{NU}{KP^{0.7}} \)

Y  \( (NU/ KP^{0.7})(T_s/T_{sw})^4 \)

PE  PEDLET NUMBER  \( \frac{\sqrt{A} \rho_L}{k h_f g(\rho_L - \rho_v)^{\frac{1}{2}}} \)

T_s  MEASURED BOILING TEMPERATURE  °K

T_{sw}  BOILING POINT WATER  °K
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**CARBON TETRACHLORIDE**

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PRESSURE RESULTS.

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\]

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\]

\[
\frac{\sigma}{\varepsilon (\rho_L - \rho_v)^\frac{1}{2}}
\]

\[
\frac{\sigma}{\varepsilon (\rho_L - \rho_v)}^\frac{1}{2}
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\[
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Table 183

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N. HEPTANE

REF. (41)
**TABLE (187)**

**N HEP TANE**

**REF. (41)**

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ISOPROPYL ALCOHOL/WATER MIXTURES.
\[ \text{KP} \quad \text{PRESSURE TERM} \quad \frac{P}{\sigma g (\rho_L - \rho_v)^{\frac{1}{2}}} \]

\[ \text{BF} \quad \text{BINARY FACTOR} \quad 1 + |x^* - x| \left( \frac{\alpha'}{\Delta d} \right)^{\frac{1}{2}} \]

\[ \text{DT} \quad \text{SURFACE SUPERHEAT} \quad \Delta t = T_w - T_s \]

\[ \text{Q/A} \quad \text{HEAT FLUX} \quad \frac{Q}{A} \]

\[ \text{NU} \quad \text{NUSELT NUMBER} \quad \frac{\frac{Q}{A}}{\Delta t} \frac{k}{\rho_c} \left( \frac{\sigma}{g (\rho_L - \rho_v)} \right)^{\frac{1}{2}} \]

\[ \text{FLF} \quad \text{FLUENT NUMBER} \quad (\text{NU}/k^{0.7})(T_s/T_{sw})^{1/4} \]

\[ \text{PE} \quad \text{PEOLET NUMBER} \quad \frac{\frac{Q}{A} \rho_L}{k \frac{h}{f_g} \rho_v} \left( \frac{\sigma}{g (\rho_L - \rho_v)} \right)^{\frac{1}{2}} \]

\[ \text{PE/EF} \quad \text{PEOLET NUMBER/BINARY FACTOR} \]

\[ T_s \quad \text{MEASURED BOILING POINT} \]

\[ T_{sw} \quad \text{BOILING POINT WATER} \]

\[ T_w \quad \text{SURFACE TEMPERATURE} \]
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WATER/GLYCERUL  49.8  WT. PERCENT

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4295.49  4.800

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### Table 214

**WATER/GLYCEMUL 74.7 wt. PERCENT**

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ETHYLENE GLYCOL/WATER MIXTURE.
TABLE ( 215 )

WATER/ETHYLENE GLYCOL 95.5 wt. percent

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4683.91 1.26

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**Table 216**

**WATER/ETHYLENE GLYCOL 90.5 wt. percent**

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**WATER/EthanE GLYCOL 47.65 WT. PERCENT**

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**Water/Ethylene Glycol 19.3 wt. percent**

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**WATER/EthylenE glycol 10.1 wF. PErcent**

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**WATER/ETHYLENE GLYCOL 0.28 wt. percent**

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CONVECTIVE REGION.
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### TABLE (223)

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### Table 227

**Carbon Tetrachloride**

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**Carbon Tetrachloride**

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**CARBON TETRACHLORIDE**

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**ISO Propyl Alcohol**

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**ISO Propyl Alcohol**

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TABLE (239)

NORMAL PROPYL ALCOHOL

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TABLE (240)

NORMAL PROPYL ALCOHOL

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**NORMAL PROPYL ALCOHOL**

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8. CONCLUSIONS
8. CONCLUSIONS.

When considering water, vibration of the surface would seem an effective method of increasing heat transfer. The vibrations should be such that the amplitude is the maximum possible and that the frequency will be determined by this amplitude and the power available. Since the 'G' force increases as the square of the frequency and only linearly for the amplitude this would also keep the 'G' force to a minimum.

For the correlation of the data given by:

$$\frac{C_p \Delta t}{h f x^2} \text{ versus } \frac{Q/A}{\mu h f x^2} \left( \sigma/\rho g (\rho_L - \rho_v) \right)^{1/2} \left( \frac{\rho_v}{\rho_p} + 2 \alpha T / (2d)^{1/2} \right)^{1/2} \quad (108)$$

there are two lines. For the lower range values this is interpreted as the region of separate bubbles while the upper range values is the region of fully developed boiling. This results in two values of exponent and constant $C_{st}$. For the present experiments these are 1 and 3, respectively and 0.0227 and 0.0187 respectively.

As regards the effect of vibrations on pure organic liquids, within the range of parameters used, they had no effect and may even be detrimental. Further research, such as extending the range of vibration parameters, will be necessary to conclusively prove this point.

A correlation for heat transfer to pure organic liquids for a stationary surface is proposed:

$$(Nu/K_p^{0.7})(T_s/T_{sw})^{1/2} = K Pr^{0.7} \quad (109)$$

where $K$ has the value 0.000645 for the present experiments.

This correlation is then extended to correlate binary systems as follows:
\[
\frac{(\text{Nu}/K_{p}^{0.7})(T_g/T_{sw})^{4}}{1 \times (1 + 1.5 - x)(\alpha' / \beta)^{0.7}} = K \frac{(\text{Pe}/(1 + 1.5 - x)(\alpha' / \beta)^{0.7})}{100}
\]

where \( K \) has the same value as for the pure organic liquids.

All of these correlations have been further tested using data from the published literature. Some variation in the value of the exponent of the modified Peclet number was found. This was attributed, in part, to the inaccuracies in the physical property data. The differences in the constants were also attributed to the different heat transfer surfaces.

A simple graphical correlation for the convective data based on coexisting free and forced convection hydrodynamic regions is proposed:

\[
\frac{\text{Nu}}{(\text{Gr} \, \text{Fr})^{0.25}} = \phi \left( \frac{\text{Re}^2}{\text{Gr}} \right)^{0.25}
\]

It shows the gradual change from free to predominantly forced convection that occurs as vibration is increased. It also demonstrates the large increase in heat transfer that vibrations produce in the convective region.
9. SUGGESTION FOR FURTHER WORK
9. SUGGESTIONS FOR FURTHER WORK.


The most important future work will be to test the correlation with more data. This can be done in three ways:

i. To use a larger diameter test surface; in fact it will be worth while with the available power of the vibrator to use several diameters up to an amplitude to wire diameter ratio of one, say, so that the amplitude to wire diameter effect can be assessed.

ii. To use the same test wire but with a different surface finish.

iii. To use a different test wire material.

The first point can be achieved by using hyperdermic tubing so as to permit the use of the existing power supply. Firms such as 'Fine Tubes Limited' of Plymouth supply such tubes. The second point can be accomplished by using standard surface treatments such as shot blasting, etching, etc. This will also entail the proper surface examination so that the surface treatment can be quantified i.e. grain size, etc. Finally the third point will be evaluated by using stainless steel, carbon, etc. and will be closely connected to point ii.

The present tests are at relatively high frequencies and low amplitudes although the ratio of amplitude to wire diameter is large; it will be of interest to investigate the range of low frequencies (up to 10 Hz say) and large amplitudes. The point of this is that the present amplitudes are of the same order of size as the bubble diameters, if the amplitude was increased (up to 5 cm say) would it recapture bubbles in a similar manner as observed with the organics and vibrate in an 'atmosphere' of bubbles? If so would the heat transfer then be affected similarly to the organics?

Stationary Surface.

The correlation established for the pure organic liquids needs further testing by using a bigger range of liquids; perhaps cryogenics to be used? Also, as above, the test surface should be changed such that a series of diameters and different surface finishes should be tested.

Vibrating Surface.

It would also be very interesting to test the pure organic liquids in the low frequency, large amplitude range. At these low frequencies the bubbles might have time to disengage from the surface; if this happened the heat transfer might be improved.


Perhaps the most interesting aspect of this work will be to extend the modification to the Peclet number so as to be exactly similar to Scriven's growth constant i.e. by including the terms \((C_p/h_f)(\partial T/\partial x)\). The curve of temperature against concentration could be fitted by a polynomial using a standard computer technique. The differential can then easily be obtained as:

\[ T = f(x) \]

\[ \partial T/\partial x = f'(x) \]

The value of \( \partial T/\partial x \) could then be evaluated at the desired concentration, and the full term \((C_p/h_f)(\partial T/\partial x)\) computed.

It will be necessary also to test further mixtures. Sterling and Tichacek present data for several mixtures in ref. (42) but the difficulty lies in that physical properties, at the liquid mixture boiling point, do not exist in the literature. Calculated values of the physical properties could be used but the errors involved could reduce the effectiveness of the correlation, as mentioned in the discussion.
10. REFERENCES
REFERENCES

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<th>No.</th>
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<td>34.</td>
<td>F.C. McQuiston and J.D. Parker. A.S.M.E. 67 HT 49.</td>
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<td>45.</td>
<td>V.M. Borishanskii et al. Article 7 in ref. (43) p.85.</td>
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51. § 113 of ref. (50).
53. § 216 of ref. (50).
55. § 27 of ref. (50).
56. § 138 of ref. (50).
57. § 227 of ref. (50).
59. § 27 of ref. (50).
60. p.94. of ref. (54).
63. § 218 of ref. (50).
65. § 23 of ref. (50).
66. p.1549. of ref. (62).
67. § - 126. of ref. (64).
71. p.98. of ref. (54).


11. NOMENCLATURE
11. NOMENCLATURE.

\( \rho_L \) \quad Liquid density \quad \text{kg/m}^3

\( \rho_v \) \quad Vapour density \quad \text{kg/m}^3

k \quad Thermal conductivity \quad \text{W/m}^2

\( \mu \) \quad Absolute viscosity \quad \text{kg/ms}

\( h_{fg} \) \quad Latent heat of vaporisation \quad \text{J/kg}

Cp \quad Specific heat \quad \text{J/kg}\degree \text{K}

\( \sigma \) \quad Surface tension \quad \text{N/m}

\( g \) \quad Acceleration due to gravity \quad 9,812 \text{ m/s}^2

\( g' \) \quad Wire acceleration \quad 2\pi a^2

\( g_m' \) \quad Wire mean acceleration \quad \text{m/s}^2

Nu \quad Nusselt number \quad \text{a/}k \text{ or } \text{h}_d/k

Pr \quad Prandtl number \quad Cp \mu/k

Re \quad Reynolds number \quad \frac{Q/A}{h_{fg}} \left( \sigma/g(\rho_L - \rho_v) \right)^{\frac{1}{2}} \text{ in equation (11)}

Gr \quad Grashof number \quad \frac{d^3 \rho_L g \beta}{\mu^2}

Pe \quad Peclet number \quad \frac{Re \times Pr}{Q/A} = \frac{Q/A \rho_L}{h_{fg} \rho_v} \left( \sigma/g(\rho_L - \rho_v) \right)^{\frac{1}{2}}

Kp \quad Pressure term \quad \frac{P}{(\sigma/g(\rho_L - \rho_v))^{\frac{1}{2}}}

P \quad Pressure \quad \text{N/m}^2

a \quad Amplitude (peak to peak) \quad \text{m}

f \quad Frequency \quad \text{Hz}

d \quad Wire diameter \quad \text{m}

d_b \quad Bubble diameter at breakaway \quad (\sigma/g(\rho_L - \rho_v))^{\frac{1}{2}} \quad \text{m}

Re \quad Reynolds number \quad \frac{Q/A \rho_L}{\mu h_{fg} \rho_v} \left( \sigma/g(\rho_L - \rho_v) \right)^{\frac{1}{2}} \text{ in equation (17)}

Re \quad Reynolds number \quad 2af \rho_L/\mu \text{ in equation (104)}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>Coefficient of volumetric expansion</td>
<td>(1/°K)</td>
</tr>
<tr>
<td>$r$</td>
<td>Radius</td>
<td>m</td>
</tr>
<tr>
<td>$a'$</td>
<td>Amplitude in S.H.M.</td>
<td>m/2</td>
</tr>
<tr>
<td>$y^*$</td>
<td>Vapour composition in equilibrium with liquid</td>
<td>wt. fraction</td>
</tr>
<tr>
<td>$x$</td>
<td>Liquid composition</td>
<td>wt. fraction</td>
</tr>
<tr>
<td>$\alpha'$</td>
<td>Heat diffusivity</td>
<td>(m^2/s)</td>
</tr>
<tr>
<td>$D$</td>
<td>Mass diffusivity</td>
<td>(m^2/s)</td>
</tr>
<tr>
<td>$T$</td>
<td>Temperature</td>
<td>°K</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Liquid boiling temperature</td>
<td>°K</td>
</tr>
<tr>
<td>$T_{sw}$</td>
<td>Water boiling temperature</td>
<td>°K</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Temperature coefficient in equation (57)</td>
<td>°K</td>
</tr>
<tr>
<td>$n$</td>
<td>Angular velocity</td>
<td>1/s</td>
</tr>
<tr>
<td>$R$</td>
<td>Resistance</td>
<td>ohms</td>
</tr>
<tr>
<td>$R_0$</td>
<td>Resistance of test wire at 0°C</td>
<td>ohms</td>
</tr>
<tr>
<td>$R_{100}$</td>
<td>Resistance of test wire at 100°C</td>
<td>ohms</td>
</tr>
<tr>
<td>$R_{tw}$</td>
<td>Test wire resistance at $T_m$ °C</td>
<td>ohms</td>
</tr>
<tr>
<td>$T_m$</td>
<td>Test wire mean temperature</td>
<td>°C</td>
</tr>
<tr>
<td>$T_s$</td>
<td>Test wire surface temperature in equation (62)</td>
<td>°C</td>
</tr>
<tr>
<td>$R_s$</td>
<td>Standard resistance</td>
<td>ohms</td>
</tr>
<tr>
<td>$R_{o}$</td>
<td>Outside radius of wire in equations (62), (46, 47, 48)</td>
<td>m</td>
</tr>
<tr>
<td>$V_1$</td>
<td>Voltage drop across test wire</td>
<td>volts</td>
</tr>
<tr>
<td>$V_2$</td>
<td>Voltage drop across standard resistance</td>
<td>volts</td>
</tr>
<tr>
<td>$Q/A$</td>
<td>Surface heat flux</td>
<td>W/m^2</td>
</tr>
<tr>
<td>$q$</td>
<td>Heat flux</td>
<td>W/m^2</td>
</tr>
<tr>
<td>$q'$</td>
<td>Heat generated/unit volume/unit time</td>
<td>W/m^3</td>
</tr>
<tr>
<td>$q^*$</td>
<td>Heat flux/unit area/unit time</td>
<td>W/m^2</td>
</tr>
<tr>
<td>$t$</td>
<td>Temperature in equation (A13)</td>
<td>°K</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>Wall superheat</td>
<td>°C</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>$q_b$</td>
<td>Heat flow rate to bubble</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>Mass flow rate in equation (8)</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>Slope of vapour liquid equilibrium line</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>Heat transfer coefficient, stationary wire</td>
<td></td>
</tr>
<tr>
<td>$h'$</td>
<td>Heat transfer coefficient, vibrating wire</td>
<td></td>
</tr>
<tr>
<td>$G_p$</td>
<td>Free energy of bubble formation, pure liquid</td>
<td></td>
</tr>
<tr>
<td>$G_b$</td>
<td>Free energy of bubble formation, binary mixture</td>
<td></td>
</tr>
<tr>
<td>$\Delta H$</td>
<td>Enthalpy of vaporization</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Kinematic viscosity</td>
<td></td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular velocity</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Radius in equation (48)</td>
<td></td>
</tr>
<tr>
<td>$t_i$</td>
<td>Time</td>
<td></td>
</tr>
</tbody>
</table>

Symbols used in equation (24):-

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$</td>
<td>Mass fraction in vapour</td>
</tr>
<tr>
<td>$C$</td>
<td>Mass concentration in bulk liquid</td>
</tr>
<tr>
<td>$K$</td>
<td>Thermal diffusivity</td>
</tr>
<tr>
<td>$D$</td>
<td>Mass diffusivity</td>
</tr>
<tr>
<td>$\rho_v$</td>
<td>Vapour density</td>
</tr>
<tr>
<td>$L$</td>
<td>Latent heat of vaporization</td>
</tr>
<tr>
<td>$C_L$</td>
<td>Specific heat</td>
</tr>
</tbody>
</table>
APPENDICES
APPENDIX. A.

TO CALCULATE SURFACE TEMPERATURE FROM MEAN TEMPERATURE.

a. Temperature variation across wire with internal heat source.

Consider some element at radius $r$ thickness $dr$

$$q_1 = -2\pi k r \frac{dt}{dr} \quad (A1)$$

$$q_2 = -2\pi k (r + dr) \left[ \frac{dt}{dr} + \frac{d^2t}{dr^2} dr \right] \quad (A2)$$

$$dq = q' 2\pi r \, dr \quad (A3)$$

where $q'$ is heat generated/unit volume/unit time.

For conservation of energy

$$-2\pi k r \frac{dt}{dr} + q' 2\pi r \, dr = -2\pi k r \frac{dt}{dr} - 2\pi k r \frac{d^2t}{dr^2} \quad (A4)$$

$$-2\pi k \frac{dr}{dt} \frac{dt}{dr} - 2\pi k (dr)^2 \frac{d^2t}{dr^2} \quad (A4')$$

that is

$$q' r = - k r \frac{d^2t}{dr^2} - k \frac{dt}{dr} - k \frac{dr}{dr} \frac{d^2t}{dr^2} \quad (A5)$$

Ignoring last term because it contains product of differentials

$$\frac{q' r}{k} = - r \frac{d^2t}{dr^2} - \frac{dt}{dr} \quad (A6)$$

Now

$$\frac{d (r \, dt)}{dr} = dt + r \frac{d^2t}{dr^2} \quad (A7)$$
that is \[ \frac{q'}{k} r = - \frac{d}{dr} (r \frac{dt}{dr}) \] (A8)

that is \[ \frac{q'}{2k} r^2 = - \frac{d}{dr} (r \frac{dt}{dr}) + C \] (A9)

For centre of wire \( r = 0 \) and \( \frac{dt}{dr} = 0 \)
therefore \( C = 0 \)

that is \[ \frac{q'}{2k} r^2 = - \frac{dt}{dr} \] (A10)

therefore \[ \frac{q'}{4k} r = - t + D \] (A11)

For \( r = R_s \) and \( t = T_s \)
\[ \frac{q'}{4k} R_s^2 = - T_s + D \] (A12)

that is \[ D = \frac{q'}{4k} R_s^2 + T_s \] (A13)

therefore \[ t = - \frac{q'}{4k} r^2 + \frac{q'}{4k} R_s^2 + T_s \] (A14)

b. Calculation of surface temperature from mean temperature.

Mean temperature defined as:-
\[ T_m = \frac{\int t \, dv}{\int dv} \] (A15)

where \( t = t(r) \) and \( v = v(r) \)

\[ T_m = \frac{\int_0^{R_s} \left[ - \frac{q'}{4k} r^2 + \frac{q'}{4k} R_s^2 + T_s \right] r \, dr}{\int_0^{R_s} r \, dr} \] (A16)

\[ = \frac{\left[ - \frac{q'}{4k} R_s \right] R_s + \left\{ \frac{q'}{4k} R_s^2 + T_s \right\} \frac{R_s^2}{2} }{\left[ \frac{R_s^2}{2} \right] R_s} \] (A17)

\[ = \frac{-\frac{q'}{4k} R_s + \left[ \frac{q'}{4k} R_s^2 + T_s \right] R_s^2}{\frac{R_s^2}{2}} \] (A18)
Therefore

\[ T_s = T_m + \frac{q^*}{k} \left( \frac{R_m^2}{\delta^2} - \frac{R_s^2}{4} \right) \]

\[ = T_m - \frac{q^* R_s^2}{8k} \]  

If \( q^* \) is surface heat flux then:

\[ \pi R_s^2 L q^* = 2\pi R_s L q^* \]  

that is

\[ q^* = \frac{2 q^*}{R_s} \]

therefore

\[ T_s = T_m - 2 \frac{q^* R_s}{8k} \]

\[ = T_m - \frac{q^* R_s}{4k} \]

\[ = T_m - \frac{q^* D}{8k} \]

where \( D \) is diameter of wire.
### Sample Calculations

#### B.1. Water, Nucleate Boiling Region

More accurate computer value shown in brackets after calculated value.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>0.000315 m</td>
</tr>
<tr>
<td>Wire length</td>
<td>0.0715 m</td>
</tr>
<tr>
<td>Standard resistance</td>
<td>0.784 ohms</td>
</tr>
<tr>
<td>Test wire resistance at 0°C</td>
<td>0.2618 ohms</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>0.00259/°C</td>
</tr>
<tr>
<td>Frequency</td>
<td>64 Hz</td>
</tr>
<tr>
<td>Acceleration of gravity</td>
<td>9.81 m/s²</td>
</tr>
<tr>
<td>Voltage drop standard resistance</td>
<td>8.392 volts</td>
</tr>
<tr>
<td>Voltage drop test wire</td>
<td>3.640 volts</td>
</tr>
<tr>
<td>Ratio of wire to gravity acceleration G</td>
<td>17.0</td>
</tr>
<tr>
<td>Measured pool temperature</td>
<td>100.3°C</td>
</tr>
</tbody>
</table>

\[
G = \frac{g'}{g} = \frac{2\pi^2a^2}{g} = 17 = \frac{2\pi^2a}{64^2}/9.81
\]

\[
a = 0.00206 \text{ m} (0.002032)
\]

Heat generated in wire = \( V_1 V_2/R_s = 8.392 \times 3.64/0.784 \)

\[= 39.1 \text{ watts} \]

Surface heat flux = \( Q/A = 39.1/\pi d_1 = 39.1/\pi \times 0.000315 \times 0.0715 \)

\[= 550,000 \text{ W/m}^2 (549801) \]

\[
R_t = \frac{V_1 R_s}{V_2} = 3.64 \times 0.784/8.392
\]

\[= 0.34 \text{ ohms} \]

\[
R_t = R_o (1 + \alpha T_m)
\]

\[
T_m = \frac{(R_t - R_o)}{\alpha R_o} = (0.34 - 0.2618)/(0.00259 \times 0.2618)
\]
\[ T_m = \frac{0.0782}{(0.00259 \times 0.2618)} = 115.3 \, ^\circ C = \text{mean wire temperature} \]

\[ T_s = T_m - \frac{Q/A \cdot d}{8k} \]

where \( k \) is the thermal conductivity of 'Alumel' wire

\[ k' = 0.22 \times 85.98(1 + 0.00441 \, T_m - 0.0000081 \, T_m^2) \]

\[ T_s = T_m - \frac{Q/A \cdot d}{8 \times 0.22 \times 85.98(1 + 0.00441 \, T_m - 0.0000081 \, T_m^2)} \]

\[ = 115.3 - 550,000 \times 0.000315/(8 \times 0.22 \times 85.98(1 + 0.00441 \times 115.3 - 0.0000081 \times 115.3^2)) \]

\[ = 115.3 - 21.6/(0.22 \times 85.98 \times 1.389) \]

\[ = 114.5 \, ^\circ C \]

Mean film temperature = \( T_F = (114.5 + 100.3)/2 \)

\[ = 107.4 \, ^\circ C \left( 107.3 \right) \]

Wire superheat = \( D_T = T_s - \frac{R_M}{R} = 114.5 - 100.3 \)

\[ = 14.2 \, ^\circ C \left( 14.0 \right) \]

Physical properties of water from property graphs

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid density ( \rho_L )</td>
<td>953 kg/m³</td>
</tr>
<tr>
<td>Vapour density ( \rho_v )</td>
<td>0.8 kg/m³</td>
</tr>
<tr>
<td>Viscosity ( \mu )</td>
<td>0.000262 kg/ms</td>
</tr>
<tr>
<td>Latent heat ( h_{\text{th}} )</td>
<td>2234000 J/Kg</td>
</tr>
<tr>
<td>Specific heat ( C_p )</td>
<td>4230 J/Kg°C</td>
</tr>
<tr>
<td>Thermal conductivity ( k )</td>
<td>0.674 W/°Cm²/m</td>
</tr>
<tr>
<td>Surface tension ( \sigma )</td>
<td>0.057 N/m</td>
</tr>
</tbody>
</table>

\[ g'_m = \text{mean wire acceleration} \]

\[ = \frac{(17.0 \times 9.81) + 9.81}{2} - (17.0 \times 9.81) - 9.81 \]

\[ = 166.6 \, m/s^2 \left( 166.4 \right) \]
Ripple diameter at breakaway = $DB = \left(\sigma/\rho_m\right)^{\frac{1}{2}}(\rho_L - \rho_v)\right)^{\frac{1}{2}}$

$= (0.057/166.6(953 - 0.8))^{\frac{1}{2}}$

$= 0.0006 \text{ m (0.0006)}$

$FR = 2af/(gd)^{\frac{1}{2}} = 2 \times 0.00206 \times 64/\left(9.81 \times 0.000315\right)^{\frac{1}{2}}$

$= 4.7 (4.68)$

$Z = \left(g_m^v/g + 2af/(gd)^{\frac{1}{2}}\right)^{\frac{1}{2}} = (17.0 + 4.7)^{\frac{1}{2}}$

$= 2.16 (2.158)$

Prandtl number = $\frac{C_p \mu/k}{\mu/h_g \Pr} = 4230 \times 0.000267/0.674$

$= 1.64 (1.638)$

$X = \frac{C_p \Delta t/h_g \Pr}{4230 \times 14.2/(223,000 \times 1.64)}$

$= 0.0161 (0.0161)$

$Y = \frac{\gamma}{\mu/h_g} \left(\sigma/\rho_m\right)^{\frac{1}{2}}(\rho_L - \rho_v)\right)^{\frac{1}{2}}(g_m^v/g + 2af/(gd)^{\frac{1}{2}}\right)^{\frac{1}{2}}$

$= 550,000 \times 0.0006 \times 2.16/(0.0262 \times 2.234)$

$= 1.22 (1.225)$
Isopropyl Alcohol/water, Nucleate Boiling Region.

74 wt. percent IPA. Stationary wire.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>0.000315 m</td>
</tr>
<tr>
<td>Wire length</td>
<td>0.0722 m</td>
</tr>
<tr>
<td>Standard resistance</td>
<td>0.784 ohms</td>
</tr>
<tr>
<td>Test wire resistance at 0°C</td>
<td>0.256 ohms</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>0.00259/°C</td>
</tr>
<tr>
<td>Measured pool temperature</td>
<td>80.8°C</td>
</tr>
<tr>
<td>Voltage drop standard resistance</td>
<td>5.489 volts</td>
</tr>
<tr>
<td>Voltage drop test wire</td>
<td>2.273 volts</td>
</tr>
</tbody>
</table>

Physical properties of mixture from property graphs

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity</td>
<td>0.215 W/m°C</td>
</tr>
<tr>
<td>Latent heat</td>
<td>970,000 J/Kg</td>
</tr>
<tr>
<td>Viscosity</td>
<td>0.00063 kg/ms</td>
</tr>
<tr>
<td>Liquid density</td>
<td>782 kg/m³</td>
</tr>
<tr>
<td>Vapour concentration</td>
<td>81 wt. % IPA</td>
</tr>
<tr>
<td>Vapour density</td>
<td>1.26 Kg/m³</td>
</tr>
<tr>
<td>Surface tension</td>
<td>0.0195 N/m</td>
</tr>
<tr>
<td>Mass diffusivity</td>
<td>t.6 x 10⁻⁹ m²/s</td>
</tr>
<tr>
<td>Specific heat</td>
<td>3550 J/Kg°C</td>
</tr>
<tr>
<td>Liquid concentration</td>
<td>74 wt. % IPA</td>
</tr>
</tbody>
</table>

Heat generated in wire = \( V_1 V_2 / R_s = 5.489 \times 2.273 / 0.784 \)

= 15.93 watts

Surface heat flux = \( Q/A = 15.93/\pi \times d l \)

= 15.93/\pi \times 0.000315 \times 0.0722

= 223,000 W/m² (223,000)

More accurate computer value shown in brackets after calculated value.
\[ R_t = V1 R_g/V2 = 2.273 \times 0.739/5.439 \]
\[ = 0.324 \text{ ohms} \]

\[ T_m = (R_t - R_o)/\alpha R_o = (0.324 - 0.256)/0.256 \times 0.00259 \]
\[ = 103.5^\circ C \]

\[ T_s = T_m - (Q/A \Delta t)/\alpha k' \]

where \( k' \) is the thermal conductivity of 'Alumel' wire
\[ k' = 0.215 \times 10^2 \text{ W/m}^0 \text{C} \]

\[ T_s = 103.5 - (223,000 \times 0.000315/(3 \times 21.5)) \]
\[ = 103.5 - 0.4 \]
\[ = 103.1 \]

Wire superheat = \( T_s - \Delta T_m = 103.1 - 80.8 \)
\[ = 22.3^\circ C (22.3) \]

Nusselt number = \( \frac{Q/A}{\Delta t k} (\sigma/\epsilon (\rho_L - \rho_v))^{1/2} \)
\[ = (223,000/22.3 \times 0.215)(0.0195/9.81(782 - 1.3))^{1/2} \]
\[ = 76 (75) \]

\[ K_p = P/(g\sigma/(\rho_L - \rho_v))^{1/2} = 1.013 \times 10^5/(9.81 \times 0.0195(782 - 1.3))^{1/2} \]
\[ = 8400 (8418.5) \]

\[ K_p^{0.7} = 560 \]

\[ (T_s/T_{sw})^{1/4} = (353.8/373)^{1/4} \]
\[ = 0.81 \]

\[ FLF = (\mu u/k_p^{0.7})(T_s/T_{sw})^{1/4} = 0.166 (0.105) \]

Peclet number = \( \frac{Q/A C_p \rho_L}{k_{fg} \rho_v} (\sigma/\epsilon (\rho_L - \rho_v))^{1/2} \)
\[ = \frac{223,000 \times 3550 \times 782}{970,000 \times 0.215 \times 1.26} (0.0195/9.81(782 - 1.3))^{1/2} \]
\[ = 3800 (3812) \]
Thermal diffusivity $= \alpha' = k/\rho_L C_p = 0.215/782 \times 3550$
$= 7.78 \times 10^{-7}$

$(\alpha'/D)^{\frac{1}{2}} = (7.78 \times 10^{-7}/1.6 \times 10^{-9})^{\frac{1}{2}}$
$= 6.7$

$y^* - x = 0.81 - 0.74$
$= 0.07$

Binary factor $= BF = 1 + (y^* - x) (\alpha'/D)^{\frac{1}{2}}$
$= 1 + (0.07 \times 6.7)$
$= 1.465 (1.47)$

Peclet number/Binary factor $= 3800/1.465$
$= 2600 (2593)$
B.3. Normal Propyl Alcohol, Convective Region.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire diameter</td>
<td>(d) (0.000315) m</td>
</tr>
<tr>
<td>Wire length</td>
<td>(l) (0.0722) m</td>
</tr>
<tr>
<td>Standard resistance</td>
<td>(R_s) (0.784) ohms</td>
</tr>
<tr>
<td>Test wire resistance at 0°C</td>
<td>(R_o) (0.256) ohms</td>
</tr>
<tr>
<td>Temperature coefficient</td>
<td>(\alpha) (0.00259/\degree C)</td>
</tr>
<tr>
<td>Measured pool temperature</td>
<td>BRM (97\degree C)</td>
</tr>
<tr>
<td>Voltage drop standard resistance</td>
<td>(V_1) (4.842) volts</td>
</tr>
<tr>
<td>Voltage drop test wire</td>
<td>(V_2) (2.085) volts</td>
</tr>
<tr>
<td>Physical properties of NPA from property table</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>(k) (0.144) W/m\degree C</td>
</tr>
<tr>
<td>Latent heat</td>
<td>(h_{fg}) (974,000) J/kg</td>
</tr>
<tr>
<td>Viscosity</td>
<td>(\mu) (0.000475) kg/ms</td>
</tr>
<tr>
<td>Liquid density</td>
<td>(\rho_L) (736) kg/m(^3)</td>
</tr>
<tr>
<td>Surface tension</td>
<td>(\sigma) (0.0175) N/m</td>
</tr>
<tr>
<td>Vapour density</td>
<td>(\rho_v) (1.97) kg/m(^3)</td>
</tr>
<tr>
<td>Specific heat</td>
<td>(C_p) (3193) J/kg\degree C</td>
</tr>
<tr>
<td>Coeff. of vol. expansion</td>
<td>(\beta) (0.00121/\degree C)</td>
</tr>
</tbody>
</table>

Heat generated in wire = \(V_1 \frac{V_2}{R_s}\)

\[
= 4.842 \times 2.085 / 0.784 \\
= 12.87 \text{ watts}
\]

Surface heat flux = \(q/A = 12.87/\pi \text{ dl}\)

\[
= 12.87/\pi \times 0.000315 \times 0.0722 \\
= 180,200 \text{ W/m}^2 \ (180,424)
\]

More accurate computer value shown in brackets after calculated value.

\(R_t = V_1 \frac{R_s}{V_2} = 2.085 \times 0.784/4.842\)

\(= 0.338\) ohms
\[ T_m = \frac{(R_t - R_o)/\alpha R_o}{0.338 - 0.256}/0.00259 \times 0.256 = 123.5^\circ C \]

\[ T_s = T_m - \frac{(Q/A d)/8k}{8k} \]

where \( k' \) is the thermal conductivity of 'Alumel' wire

\[ k' = 0.215 \times 10^2 \text{ W/m°C} \]

\[ T_s = 123.5 - \frac{(180,200 \times 0.000315)/(8 \times 21.5)}{} = 123.5 - 0.5 = 123^\circ C \]

Wire superheat = \( T_s - \text{BPM} = 123 - 97 \)

= 26^\circ C \ (27.45) \]

Nusselt number = \( h d/k \)

= 14.4 \ (14.406) \]

Reynolds number = \( v d \rho_f / \mu = 2 \alpha f d \rho_f / \mu \)

Amplitude = 0.002 m and frequency = 64 Hz

i.e. \( \alpha f = 0.13 \text{ m/s} \)

i.e. Reynolds number = \( 2 \times 0.13 \times 0.000315 \times 736/0.000475 \)

= 127 \ (126.998) \]

Grashof number = \( d^3 \rho_f^2 g \beta \Delta t / \mu^2 \)

= \( 0.000315^3 \times 736^2 \times 9.81 \times 0.00121 \times 27.5/0.000475^2 \)

= 24.5 \ (24.446) \]

Prandtl number = \( \text{Cp} \mu/k = 3193 \times 0.000475/0.144 \)

= 10.6 \]

\( (Re^2/Gr)^0.25 = (127^2/24.5)^0.25 = 5.06 \ (5.068) \]

\( Nu/(Gr Pr)^0.25 = (14.4)/(24.5 \times 10.6)^0.25 = 3.6 \ (3.594) \)