NUCLEATE POOL BOILING OF LIQUID MIXTURES

BY

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CERTIFICATE

It is certified that the thesis entitled "NUCLEATE POOL BOILING OF LIQUID MIXTURES" which is being submitted by Shri Sheikh Sadar Alam in fulfilment of the requirements for the award of the degree of DOCTOR OF PHILOSOPHY in Chemical Engineering at the University of Roorkee is a record of candidate's own work carried out by him under the supervision and guidance of the undersigned. The matter embodied in this thesis has not been submitted for award of any other degree.

This is further certified that the candidate has worked for a period of about four years from October, 1968 for preparing this thesis.

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ABSTRACT

An experimental investigation of heat transfer in pool boiling of pure liquids : distilled water, acetic acid, and acetone; and binary mixtures: water-glycerine, water-ethylene glycol, water-acetic acid, and acetone-water was carried out at 1 atmosphere pressure. Acetic acid and acetone were of chemically pure grade; whereas glycerine and ethylene glycol of commercial grade. Two test sections of brass tubes of 25.6 mm., and 27 mm. outside diameter were used. The outer surface of smaller diameter tube was silver-plated to resist the corrosive action of acetic acid. The test section was oriented horizontally in the pool of liquid in the vessel. Liquid and surface temperatures were measured by means of copper-constantan thermocouples. Heat fluxes in the range of 6.9×10^3 to 39.97×10^3 Kcal/hr.m^2 were used. Liquid temperatures were varied to cover from non-boiling through subcooled to saturated boiling regions. The data were taken for wide range of compositions for all the binary mixtures. In all the series of test runs the heat flux was approached progressively to the highest value starting at a low heat flux.

The experimental data on the pool boiling of saturated water have been found to compare well with the data of others (30, 49, 57, 58) at 1 atmosphere pressure. The experimental data on the saturated boiling of water-ethylene glycol mixture showed a good agreement with the data of Sternling and Tichacek (45).

The experimental data on boiling of saturated binary mixture showed a minimum in the values of heat transfer coefficient when plotted against the concentration of more volatile component. The concentration corresponding to this minimum value of heat transfer coefficient compared well with the predicted value by the method of Grigorev (18), Tolubinskii et al (14) and van Stralen (16) for all the mixtures.

As a result of data analyses, the following correlation has been found best to represent the experimental data on subcooled and saturated boiling of 4 binary liquid mixtures studied in the present investigation with a standard deviation of 31.88 % and average deviation of 31.84 %.

$$Nu_B = 0.0576\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}\,(K_c)^{-0.034}$$

The maximum error of ± 31 % covered about 95 % of 697 data points.

The experimental data on subcooled and saturated pool boiling of 8 pure liquids have been correlated by the following equation with a standard deviation of 20.54 % and average deviation of 20.16 %.

$$Nu_B = 0.084\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}$$

About 133 data points were found to be represented by the above correlation within a maximum error of ± 24 %. The merit of this correlation has been examined with respect to other correlations available in the literature.

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NOMENCLATURE

A	Surface area	m^2
C	Specific heat at constant pressure	Kcal/kg. °C
C_1	Bubble growth constant, $R/\vartheta\,\theta^{1/2}$	
d	Diameter of test section	m
d_b	Diameter of bubble, $\sqrt{\frac{\sigma}{(\rho_l - \rho_v)}}$	m
D	Mass diffusivity	m^2/hr
F	Gibbs' free energy	Kcal/kg mole
g	Acceleration due to gravity	m/sec^2
Gd	Vaporized mass fraction	
h	Heat transfer coefficient	Kcal/hr m^2 °C
J	Mechanical equivalent of heat	Kg. m/Kcal
k	Thermal conductivity	Kcal/hr m °C
K	Equilibrium constant, y/x	
P	Pressure	Kg/m^2
q	Heat flux	Kcal/hr.m^2
Q	Heat transfer rate	Kcal/hr
R	Curvature radius of bubble	m
S	Molal entropy	Kcal/kg mole. °K
t	Temperature	°C
T	Absolute temperature, (t + 273)	°K
Δt	Temperature difference, $(t_W - t_L)$	°C
Δt_{sub}	Degree of subcooling, $(t_S - t_L)$	°C

Δt_x	Temperature difference between dew temperature of vapor in bubbles and boiling temperature of original liquid in binary mixture	°C
Δt_{sup}	Degree of superheat, $(t_w - t_s)$	°C
V	Molal volume	m^3/kg mole
x	Mass fraction of more volatile component in liquid phase	
X	Mole fraction of more volatile component in liquid phase	
y	Mass fraction of more volatile component in vapor phase	
Y	Mole fraction of more volatile component in vapor phase	

GREEK LETTERS

α	Thermal diffusivity, $k/\rho C$	m^2/hr
β	Coefficient of volumetric expansion	1 / °C
Δ	Difference	
θ	Time elapsed since bubble departure during delay time	Sec
λ	Latent heat of vaporization	Kcal/kg
μ	Viscosity	Kg/hr.m
ρ	Density	Kg/m^3

σ	Surface tension	Kg/m.
ν	Kinematic viscosity, μ/ρ	m^2 /hr
ϑ	Instantaneous uniform superheating of microlayer	^oC

SUBSCRIPTS

sub	Subcooling
B	Boiling
c	Critical or convective
HB	High boiling
LB	Low boiling
L	Liquid
MP	Melting point
R	Reduced
s	Saturation
v	Vapor
W	Wall
min	minimum

DIMENSIONLESS GROUPS

Ar	Archimedes number	$\frac{g}{\nu^2}\left(\frac{\sigma}{\rho_L-\rho_v}\right)^{3/2}\left(1-\frac{\rho_v}{\rho_L}\right)$
Ga	Gallilean number	$=\frac{g}{\nu^2}\left(\frac{\sigma}{\rho_L-\rho_v}\right)^{3/2}$
Gr	Grashof number	$=\frac{g d^3}{\nu^2}\beta\Delta t$

K_c	Criterion for concentration term	$= 1 + \frac{(Y-x)^2}{Y(1-Y)}$
K_p	Criterion for pressure term in boiling	$= \frac{P}{\sqrt{\sigma(\rho_L-\rho_v)}}$
K_{sub}	Criterion for subcooling term	$= 1 + \sqrt{\frac{\rho_L}{\rho_v}}\frac{\Delta t_{sub}}{t_s}$
K_t	Criterion for bubble break off frequency	$= \frac{J(\rho_v\lambda)^2}{c t_s \rho_L \sqrt{\sigma(\rho_L-\rho_v)}} = \frac{1}{K_u}$
Nu_B	Nusselt number for boiling	$= \frac{h}{k}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}$
Pe_B	Peclet number for boiling	$= \frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}$
Pr	Prandtl number	$= \frac{c\mu}{k} = \frac{\nu}{\alpha}$
Re_B	Reynolds number	$= \frac{q\rho_L}{\lambda\rho_v\mu}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}$

CHAPTER 1

INTRODUCTION

A large effort has been made to research aimed at gaining fruitful understanding of boiling heat transfer process of pure liquids. Pending to some conclusions, our present day knowledge of this complex process is quite limited. Recently considerable interest has been shown to the problems related to the critical heat flux density in nucleate boiling, which is of decisive importance in nuclear reactors because this value of heat flux density determines the highest limit of safe working of nuclear reactor. Intensive liquid agitation (1, 2), degree of subcooling of liquid (3, 4, 5, 6,), increase of pressure upto one-third of the critical pressure (7, 8, 9) and other factors have been used to increase the limit of critical heat flux. Use of binary liquid mixtures (8, 9, 10, 11, 12, 13) was centered primarily on the determination of the conditions which govern the point of maximum heat flux. A favourable effect, increase in critical heat flux, occurs at a certain concentration of more volatile component in the binary mixtures. However, there is an important field of process industries where the boiling of binary or multicomponent liquid mixtures is of common occurence at heat fluxes much less than the critical values and the pressure usually low at or about 1 atmosphere. The binary mixtures involved in process industries may extend over a wide composition range. Till recently the process design calculations of the equipments - evaporators, vaporizers and reboilers, dealing with the boiling of binary or multicomponent systems were made based on the tacit assumption that boiling mechanism of mixtures is similar to that of pure liquids. Thus the average physical properties of the liquid mixtures were used in the correlations applicable to pure liquids for determining the boiling heat transfer coefficient. Recent research findings based on experimental (14, 15, 16) and analytical (16, 17, 18, 19) approaches have shown that the mechanism of boiling heat transfer in binary and ternary liquid mixtures differ from that in the pure liquids. This fact has prompted a few workers for initiating research to collect experimental data on boiling heat transfer of binary liquid mixtures. However these data are scant and the systems studied are also quite a small in number because of extremely complex nature of the process. Most of the available data for binary liquid mixtures have been obtained either at only one composition or over a very limited composition range. However, some work is available where data have been obtained at over a wide range of compositions. Based on the experimental data, small number of correlations are also available which are claimed to be valid for the given conditions of parameters and system. No work seems to have been published on pool boiling of subcooled binary liquid mixtures.

In view of the foregoing it was considered desirable to collect and analyse experimental data on pool boiling of pure liquids and their mixtures. The present investigation, therefore, was undertaken with the following objectives :

1. To collect experimental data on saturated and subcooled boiling of pure liquids at low heat flux values and 1 atmosphere pressure.
2. To collect experimental data on boiling of binary liquid mixtures at low heat flux values and 1 atmosphere pressure over a wide range of compositions.
3. To compare the observed values of concentration corresponding to minimum rate of heat transfer with those theoretically predicted for the binary mixtures studied.
4. To develop, as a result of data analyses, a generalized correlation to predict heat transfer coefficient for both subcooled and saturated boiling of binary liquid mixtures and their components in pure state.
5. To check the validity of the correlations available in literature to the pure liquids investigated; and to obtain a generalized correlation applicable to saturated as well as subcooled boiling of pure liquids.

CHAPTER 2

LITERATURE REVIEW

Boiling heat transfer has recently assumed the status of a major interest area in heat transfer. During the last three decades a vast amount of research on boiling heat transfer has been undertaken. As a result of the extensive investigations, the underlying thermodynamic and hydrodynamic principles involved in the vapor bubble formation and growth and their effect on heat transfer rates are becoming known. This is leading to fundamental approach for deriving design equations of process equipments and ascertaining the semi-empirical design procedures.

2.1 NUCLEATE POOL BOILING CORRELATIONS FOR SATURATED PURE LIQUIDS

Much information is now available to calculate boiling heat transfer coefficients in the nucleate boiling region. Unfortunately no single generalized correlation has so far been derived which would correlate all or most of the experimental data in this regime. The reason for this is that the heat flux does not depend solely on the temperature difference, pressure and the properties of the liquid and vapor but depends also on the nucleation characteristics of heating surface.

A number of correlations have been recommended for calculating heat transfer coefficient in nucleate pool boiling. These may be expressed in the following general form :

$$h_B = C\,(t_W - t_s)^n \qquad (2.1)$$

The constant C in Eq. (2.1) is found to depend on the thermodynamic and transport properties of the vapor and the liquid. The exponent, n generally varies from 1 to 3. Experiments have shown that nucleation characteristics (microroughness and wettability) of heat transfer surface affect not only the value of the constant, C but also the value of the exponent, n. For example, the value of n may vary from 1 to 25 as a result of polishing the surface with different grades of emery paper (20, 21). Unfortunately no method has been devised so far which would give a quantitative description of the nucleation characteristics of the surface.

One of the most widely used correlations for nucleate boiling region is due to Rohsenow (22)

$$Nu_B = \frac{1}{Cs_f}\,(Re_B)^{0.67}\,(Pr)^{-0.7} \qquad (2.2)$$

The constant Cs_f in Eq. (2.2) depends on the surface-liquid combinations as reproduced in Table 2.1.

Table 2.1 Values of Cs_f in Eq. 2.2 (20)

Liquid-Surface combination	Cs_f	Liquid-Surface combination	Cs_f
Water-nickel	0.006	n-Pentane-chromium	0.015
Water-platinum	0.013	Ethanol-chromium	0.0027
Water-copper	0.013	Isopropyl alcohol-copper	0.0025
Water-brass	0.006	35 % K_2Co_3 - copper	0.0054
$C\,cl_4$ - copper	0.013	50 % K_2Co_3 - copper	0.0027
Benzene-chromium	0.010	n-Butyl alcohol-copper	0.0030

Sciance et al (23) have studied the pool boiling of saturated hydrocarbons, ethane, propane, and n-butane outside a horizontal gold-plated cylinder. They succeeded in correlating all the data of the hydrocarbons (but not ethane) by modifying the Rohsenow's equation in the following form :

$$\frac{\frac{q}{A}\sqrt{\frac{\sigma}{\rho_L-\rho_v}}}{\lambda\mu} = C\left[\frac{C_L\,\Delta t}{\lambda}\left(\frac{T_R}{P_r}\right)^{1.18}\right]^{n} \qquad (2.3)$$

The constant, C, and exponent, n are given in Table 2.2

Table 2.2 The constants in Eq. (2.3)

Liquid	$C \times 10^{-5}$	n
Methane	3.25	2.89
Propane	5.77	2.6
n-Butane	2.33	2.84

There exists a large number of other correlations (24, 25, 26, 27, 28, 29, 30) which have been proposed so far. They give different results for different types of substances. Some of the important empirical equations for nucleate pool boiling heat transfer have been mentioned in Table 2.3.

2.2 BOILING OF SUBCOOLED LIQUIDS

The boiling process of liquid on a submerged surface without net generation of vapor is usually called subcooled boiling or surface boiling. The bulk liquid temperature is below the saturation temperature but its boundary layer is sufficiently superheated in which bubbles form. Recently subcooled boiling has been regarded of particular interest and important application because the periodic formation and collapsing of vapor bubbles on or close to heating surface (31) cause agitation of the boundary layer and therefore enhance the coefficient of heat transfer between surface and liquid enormously. There are many engineering applications where the advantages of subcooled boiling can be profitably used. Some of the systems, where subcooled boiling occurs, are in the cooling of rocket motors, in the entrance regions of both conventional and nuclear boiler tubes, in the early sections of evaporator tubes and other equipments of process heat transfer. Subcooled boiling always precedes the process of boiling with net vapor generation.

Ellion (20) describes the flow pattern induced by a bubble in a subcooled boiling liquid in a lucid manner. When the vapor-

TABLE.2·3 CORRELATIONS FOR POOL BOILING OF SATURATED LIQUIDS.

No.	AUTHOR	CORRELATION
1	**Rohsenow (22)**	$\frac{h}{K}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}} = \frac{1}{C_{sf}}\left[\frac{q}{\mu\lambda}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right]^{0.67}\left(\frac{c\mu}{K}\right)^{-0.7}$
2	**McNelly (24)**	$\frac{h\,d}{K} = 0.225\left(\frac{q.d}{\mu\lambda}\right)^{0.69}\left(\frac{Pd}{\sigma}\right)^{0.31}\left(\frac{\rho_L-\rho_v}{\rho_v}\right)^{0.33}\left(\frac{c\mu}{K}\right)^{0.69}$
3	**Forster & Grief (27)**	$q = 1.2\times10^{-3}\frac{\alpha c\rho_L t_s}{J\lambda\rho_v\alpha^{1/2}}\left(\frac{c t_s\cdot\alpha^{1/2}}{J(\lambda\rho_v)^2}\right)^{1/4}\left(\frac{\rho_L}{\mu}\right)^{5/8}\left(\frac{c\mu}{K}\right)^{1/3}\Delta P^2$
4	**Kichigin & Tobilevich (30)**	$\frac{h}{K}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}} = 1.04\times10^{-4}\left(\frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right)^{0.7}\left(\frac{P}{\sqrt{\sigma(\rho_L-\rho_v)}}\right)^{0.7}\left[\frac{g}{\nu^2}\left(\frac{\sigma}{\rho_L-\rho_v}\right)^{3/2}\left(1-\frac{\rho_v}{\rho_L}\right)\right]^{0.125}$
5	**Kutateladze (30)**	$\frac{h}{K}\sqrt{\frac{\sigma}{\rho_L-\rho_v}} = 7.0\times10^{-4}\left(\frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right)^{0.7}\left(\frac{c\mu}{K}\right)^{-0.35}\left(\frac{P}{\sqrt{\sigma(\rho_L-\rho_v)}}\right)^{0.7}$
6	**Borishankii & Minchenko (30)**	$\frac{h}{K}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}} = 8.7\times10^{-4}\left(\frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right)^{0.7}\left(\frac{P}{\sqrt{\sigma(\rho_L-\rho_v)}}\right)^{0.7}$
7	**Kruzhilin & Averin (25)**	$\frac{h}{K}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}} = 0.082\left(\frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right)^{0.7}\left(\frac{c\mu}{K}\right)^{-0.5}\left(\frac{(\rho_v\lambda)^2}{Jct_s\rho_L\sqrt{\sigma(\rho_L-\rho_v)}}\right)^{0.377}$
8	**Labuntsov (29)**	$\frac{h}{K}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}} = 0.125\left(\frac{q}{\rho_v\lambda\alpha}\sqrt{\frac{\sigma}{(\rho_L-\rho_v)}}\right)^{0.65}\left(\frac{c\mu}{K}\right)^{-0.32}\left(\frac{(\rho_v\lambda)^2}{Jct_s\rho_L\sqrt{\sigma(\rho_L-\rho_v)}}\right)^{0.35}$

bubble becomes considerable in size and its top surface extends into cooler liquid, the condensation rate at the top of the bubble increases to such an extent that it exceeds the evaporation at the bottom, and bubbles begin to collapse. Subsequent pictures show the continuing collapse followed by the inrushing cold liquid which tends to reduce the surface temperature locally. Heat transfer from the wall again superheats the wall and the liquid; and the bubble cycle repeats.

Various aspects of surface-boiling heat transfer with forced circulation have been studied. Some of the important investigations carried out include the measurement of actual vapor volume flow fraction (32, 33), effect of degree of subcooling on the thickness of the bubble boundary layer (34), interaction of liquid velocity on turbulence created by boiling process (34, 35), and parameters affecting the bubble growth rate in subcooled nucleate boiling (36, 37). A number of correlations (32, 38, 39, 40) have been recommended for calculating heat transfer coefficients for subcooled boiling of liquids in tubes.

Subcooling has been found to increase the value of critical heat flux considerably. The observed increase of the critical heat flux is, in general, mainly due to an appreciable reduction of the direct vapor formation in the neighbourhood of the heating surface due to subcooling, whence the onset of film boiling is delayed. Amongst many others some of the important correlations for critical heat flux are due to Zuber et al (4), Ivey and Morris (5), Sterman (6) and Kutateladze (7).

2.3 NUCLEATE BOILING OF BINARY LIQUID MIXTURES

Broadly speaking the study of boiling heat transfer in binary liquid mixtures has been initiated to gain two aims. One group of workers confined their studies to determine the heat transfer coefficient during nucleate boiling while the other to obtain the conditions of parameters so that the peak heat flux could be increased considerably by adding an appropriate quantity of some suitable component to the pure liquid.

It was as early as 1937, Cryder and Finalborgo (41) initiated the study of heat transfer in nucleate pool boiling using 20 Wt. % glycerine in water. The saturated temperature of the mixture ranged from 56.7 °C to 113.2 °C and heat flux from 7×10^3 to 36×10^3 $\mathrm{Kcal/hr.m^2}$. The heat transfer surface was made of brass smooth polished pipe which was internally heated by electric heater. Based upon experimental data the following equation was suggested for calculating heat transfer coefficient.

$$h = 1.89\, q^{0.7} \left(\frac{t_s}{56.7}\right)^{1.32} \qquad (2.4)$$

Bonilla and Perry (42) determined the effect of adding ethanol, butanol and acetone to water on boiling heat transfer at atmospheric pressure. They compared these results with those of pure liquids.

In 1945 Cichelli and Bonilla (8) undertook the experimental study of nucleate pool boiling of propane-n heptane mixtures.

The test surface was a horizontal copper chrome-plated plate which was externally electrically heated. Their study was conducted for 33 Wt. % and 80 Wt. % n heptane mixtures, at pressure range of 17.93 to 32 kg/cm^2 and 4.15 to 15 kg/cm^2, for heat fluxes 5×10^4 to 5×10^5 $Kcal/hr.m^2$ and 2.5×10^3 to 37×10^4 $Kcal/hr.m^2$ respectively. For these systems the following respective equations for calculating heat transfer coefficients were recommended.

$$h = 1.07\, q^{0.7} \left(\frac{P}{17.93} \right)^{0.59} \tag{2.5}$$

and

$$h = 1.9\, q^{0.7}\, P^{0.62} \tag{2.6}$$

For 80 Wt. % heptane in the mixture in which pressure varied from 0.46 to 15.1 kg/cm^2 and heat flux from 35×10^3 to 38×10^4 $Kcal/hr.m^2$ with heating surface same as above, they recommended that the heat transfer coefficient can be calculated by the equation :

$$h = 1.3\, q^{0.7}\, P^{0.36} \tag{2.7}$$

Chernobyl'skii and Lukach (43) conducted experimental study to determine heat transfer coefficient from heated surface to boiling binary mixtures, benzene-toluene and ethanol-water, of varying concentrations using laboratory single tube vaporizers with the required control and measuring instruments. The heat flux was varied between 16,000 and 130,000 $Kcal/hr.m^2$ at 1 atmosphere pressure. The results have been expressed in the following form :

$$h = c\, q^{n} \tag{2.8}$$

The values of c and n vary with concentration of the more volatile component in the mixture.

Chi-Fang Lin et al (44) conducted boiling heat transfer studies of binary mixtures, ethanol-water and benzene-toluene, for heat flux ranging from 4,000 to 40,000 Kcal/hr.m^2 at pressures 200-760 mm. Concentrations of ethanol in ethanol-water were 5, 25, 60 and 91.8 percent by weight and that of benzene in benzene-toluene mixtures were 0, 12, 25, 50, 75, 88 and 100 Wt. percent. The heat transfer coefficient of pure liquid under various pressures have been correlated in the following forms :

Water

$$h = 4.0\ P^{0.2}\ q^{0.69} \qquad (2.9)$$

Benzene

$$h = 4.5\ P^{0.2}\ q^{0.6} \qquad (2.10)$$

Toluene

$$h = 3.1\ P^{0.7}\ q^{0.6} \qquad (2.11)$$

The experimental data for binary liquid mixtures have been found to be best correlated by modifying the Kruzhilin's equation (25) in the following form with error less than ± 10 percent.

$$Nu_B = 0.71\ Pr^{-0.45}\ K_q^{0.57}\ Ku^{1/3} \qquad (2.12)$$

Kutateladze's equation in its modified form correlates the data of binary mixtures with an error of approximately ± 10 percent. The modified equation assumes the following form :

$$Nu_B = 47.\times 10^{-4}\ Pr^{0.35}\ Re_B^{0.55}\ K_p^{0.65} \qquad (2.13)$$

Sternling and Tichacek (45) have determined heat transfer coefficient in a pool boiler for fourteen saturated binary mixtures at atmospheric pressure. The systems chosen for investigation were both ideal solutions or systems with strong positive and negative deviations from Raoult's law. Unlike others the experimental data have been obtained at over a wide range of compositions and heat fluxes. Experimental results of all systems tested, clearly demonstrate that boiling heat transfer coefficients decrease markedly as material of low volatility is added to the pure light component until there is specific composition of the system at which turnaround is observed. The turn around behaviour has been attributed to the changes in the rate of nucleation. In nucleate boiling, bubbles form and grow only at definite non-moving sites. Near active sites, the mixture becomes preferentially lean in light component as it feeds to the growing bubbles. In time, then, there will accumulate near the sites the material of low volatility. In order to maintain a nucleus of vapor on the site, the temperature there may have to be raised. The results show that, for the mixture possessing large relative volatility, boiling heat transfer coefficients are smaller by upto thirty fold than the appropriate average of the coefficients for the two pure components.

Huber and Hoehne (46) have measured the heat transfer coefficients for the pool boiling of benzene, diphenyl and benzene-diphenyl mixtures on a 3/8-in. out-side diameter horizontal tube at pressures ranging from 13.5 to 488.5 psia. They found that the nucleate pool boiling heat transfer coefficients for pure liquids to be best correlated by the Rohsenow (22), Gilmour (26) and Levy (28) equations. The surface superheat in the boiling benzene-diphenyl mixtures was found to be two to three times those of pure liquids at all pressures.

Tolubinskii and Ostrovskii (47) have determined the heat transfer rate during boiling of ethanol-water and ethanol-butyl alcohol mixtures at 1 atmosphere pressure. For these systems the rate of vapor bubble growth was found to be decreasing with the increase in the difference of concentrations of more volatile component in vapor and liquid phases. The experimental data of ethanol-water were correlated by the equation :

$$Nu_B = 75\,K_1^{0.7}\,Pr^{-0.2}\quad 1-(Y-X)^{1.85} \qquad (2.14)$$

Klimenko and Kozitskii (48) have studied the heat transfer in boiling of light hydrocarbon mixtures. For calculating heat transfer coefficient, the following correlation has been recommended.

$$h = 320\left[P_{crit}^{0.3}\;T_{crit}^{-0.85}\;M_{crit}^{-0.15}\right]$$

$$\times\left[0.62 + 3.0\,Pm/T_{crit}\right](F^{-m})\,q^{0.7} \qquad (2.15)$$

P and T in above equation refer to pressure and temperature respectively, M to molecular weight; F is a function for multicomponent mixtures; subscripts crit and m refer to psuedocritical conditions and to mean values respectively.

Filatkin (49) carried out experimental study in pool boiling of ammonia-water mixture on a 28 mm diam. and 450 mm long horizontal tube. The heat flux was varied four fold (from 5×10^3 to 20×10^3 Kcal/hr.m^2) and composition over a wide range. The plot of heat transfer coefficient as a function of concentration of ammonia in ammonia-water mixture shows that heat transfer coefficient decreases with the composition until there is 0.4 mole fraction ammonia at which turnaround is observed. Beyond this point heat transfer coefficient progressively increases with ammonia concentration. This characteristic behaviour is exhibited at all heat fluxes. For ammonia-water mixture the boiling heat transfer coefficient is lower than for either ammonia or water. The following reasons have been attributed to explain the turnaround in the above plots :

a. At 0.4 mole fraction ammonia, the value of (Y - X) is the maximum as a result of which the nucleation sites, where bubbles originate, are reduced to minimum values.

b. The maximum value of dynamic viscosity at 0.4 mole fraction ammonia seemingly lowers down the value of heat transfer coefficient to the lowest.

Pressure appears to increase the heat transfer coefficient of ammonia-water mixtures at low rate.

The experimental data of the above investigation have been correlated in the following form using Kruzhilin's theory of similarity. (25, 50).

$$\frac{h_L}{k}\sqrt{\frac{\sigma}{\rho_L-\rho_v}} = D\left(\frac{\alpha}{\nu}\right)^{0.45}\left[\frac{c\, t_s\, \rho_L\, \sigma^{0.5}(\rho_L-\rho_v)}{J(\lambda\, \rho_v)^2}\right]^{1/3} \times \left[\frac{J\, \rho_v\, \lambda\, q}{t_s\, k\,(\rho_L-\rho_v)}\right]^{n} \qquad (2.16)$$

The above Eq. (2.16) is valid for the following conditions :

(i) $Pr = \dfrac{\nu}{\alpha} = 1.3 \text{ to } 4.8$

(ii) $\dfrac{c\, t_s\, \rho_L\, \sigma^{0.5}(\rho_L-\rho_v)^{0.5}}{J(\rho_L\, \lambda)^2} = 1.0 \times 10^{-4} \text{ to } 206.0 \times 10^{-4}$

and (iii) $\dfrac{J\, \rho_v\, \lambda\, q}{k\, t_s\, (\rho_L-\rho_v)} = 0.3 \text{ to } 40.4$

The value of n and D can be calculated by the two expressions given below :

$$n = 0.70 - 0.24\,(Y - X) \qquad (2.17)$$

$$D = 0.083 + 0.33\,(Y - X) \qquad (2.18)$$

It may be stated that for mixtures with ammonia concentration from 0.2 to 0.41 the value of n will be minimum and that of D maximum.

Filatkin concludes that the effect of variation of Prandtl number, ν/α on heat transfer coefficient is less noticeable.

Boiling heat transfer studies of the mixtures of F-12 and F-22 have been reported to be made by O. P. Ivanov (51). Heat flux ranged from 2,000 to 25,000 Watts/m^2 and temperature from 240 $^\circ$K to 293 $^\circ$K. The concentration of low boiling component, F-22, were varied from 0 to 100 percent. For these ranges of parameters it was observed that the value of heat transfer coefficient of boiling mixture was minimum between 15 to 35 percent of F-22 concentration. The experimental data have been correlated using thermodynamic corresponding state. Ivanov has extended the method of corresponding state which was suggested by Borishanskii (52) for boiling of liquids in their pure state. Standard pressure, P*, for the mixture was taken analogous to that of pure liquids as used by Borishanskii and was calculated by the expression :

$$P^* = 0.03\, Pc^{PS} \tag{2.19}$$

where Pc^{PS} is pseudocritical pressure of the mixture and can be calculated as below taking into account the relative volatility.

$$P_c^{PS} = (P_c)_{F-12} + \psi \left[(Pc)_{F-22} - (Pc)_{F-12} \right] \tag{2.20}$$

ψ symbolizes relative volatility which is defined by the following expression

$$\psi = \frac{Y_{F-22}\,(1 - X_{F-22})}{X_{F-22}\,(1 - Y_{F-22})} \tag{2.21}$$

For ideal behaviour in both liquid and vapor phases Eq. (2.21) assumes the following form :

$$\Psi_{ideal} = \frac{(V.P.)_{F-22}}{(V.P.)_{F-12}} \qquad (2.21a)$$

Ivanov recommends the following relationship for heat transfer coefficient.

$$\frac{h/q^{0.75}}{h^{*}/q^{0.75}} = f\left[\frac{P}{P^{*}}\right] \qquad (2.22)$$

Tolubinskii et al (53) have conducted photographic study on the mechanism and have measured the heat transfer rate to the saturated boiling of water-glycerine mixtures at 1 atmosphere pressure over a wide range of concentrations. This study reveals that no reduction in break off diameters of vapor bubbles in boiling water-glycerine mixtures upto 70 Wt. percent glycerine was observed. Conversely, with increasing glycerine concentration the break off diameter d_b increased slightly with reduction in break off frequency, f, which resulted in a slight increase in rate of vapor bubble growth. For glycerine concentrations greater than 70 Wt. percent it was found that break off diameter, d_b was somewhat reduced and at very high concentration (94 Wt. percent) the diameter became markedly smaller and the frequency of the bubble break off dropped rapidly.

A continuous reduction in boiling heat transfer coefficient with increase in concentration of glycerine without any intermediate minimum upto 96 Wt. percent was observed.

Wright et al (54) have presented results for saturated nucleate and film pool boiling heat transfer to the binary mixtures of ethane and ethylene containing approximately 25, 50 and 75 mole percent ethylene as well as for the pure components. The pressure in their study ranged from near atmospheric to an approximate reduced pressure of 0.75. Boiling took place on the horizontal gold-plated surface of 13/16-in. diam. and 3.5-in. long cylinder. All nucleate boiling data were recorded with increasing heat flux and were taken prior to initiation of the film boiling to prevent high temperature deterioration of the gold-plated surface. The authors have compared the data obtained with pure components and binary mixtures with correlations developed for boiling pure components. Both Mc Nelly (24) and Kutateladze (30) equation correlate the data with average deviation of 42 percent and Borishanskii - Minchenko (30) with average absolute deviation of 48.7 percent.

Wright et al employed the Rohsenow's equation (22) in the empirically modified form proposed by Sciance et al (23) and was found to correlate all of the data with an average absolute deviation of 55.7 percent. The best fit line for the data was obtained in the following form :

$$\frac{\frac{q}{A}}{\lambda \mu_L} \sqrt{\frac{\sigma}{g(\rho_L - \rho_v)}} = 683.3 \left[\frac{C_L \Delta t}{\lambda} \left(\frac{T_R}{P_R} \right)^{1.18} \right]^{1.243} \qquad (2.23)$$

For a given mixture concentration both the nucleate and film boiling curves generally shifted to lower Δt values with increased pressure. The nucleate boiling data exhibit maximum Δt values corresponding to mixtures having highest relative volatilities.

2.4 GROWTH OF VAPOR BUBBLE IN BINARY LIQUID MIXTURE

The growth rate of a vapor bubble in a pure component depends only on the heat flow towards the bubble boundary to satisfy the heat requirement of evaporation (55, 56). In mixtures mass transfer of the more volatile component plays an important role in bubble growth and its frequency because this component is rapidly exhausted from the liquid layer near the bubble. This, in its turn, affects the physical properties of the liquid in the liquid layer, in particular, increases the saturation temperature, since the less volatile component predominates in the layer. Consequently, the process takes place with a reduced superheating of the liquid in the layer which results in a decreased bubble growth. Some of the important studies on growth rate of bubbles are discussed in the following paragraphs.

Grigorev and Usmanov (18) have determined analytically the effect of binary mixture composition on the value of minimum radius of curvature of a nucleation site, R_{min}, in a heating surface. The value of R_{min} can be calculated by the following equation :

$$R_{min} = \frac{2\sigma}{\left(\frac{dP}{dT}\right)_s (t_w - t_s)} \qquad (2.24)$$

The term $\left(\frac{dP}{dT}\right)_s$ is evaluated by Clausius-Clapeyron equation in case of pure liquids.

$$\left(\frac{dP}{dT}\right)_s = \frac{\lambda \rho_L \rho_v}{T_s(\rho_L - \rho_v)} \tag{2.25}$$

Unlike pure liquids the vapor pressure of a component in binary mixture depends upon the temperature as well as on the liquid composition. The following equation expresses vapor pressure as a function of temperature and liquid composition.

$$\left[(V_v - V_L) - (Y-x)\left(\frac{\partial V}{\partial x}\right)_{PT}\right] dP = \left[\frac{\partial^2 F}{\partial x^2}\right](Y-x)\, dx$$

$$+ \left[(S_v - S_L) - (Y-x)\left(\frac{\partial S}{\partial x}\right)_{PT}\right] dT \tag{2.26}$$

For the conditions of the systems (much away from the critical point) the following is found to be valid.

$$(V_v - V_L) >> (Y-x)\left(\frac{\partial V}{\partial x}\right)_{PT}$$

and

$$(S_v - S_L) >> (Y-x)\left(\frac{\partial S}{\partial x}\right)_{PT}$$

On using the above inequalities in Eq. (2.26) the following equation results

$$(V_v - V_L)\, dP = (S_v - S_L)\, dT + (Y-x)\left(\frac{\partial^2 F}{\partial x^2}\right) dx \tag{2.27}$$

or $$\frac{dP}{dT} = \frac{(S_v - S_L)}{(V_v - V_L)} + \frac{(Y-x)}{(V_v - V_L)} \frac{\partial^2 F}{\partial x^2} \frac{dx}{dT} \qquad (2.27a)$$

Substitution of value of $\frac{dP}{dT}$ from Eq. (2.27a) in Eq. (2.24) leads to the following form :

$$R_{min} = \frac{2\sigma}{\left[\left(\frac{S_v - S_L}{V_v - V_L}\right) + \left(\frac{Y-x}{V_v - V_L}\right) \frac{\partial^2 F}{\partial x^2} \frac{dx}{dT}\right](t_w - t_s)} \qquad (2.28)$$

The Eq. (2.28) shows that the value of R_{min} depends also on the concentration of boiling mixture.

It is important to examine the effect of the concentration term appearing in the denominator of Eq. (2.28), which is reproduced below, on the value of R_{min} in more perspective manner.

$$B = \left(\frac{Y-X}{V_v - V_L}\right) \left(\frac{\partial^2 F}{\partial X^2}\right) \frac{dX}{dT}$$

The term Y-X will always be positive for non-azeotropic binary mixtures whereas for azeotropic mixtures it is positive upto the point of azeotrope and negative beyond it. The complex B may have either a positive or negative sign. The effect of sign before B on R_{min} is discussed as follows for non-azeotropic mixtures only.

a. If the sign is positive, then an increase in the value of (Y-X) will activate a greater number of nuclei by making smaller ones active. This, in turn, will raise the rate of vapor bubble formation and thereby the value of heat transfer coefficient will be increased.

b. For negative sign of B, increase in the value of (Y-X) will activate the limited number of nuclei. Thus the heat transfer coefficient will be decreased.

The sign before complex B depends upon the signs of the terms, $\left(\frac{Y - X}{V_v - V_L}\right)$ and $\left(\frac{\partial^2 F}{\partial X^2}\right)\frac{dX}{dT}$ which are considered separately as follows :

For the state of the system, far from critical point, $(V_v - V_L)$ is always positive. The sign, therefore, depends upon the sign of (Y - X) which is always positive for non-azeotropic mixtures.

Expressing the second term in the following form provides better understanding as regards the sign before it.

$$\left(\frac{\partial^2 F}{\partial x^2}\right)_v \frac{dx}{dT} = \frac{Q_{12}}{T}\left\{\frac{\lambda_{LB} - \lambda_{HB}}{Q_{12}} + \frac{(\Delta V)_{HB} - \Delta V_{LB}}{V_{12}}\right\} \qquad (2.29)$$

Q_{12} is differential latent heat of vaporization. For the state of system, far from critical point, the following is found to hold true .

$$\frac{\lambda_{LB} - \lambda_{HB}}{Q_{12}} >> \frac{\Delta V_{HB} - V_{LB}}{V_{12}}$$

Therefore Eq. (2.29) assumes the form

$$\left(\frac{\partial^2 F}{\partial x^2}\right)_v \left(\frac{dx}{dT}\right) \cong \frac{\lambda_{LB} - \lambda_{HB}}{T} \qquad (2.30)$$

The above treatment suggests that the sign before left hand side term depends upon the difference of values of latent heat of vaporization of more volatile component and less volatile component in the mixture.

Recently a considerable number of workers (14, 15, 16),) have determined the size of vapor bubbles in different binary systems by taking their photographs. The photographic study has proved quite useful to calculate the growth of vapor bubble in liquid mixtures. An extensive photographic study was carried out by Tolubinskii et al (14) to calculate the growth rate of vapor bubbles on a superheated surface in pure liquids and binary mixtures. They have shown the effect of concentration of more volatile component on the rate of vapor bubble growth. In this study binary mixtures of two types - azeotropic and non azeotropic were included. Based on the results of the photographic study, the following important conclusions were drawn.

The rate of vapor bubble growth in non-azeotropic binary mixture is found to decrease with the increase in concentration of more volatile component upto a certain concentration. Beyond this concentration it begins to increase. The concentration at which the rate of bubble growth is minimum corresponds to a maximum value of (Y - X). The quantity (Y - X) is observed to affect the rate of vapor bubble growth in binary liquid mixtures significantly.

In his most extensive investigations on boiling of binary mixtures van Stralen (16) has analysed the problem of growth rate of a vapor bubble which is generated on a superheated heating surface. The radius R of a free, spherically symmetric growing, bubble the boundary of which is entirely surrounded by an infinite volume of superheated liquid, is given by

$$R = \left(\frac{12}{\pi}\right)^{1/2} \frac{k}{\rho_v \lambda \alpha^{1/2}} \vartheta_o \theta^{1/2} \tag{2.31}$$

$$= C_1 \vartheta_o \theta^{1/2} \tag{2.32}$$

Where ϑ_o is superheating of the heating surface. The growth Eq. (2.32) is also valid for binary mixtures. The growth constant C_1 for a constant liquid superheating depends then on the concentration of the more volatile component according to the expression:

$$C_1 = \left(\frac{12}{\pi}\right)^{1/2} \frac{\alpha^{\frac{1}{2}}}{\frac{\rho_v}{\rho_L}\left\{\frac{\lambda}{c} + \left(\frac{\alpha}{D}\right)^{1/2} \frac{\Delta t_x}{G_d}\right\}} \tag{2.33}$$

Eq. (2.33) shows that C_1 possesses a minimum value in coincidence with a maximum in $\Delta t_x / Gd$, usually occuring at a small concentration of more volatile component. A relationship between $\Delta t_x / G_d$ and concentration x has been derived from equilibrium data in the following form :

$$\frac{\Delta t_x}{G_d} = -x_o (K-1) \left(\frac{dt}{dx}\right)_{x = x_o} \tag{2.34}$$

The photographic study of the vapor bubble growth in water-methyl ethyl ketone was found to agree well with the theoretical prediction by Eq. (2.32).

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 EXPERIMENTAL SET UP

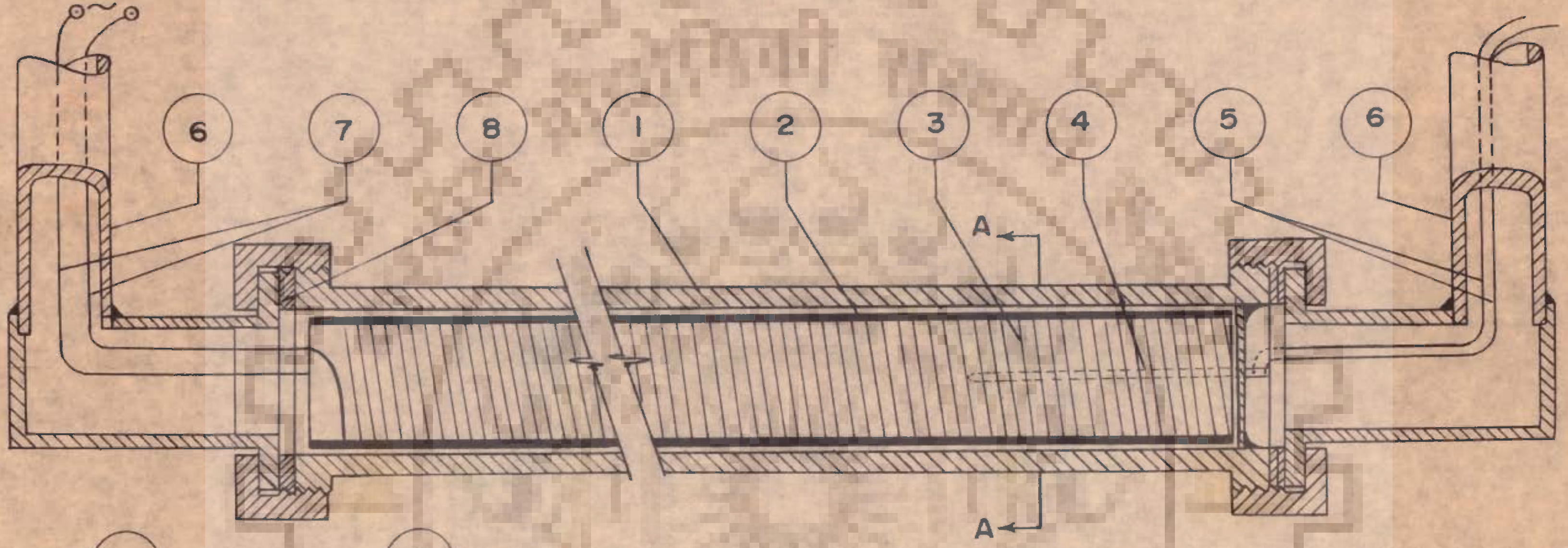
The experimental set-up is shown schematically in Figure 3.1 and by photograph in Figure 3.2. The vessel for holding the test liquid was made of aluminium. It was cylindrical in shape 282 mm inside diameter and 425 mm long provided with a conical bottom and a flanged top cover. A 3-kilowatt auxiliary heater was fitted in the cylindrical portion of the vessel near the bottom in order to raise the liquid temperature to the desired value and also to drive off the dissolved air from the test liquid before taking the experimental runs. The electrical power to the heater was regulated by a temperature controller. A water-cooled condenser was provided below the cover of the vessel to condense the vapors and return the condensate back to the pool of liquid. The condensate drips are likely to generate additional turbulence in the boundary layer near the test surface which can affect the rate of heat transfer from the surface to the liquid. To safeguard against this source of error a clearance of about 140 mm between the condenser and the top of the pool of liquid was provided. Thus the descending condensate drips could be heated up by the ascending vapors before joining the top of the pool, and the penetration of the drips was restricted to a very small distance down the top of the pool. Besides this the test section was submerged to a depth of about 150 mm from the top of the liquid pool. Hence the boundary layer could be kept away from the turbulence due to condensate drips joining the liquid pool.

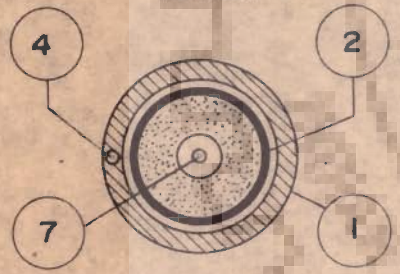
Another important consideration was to maintain the uniformity of the concentration of liquid mixtures as far as practicable without causing much additional turbulence. In order to achieve uniformity of concentration a recirculation loop attached to the side of the vessel was provided. The details of the loop are readily identified in Figures 3.1 and 3.2. The level of the pool in the vessel was kept high enough so that the recirculation loop was always full of liquid. The valves B and C were kept open wide. On heating, the liquid in the vessel becomes less dense and thus heated liquid rises upward in the vessel; while liquid in the recirculation loop moves downward as it becomes denser due to cooling in the jacket. As such a closed liquid circulation circuit set in which helped in equalizing the concentration of the liquid mixture throughout the pool considerably and without adding appreciable turbulence.

Diametrically opposite sight glasses were provided in the vessel to permit the visual observation of the bubble dynamics on and near the test section. The vessel body was thoroughly lagged with rockwool insulation so that the heat loss from the vessel to the surrounding was almost negligible. Since the vessel dimensions were large as compared to those of test surface, the temperature gradient existed only within a small distance off the test surface (boundary layer) beyond which the temperature gradient was negligible when heat transfer took place from the test surface.

The details of test section are shown in Figure 3.3. The test section consisted of a horizontal brass tube of 27 mm outside diameter, 3.5 mm thick and 160 mm long. The outer surface of the test section was turned smooth and was further rubbed against emery paper. The internal heating by an electric heater was done in the present investigation. The heating element was made of nichrome wire (gauge 26) wound on a porcelain rod 16 mm outside diameter with 8 turns per cm on it. The rod alongwith element was thoroughly wrapped with thin mica sheet which ensured electrical insulation between the heating element and the test section tube. Alternate current was supplied to the electric heater and was regulated by an auto-transformer. The supply voltage was held constant by means of an A.C. voltage stabilizer. Thus the heat flux could be maintained constant at desired value. The energy input to the heater was measured by a single phase electrodynamometer type wattmeter with an accuracy of less than 1.25 percent. The whole assembly of test section was suspended from the top cover of the vessel which is shown in Figure 3.1. Experimental data of water-acetic acid and acetone-water mixtures were taken on a similar test section of brass tube, 25.6 mm outside diameter, 3.3 mm thick and 155 mm long. The outer surface of the test section was silver plated.

One of the objectives in the present investigation was to obtain the local heat transfer coefficients because this information permits a detailed study of the thermal response to the changes in heat flux, temperature levels and concentrations of the liquid





SECTION AT A–A

1. TEST SECTION
2. MICA SHEET
3. ELECTRICAL HEATER
4. THERMOCOUPLE
5. THERMOCOUPLE LEADS
6. COPPER TUBE
7. ELECTRICAL LEADS
8. GASKET

FIG. 3·3 TEST SECTION DETAILS

mixtures, and provides a nearly complete physical picture of the process. The local heat transfer coefficient can be readily calculated by using the values of local temperatures in the following equation

$$h = \frac{q}{(t_W - t_L)} \qquad (3.1)$$

The important consideration, therefore, was the measurement of the wall and liquid temperatures. A calibrated copper-constantan thermocouple (gauge 26) was used to register the heat transfer surface temperature. The thermocouple bead (hot junction) was inserted in a hole bored in the wall of the test section at an axial distance of 50 mm from the right end (Fig. 3.3) and oriented in the horizontal plane passing through the axis and the hole was filled with araldite. Thermocouple location in the wall is shown in the sectional view at A - A in Figure 3.3. As the thickness between the thermocouple location and outer surface of the test section was very small and the thermal conductivity of metal (brass) was high, the temperature drop across the metal thickness was observed to be negligibly small (Appendix F) hence the thermocouple readings represented the outer surface temperature.

There raised a potential problem as to where to locate the liquid thermocouple position in the horizontal plane passing through the axis of the test section so that it may monitor the bulk-liquid temperature. This prompted to measure liquid temperature variation at normal distances from the test section. From the experimental data, as shown in Figures A-1, A-2 and A-3 of Appendix A, it is clear that the maximum distance beyond which temperature does not vary any more is about 5 mm off the heating surface. However, a calibrated copper-constantan thermocouple probe was placed at a distance of 20 mm from the test surface. The probe consisted of a copper-constantan thermocouple (Gauge 26) passing through a 6 mm diameter glass tube with its bead (hot junction) just projecting from one end of the tube. The couple leads were taken out from the other end which, in turn, were connected to a selector switch through proper sheath. The bead end of glass tube was made leakproof by sealing with an adhesive (araldite). The probe was positioned through the vessel cover as shown in Figure 3.1. The thermocouples (wall and liquid) were connected through a selector switch to a cold junction and a potentiometer. The cold junction was maintained at 0 °C by dipping it in melting ice bath. The e.m.f. of thermocouples was measured by a vernier potentiometer with mirror galvanometer and lamp and scale arrangement. The potentiometer could read e.m.f. upto 0.001 mV with an accuracy of 0.01 percent.

3.2 EXPERIMENTAL PROCEDURE

3.2.1 Performance of Thermocouples

The performance of the thermocouples placed in the test section wall and in the liquid was examined. A standard mercury in glass thermometer of 0.1 °C least count was placed in the liquid.

Then the liquid temperature was raised gradually by means of auxiliary heater. The readings of the thermocouples and thermometer were recorded after thermal equilibrium was attained. From the data as given in Table A-1 of Appendix A, it is seen that the thermocouple readings deviate from those of the thermometer by a maximum value of 0.1 percent.

3.2.2 Calibration of Wattmeter

The wattmeter was calibrated against a substandard wattmeter, BS-89 Grade Pr supplied by M/s. Cambridge Industrial Co. Ltd., London. The calibration readings have been recorded in Table A-2 of Appendix A which shows a maximum error of 1.08 percent.

3.2.3 Operating Procedure

The experimental apparatus was set as shown in Figures 3.1 and 3.2 and all the water, electric and thermocouple connections were made. The vessel and recirculation loop were filled with water and checked against any leaks. The electric leak was also carefully checked and rectified. Water was drained off completely and the system was filled with distilled water. Before conducting the main experiment it was felt necessary to stabilize and age the test surface. To achieve this, the auxiliary heater was switched on and the temperature controller was adjusted so that water was kept boiling at its saturation temperature for an hour. After removal of dissolved air the heating element in the test section was energized and auxiliary heater was switched off. The wall and liquid temperature were noted when they became steady at various heat fluxes. Similar runs were taken after 4 hours boiling and 24 hrs. aging and successively 8 hours boiling and 48 hrs. aging. The data collected during stabilization have been shown in Figure 3.4. After boiling for several hours and aging for several days the data were found to be reproduced which ensured the stability characteristics of the test surface. Then the first series of experimental runs were taken with distilled water.

With all the test liquids the level of the liquid in the vessel was kept above the inlet of the recirculation loop and the liquid was boiled by means of auxiliary heater at its saturation temperature for about two hours till no more escape of the dissolved air from the liquid was observed. Water supply to the water-cooled condenser and to the jacket of the recirculation loop was resumed before allowing the boiling to occur. The condenser condensed the vapors and returned the condensate back to the pool. Thus the concentration of the liquid was maintained constant as far as practicable during the period of experimentation. The condenser along-with cooling jacket also helped in adjusting and maintaining the desired degree of subcooling. After removal of last traces of dissolved air from the test-liquid, the auxiliary heater was switched on. The desired heat flux was then adjusted and the readings of thermocouples' e.m.f. and wattmeter were noted only when the wall and liquid temperature became steady. Steady state conditions of

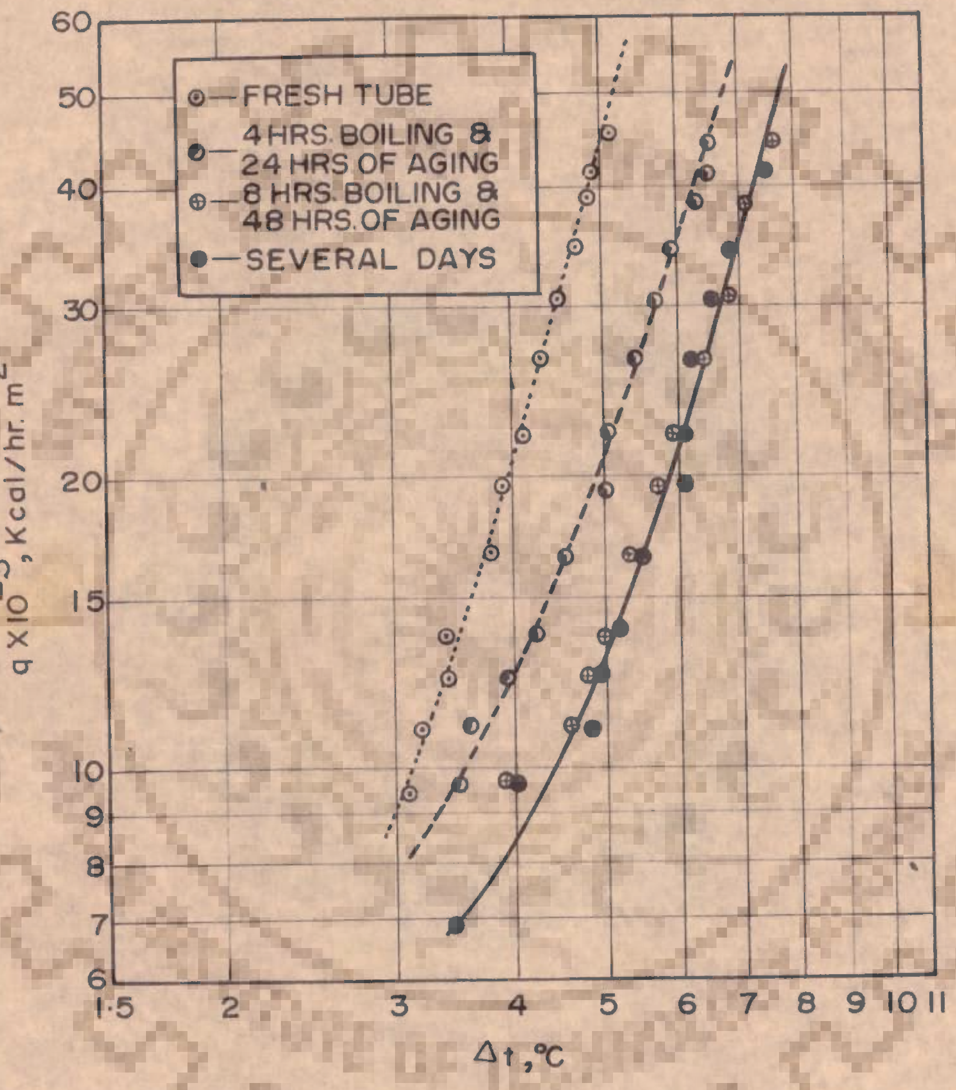


FIG. 3·4 q VERSUS Δt DURING STABILIZATION OF TEST SURFACE.

approximately 10 minutes' duration were established at each test point prior to recording the data. It was observed that the wall temperature taken just after switching off the auxiliary heater changed with time and it took about 15 minutes before the wall temperature became steady. All the data were taken with increasing heat flux.

Before switching to a new system a few experimental runs were taken with distilled water as check tests which have been shown in Figure 3.5 for both the test sections. Good agreement between values obtained prior to and after boiling data with mixtures indicates that heat transfer surface characteristics did not change significantly during the tests. The dotted curve in Figure 3.5 is for data taken on 25.6 mm O.D. test section and lower curve on 27 mm O.D. test section. The negligible difference between two curves shows that the surface characteristics of the two test sections were almost identical. The 27 mm O.D. test section was used for water-glycerine and water-ethylene glycol mixtures, and 25.6 mm O.D. silver plated test section for water-acetic acid and acetone-water mixtures. A liquid level indicator was provided to the vessel and its reading was noted before starting the experiment. During the course of whole series of runs the level of liquid almost did not change.

The binary mixture used for the present investigation were water-glycerine, water-ethylene glycol, water-acetic acid

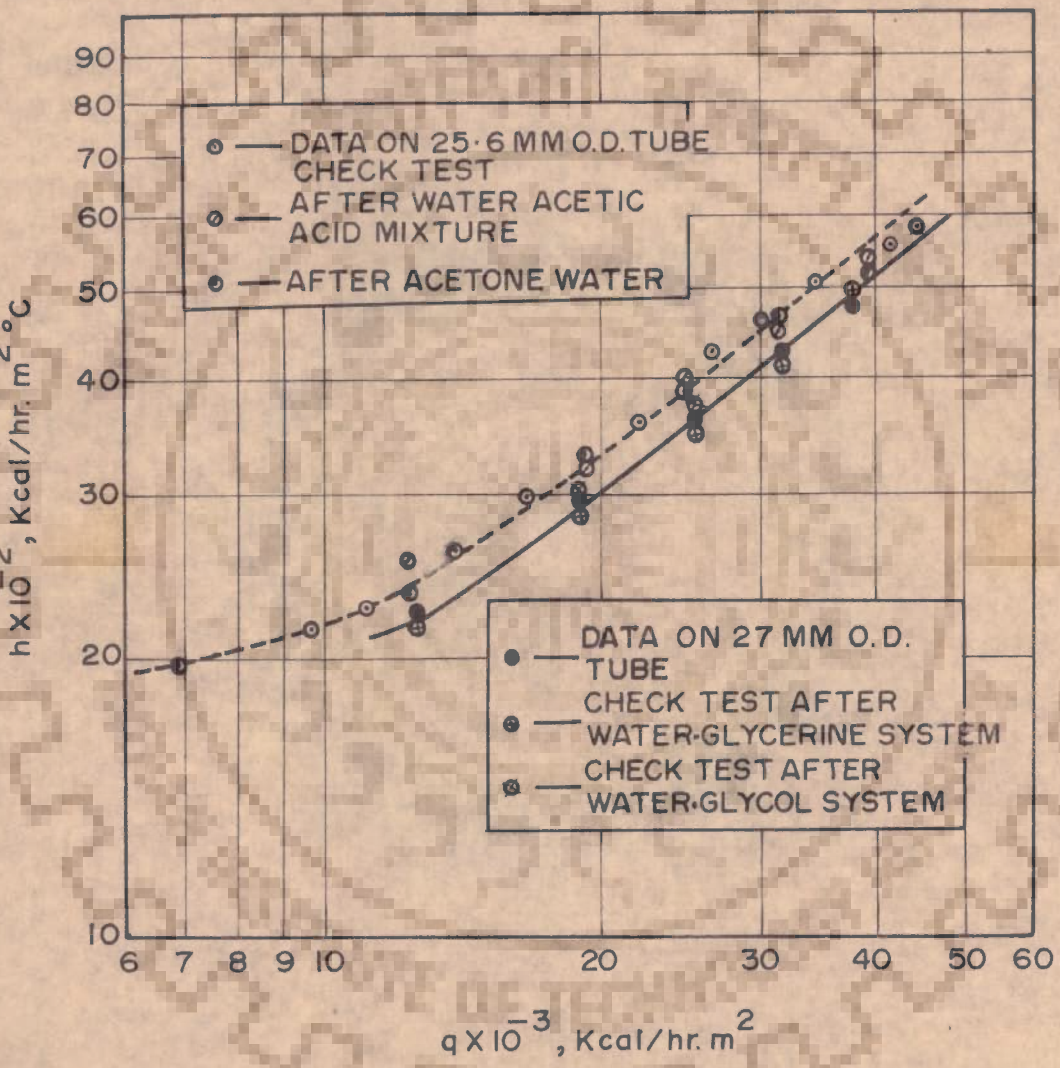


FIG. 3·5 REPRODUCIBILITY OF SURFACE CHARACTERISTICS OF TEST SECTION.

and acetone-water mixtures. Acetic acid and acetone were of reagent grade while glycerine and ethylene glycol were of commer cial grade. The heat flux changed step-wise from 6.9 x 10^3 Kcal/hr.m^2. The degree of subcooling was varied in such a way that data could cover from natural convection through subcooled to saturated boiling regions.

:CHAPTER 4

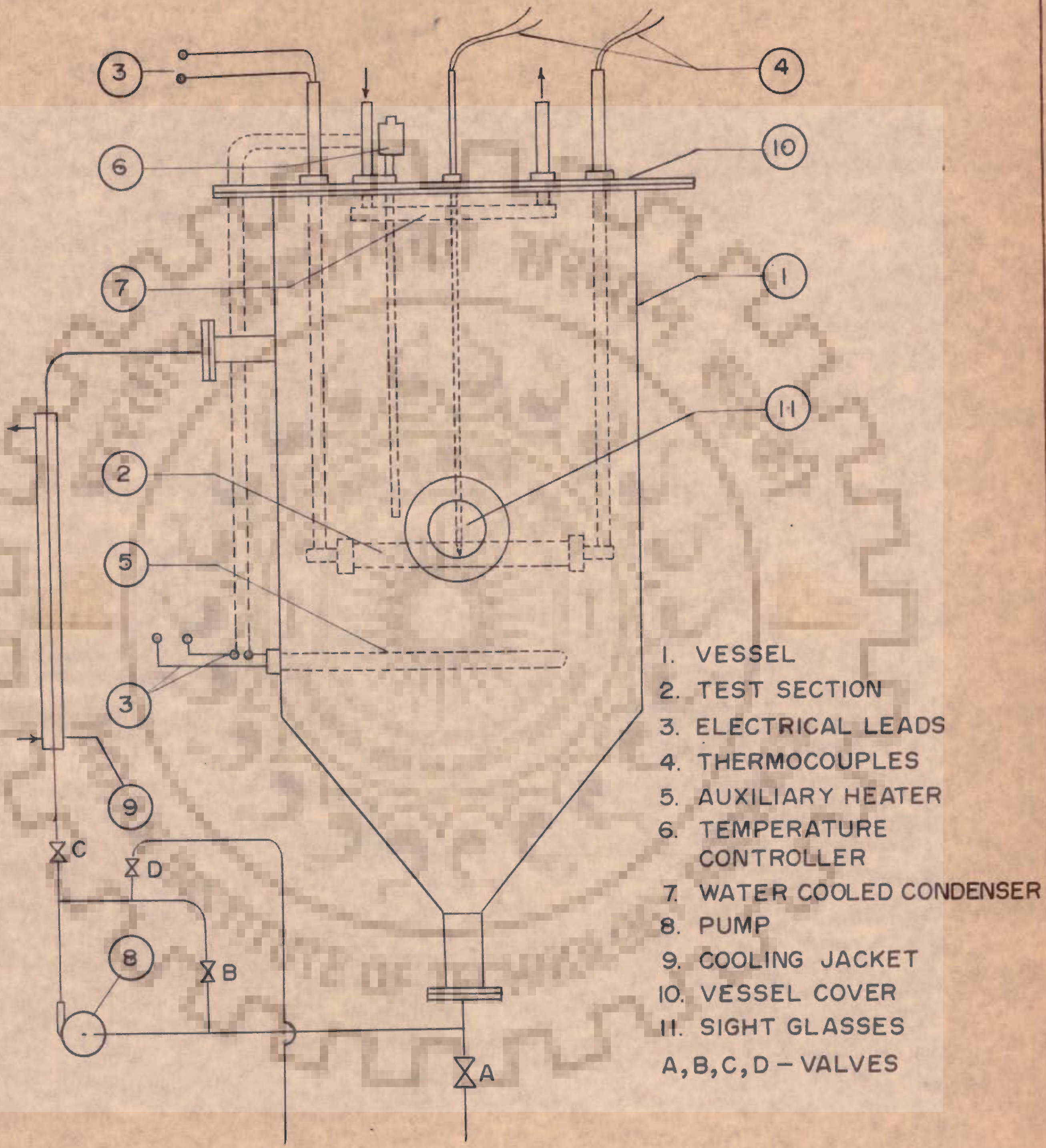
RESULTS AND DISCUSSION

In the present chapter the experimental data on pool boiling of pure liquids : distilled water, acetic acid, and acetone; and binary mixtures : water-glycerine, water-ethylene glycol, water-acetic acid, and acetone-water systems at 1 atmosphere pressure, have been discussed with reference to some of the important results. The data cover the regions of low heat flux extending from non-boiling through surface boiling to saturated boiling. Table 4.1 enlists the composition of the binary mixtures used in the present investigation.

Table 4.1 Concentrations of Binary Mixtures Studied

System No.	More volatile component	Less volatile component	Wt. % of more volatile component
1	Water	Glycerine	15, 17.5, 27.5, 50, 55.5, 65, 86, 100.
2	Water	Ethylene glycol	1, 4.5, 9.1, 14.6, 20.2, 29.8, 37.5, 57.4, 78.2, 100
3	Water	Acetic acid	0, 4.8, 9.6, 14.4, 19.3, 29.1, 38.9, 58.8, 79.3, 100
4	Acetone	Water	0, 12.25, 25.3, 39.3, 54.4, 70.4, 87.8, 100

For water-glycerine system the experimental data could not be taken below 15 Wt. percent water because of excessively high temperature on the heater which proved unsafe. The data for systems ,



1. VESSEL
2. TEST SECTION
3. ELECTRICAL LEADS
4. THERMOCOUPLES
5. AUXILIARY HEATER
6. TEMPERATURE CONTROLLER
7. WATER COOLED CONDENSER
8. PUMP
9. COOLING JACKET
10. VESSEL COVER
11. SIGHT GLASSES

A, B, C, D – VALVES

FIG. 3·1 SCHEMATIC DIAGRAM OF EXPERIMENTAL SET UP.

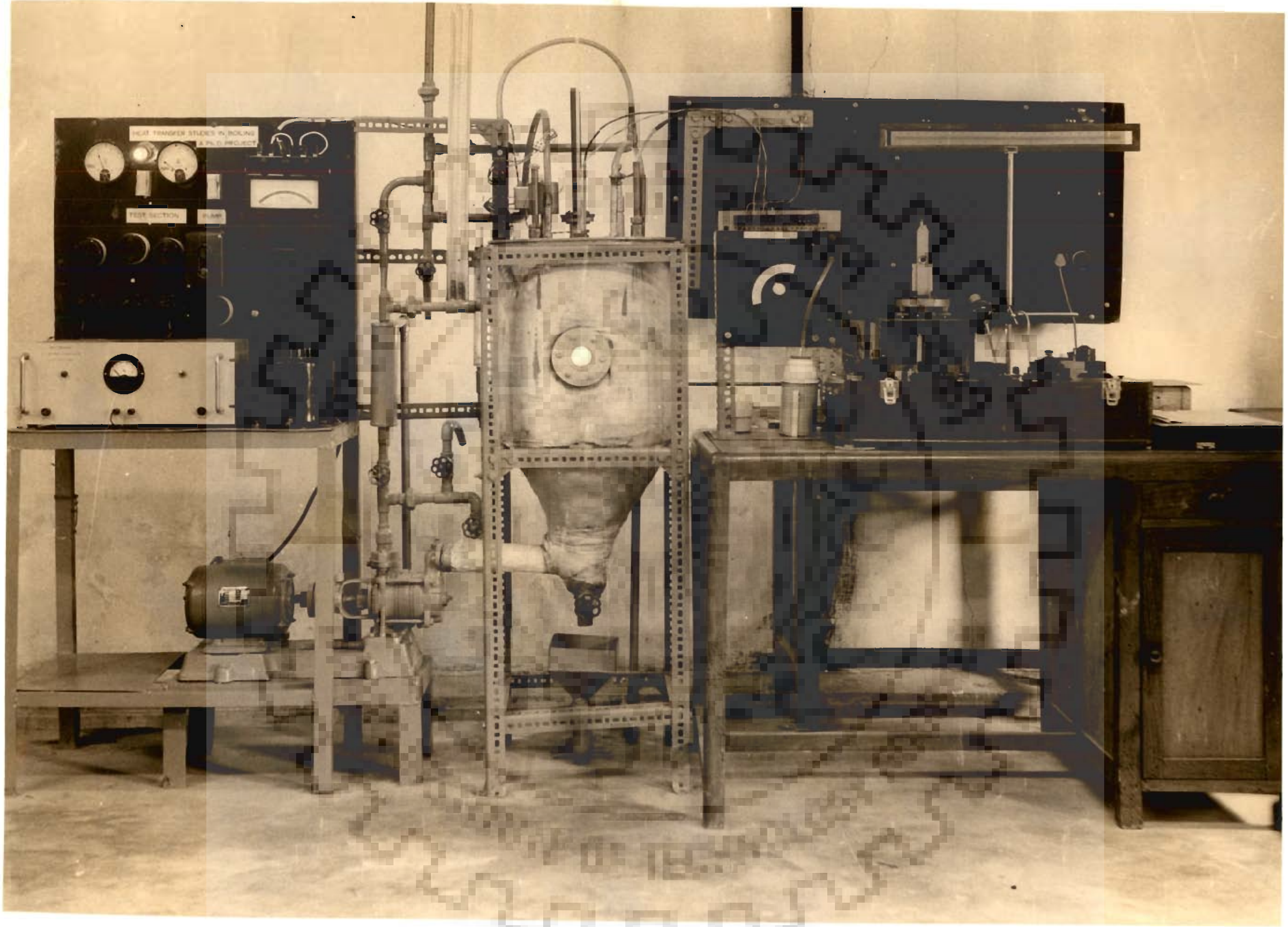


FIG. 3·2 OVERALL APPARATUS LAYOUT

water-glycerine and water-ethylene glycol were taken on the 27 mm O.D. test section at heat fluxes ranging from 12.66 x 10^3 to 38.00 x 10^3 Kcal/hr.m^2 ,while for water-acetic acid and acetone-water on 25.6 mm O.D. test section at heat fluxes from 6.9x10^3 to 39.9x10^3 Kcal/hr.m^2 .

The experimental data of the present investigation are listed in Appendix E.

4.1 NUCLEATE POOL BOILING OF PURE LIQUIDS

4.1.1 Variation of Wall Temperature with Liquid Temperature

Figures 4.1 and 4.2 show plots of wall temperature versus liquid temperature at different values of heat flux for distilled water and acetic acid, respectively. On examining these figures, the following characteristic features may be noted :

a. The wall temperature, t_W, changes linearly with the liquid temperature, t_L , upto a certain point 'B', followed by a decreasing slope which finally becomes zero. The point 'B' is distinct in all the curves and for all such points the value of t_W is essentially greater than the saturation temperature, t_s . The wall temperature corresponding to point 'B' is 101.5 °C, and 120 °C for water and acetic acid, respectively.

b. At higher values of heat flux, the curves are found to have essentially the same features as those at lower value of heat flux with the difference that the point 'B' is shifted to

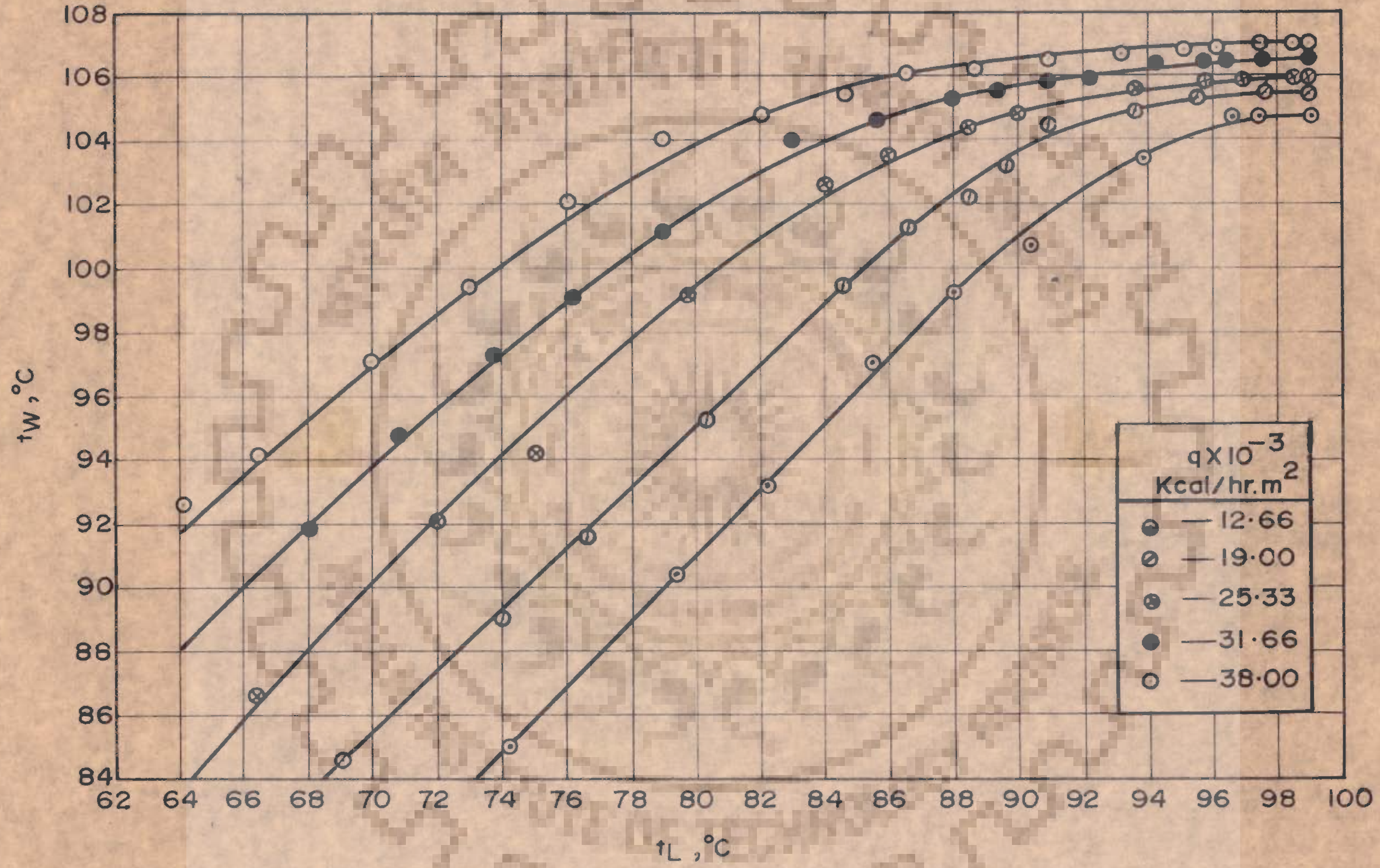


FIG. 4·1 VARIATION OF t_W WITH t_L FOR POOL BOILING OF WATER.

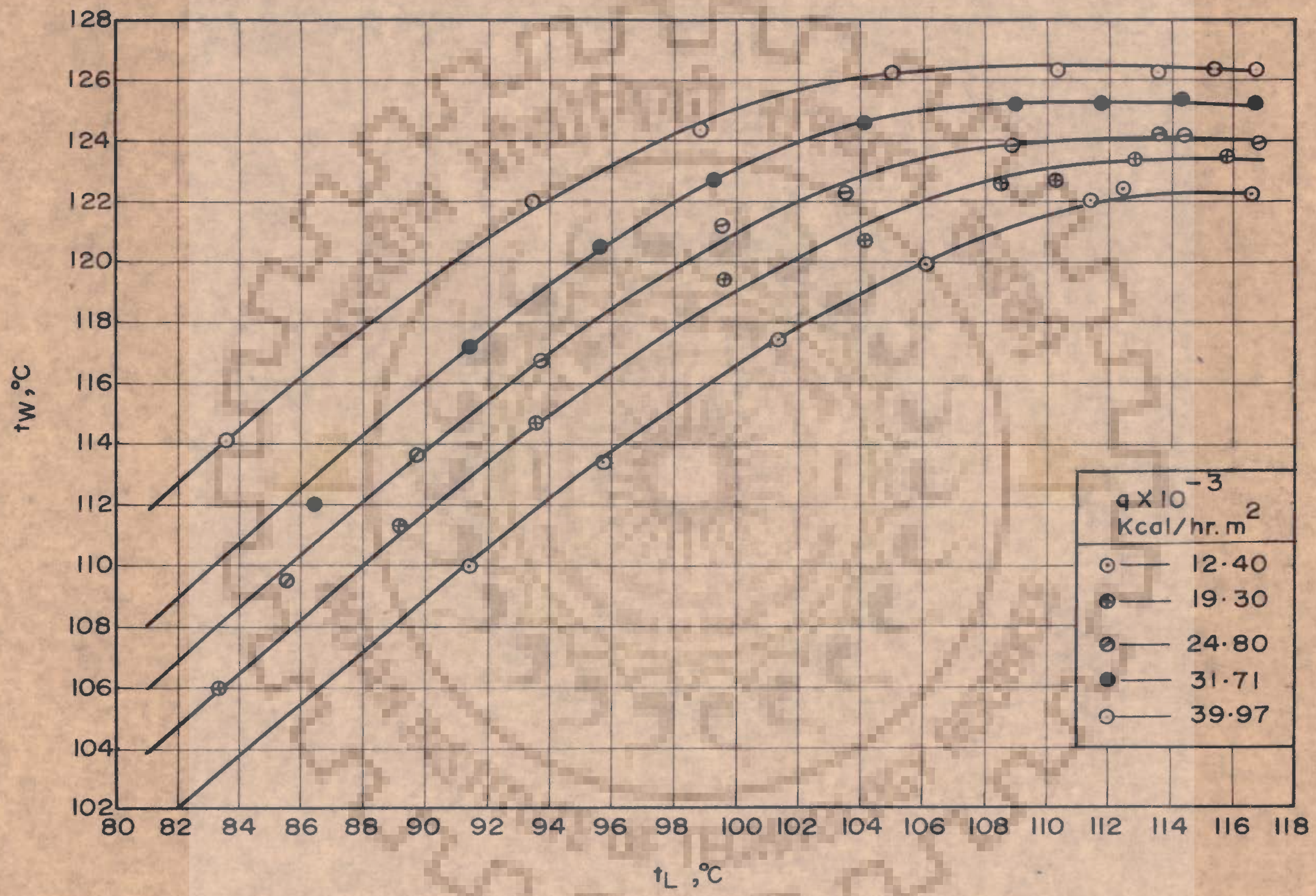


FIG. 4·2 VARIATION OF t_W WITH t_L FOR POOL BOILING OF ACETIC ACID.

the lower values of liquid temperature. However the value of t_W at point 'B' remains almost unaffected.

The region corresponding to the linear change upto point 'B' in all the curves is due to natural convective heat transfer because in this region near-constancy in the value of ($t_W - t_L$) is observed. The fact, that the natural convective region extends even for $t_W > t_s$, may be attributed to the following reason . It has been found that the minimum amount of degree of superheat, ($\Delta t_{sup} = t_W - t_s$) is absolutely necessary for facilitating the bubble formation on the heating surface in saturated liquids and it depends on the microstructure of the surface. The minimum radius of curvature of a nucleation site for bubble formation may be expressed as a function of Δt_{sup} and other parameters by the expression (59).

$$R_{min} = \frac{2\sigma}{\frac{dP}{dT}(t_W - t_s)(\rho_L - \rho_v)} \qquad (4.1)$$

As seen from Eq. (4.1), an increase in the value of Δt_{sup} activates greater number of nuclei by making smaller ones active. It is, of course, realized that Eq. (4.1) is applicable for saturated liquid boiling. It is felt that the degree of superheat required for bubble formation in subcooled liquids should be greater than that calculated by Eq. (4.1). Therefore a certain value of Δt_{sup} is necessary before significant boiling can begin. This seems to be the reason why the linear region extends upto point 'B'.

Beyond point B, a gradual increase in the value of Δt_{sup} and decrease in the value of Δt_{sub} make the boiling process increasingly effective. Therefore wall temperature changes with a decreasing rate. After a certain value of Δt_{sub} is reached, the turbulence caused by the bubble dynamics becomes so high that the adverse effect of subcooling on nucleation process becomes insignificant. Under such a condition, therefore, the wall temperature seems to attain a constant value. This observation is in accordance with the findings of Forster and Grief (27) who processed the data of Ellion (60).

Shifting of point 'B' to the lower values of t_L at higher values of heat flux is expected because the number of nuclei for bubble formation becomes increasingly more at higher heat fluxes.

4.1.2 Variation of Heat Transfer Coefficient with Heat Flux

In Figures 4.3 and 4.4, log-log plots between heat transfer coefficient and heat flux have been drawn for water and acetic acid, respectively. The experimental data of a number of other authors (49, 57, 30, 58) have also been shown in Fig. 4.3 for saturated pool boiling of water at 1 atmosphere pressure. These figures suggest the following :

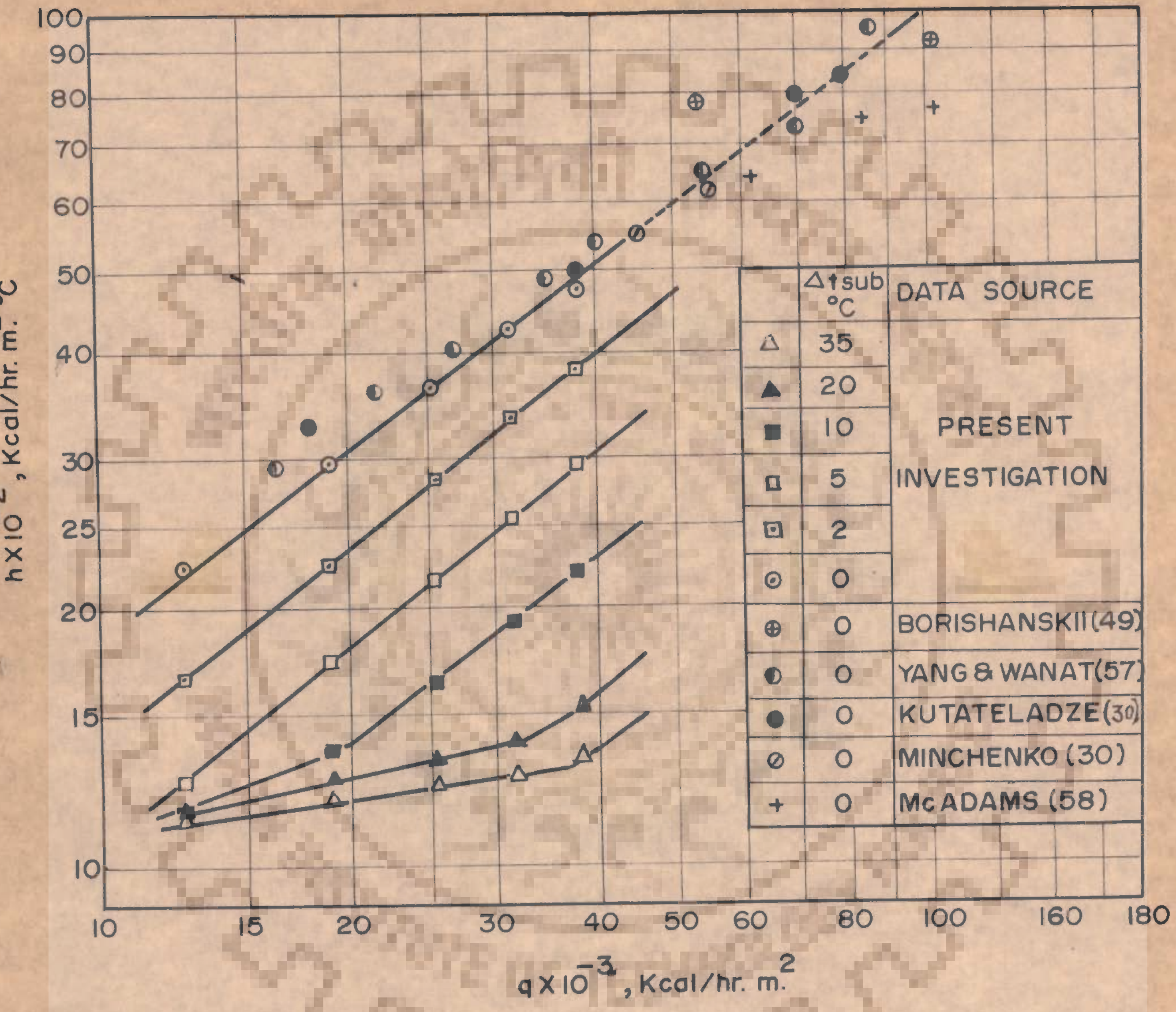


FIG. 4·3 VARIATION OF h WITH q FOR POOL BOILING OF WATER.

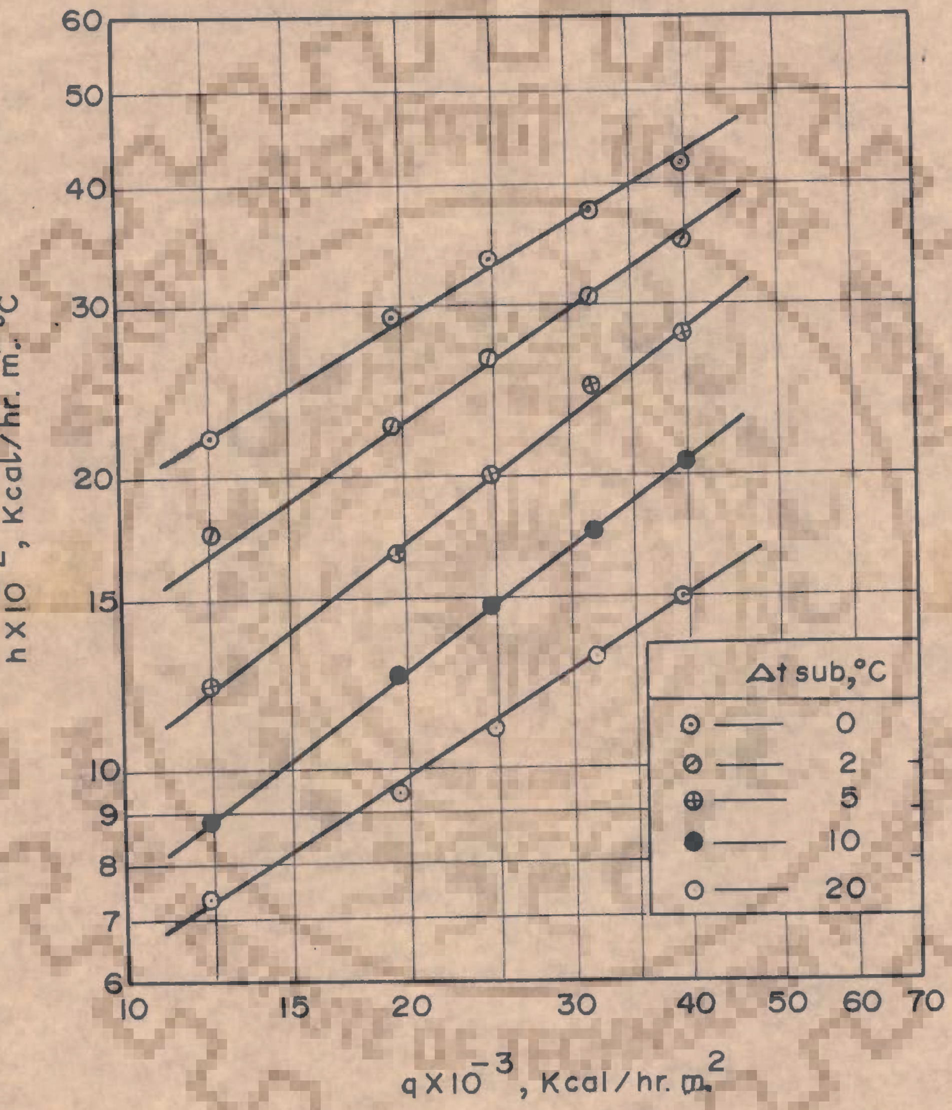


FIG. 4·4 VARIATION OF h WITH q FOR POOL BOILING OF ACETIC ACID.

a. Heat transfer coefficient increases linearly with q with a slope of about 0.7 for saturated boiling of water and about 0.66 for acetic acid. The data of others (49, 57, 30, 58) for water agree well with the data of the present investigation. This ensures that the measurements and techniques used for data collection in the present experimental investigation are reliable. A small scatter amongst the data may be attributed to the differences in the nucleation characteristics of the heating surfaces. The increase in the value of h with q is clearly understandable from the fact that the number of nucleation sites becomes greater as q is raised.

b. Increase in Δt_{sub} shifts the curve to the right suggesting that for a given heat transfer coefficient higher values of heat flux are required if Δt_{sub} is increased. The relative positions of the curves seem to suggest that bulk temperature of liquid has a considerable influence on boiling.

The higher values of Δt_{sub} suppress the boiling process and this effect is more pronounced at low values of q. But at higher values of q, the adverse effect of Δt_{sub} on the boiling process is reduced, because more centres of bubble formation become active. Therefore, the value of h tends to increase with q first slowly upto the breaks in the curves beyond which a marked rise in the values of h occurs. The decrease in the value of Δt_{sub} is favourable for the bubble growth which, in its turn, increases the value of h.

4.1.3 Boiling Curves for Pure Liquids

Figure 4.5 presents the boiling curves for saturated pool boiling of acetone, water and acetic acid. In these curves, the variation of heat flux has been shown as a function of temperature difference between the heat transfer surface and the saturation temperature of liquids on a log-log plot. A similar behaviour is noted in all the curves and it is observed that the value of Δ t increases as the heat flux is raised.

4.1.4 Effect of Subcooling on Boiling Heat Transfer

The results shown in Figures 4.3 and 4.4 seem to suggest that the degree of subcooling affects the value of heat transfer coefficient significantly. Figures 4.6 and 4.7 have been drawn in which Nusselt number is plotted as a function of degree of subcooling in the dimensionless form $\left(1 + \sqrt{\frac{\rho_L}{\rho_v}} \frac{\Delta t_{sub}}{t_s}\right)$. All the experimental data are found to be represented in the following functional form :

$$Nu_B = C_1 \left(1 + \sqrt{\frac{\rho_L}{\rho_v}} \cdot \frac{\Delta t_{sub}}{t_s}\right)^{n_1} \qquad (4.2)$$

The value of exponent is observed to be almost same for both the liquids. The constant C_1 depends on the values of Peclet number and the properties of the liquids.

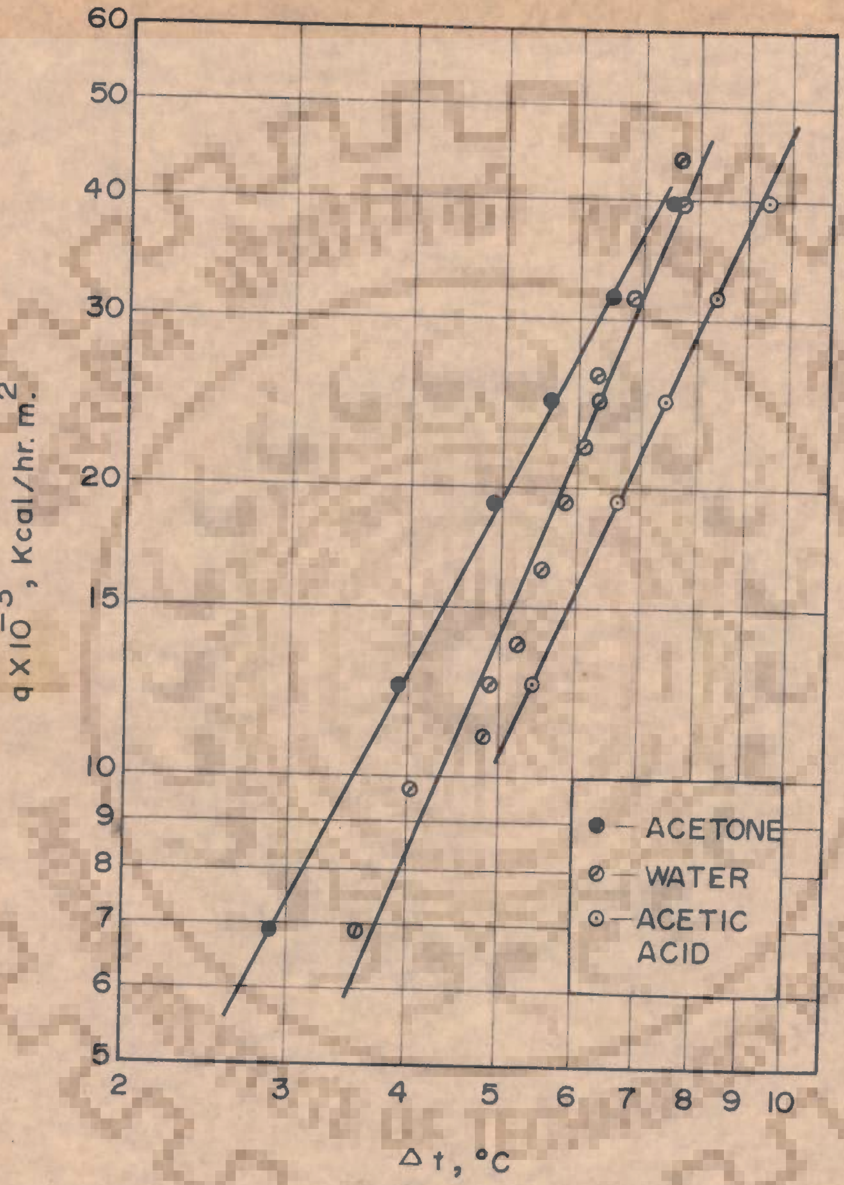


FIG. 4·5 BOILING CURVES FOR SATURATED LIQUIDS.

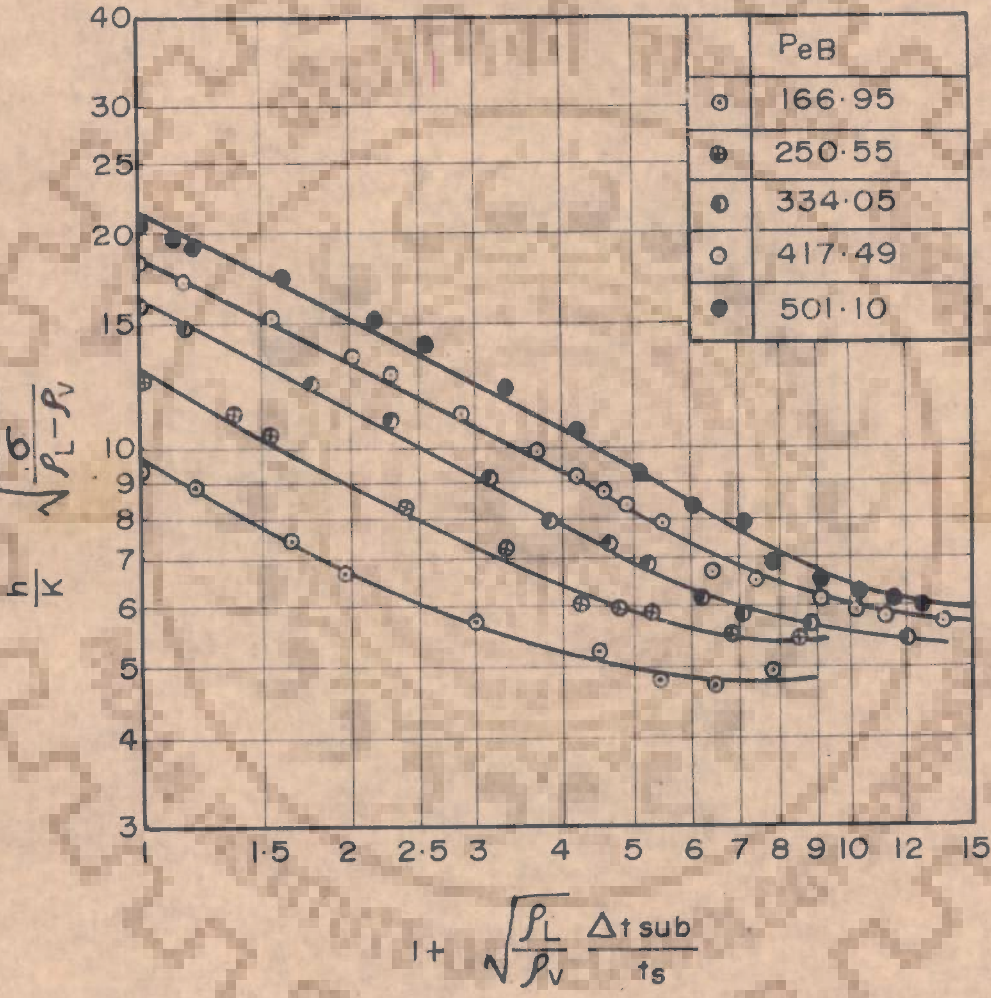


FIG.4·6 VARIATION OF Nu_B WITH SUBCOOLING CRITERION FOR WATER.

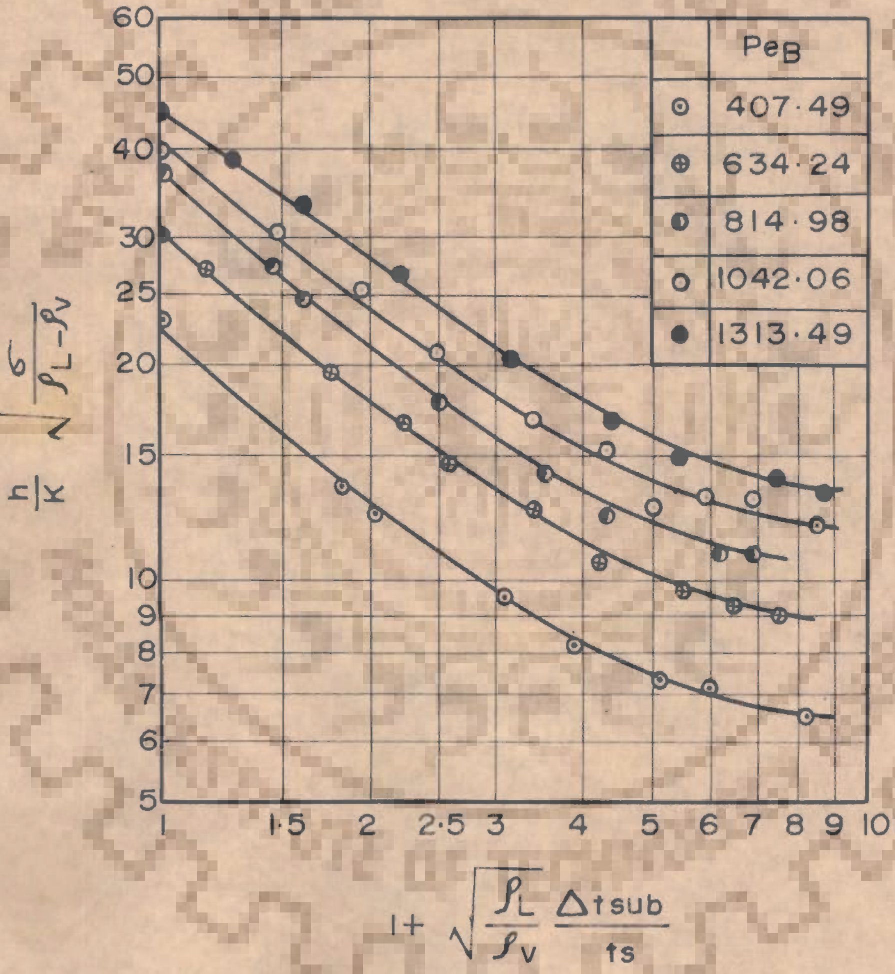


FIG. 4·7 VARIATION OF Nu$_B$ WITH SUBCOOLING CRITERION FOR ACETIC ACID.

4.1.5 Effect of Peclet Number on Boiling

Figure 4.8 shows a log-log plot of Nusselt number, Nu_B versus Peclet number, Pe_B for saturated boiling ($K_{sub} = 1$) of acetone, water and acetic acid. The best fit lines through most of the experimental data points can be represented by the equation of the following form :

$$Nu_B = C_2 (Pe_B)^{n_2} \tag{4.3}$$

Three parallel lines indicate that the value of C_2 is different for different liquids whereas exponent n_2 is almost the same for all the liquids having an average value of about 0.6.

4.2 NUCLEATE POOL BOILING OF BINARY LIQUID MIXTURES

4.2.1 Variation of t_W with t_L for Binary Liquid Mixtures

Figures 4.9 to 4.14 show the typical plots of wall temperature as a function of liquid temperature at constant heat fluxes for some compositions of the binary mixtures. Referring to the Figures 4.1 and 4.2 it is noted that the plots of t_W versus t_L for binary liquid mixtures exhibit the characteristic features essentially similar to those of pure liquids. The probable reasons of the typical variation in wall temperature with liquid temperature have been discussed in section 4.1.1.

The effect of concentration on the variation in t_W with t_L has been shown in Figures 4.15, 4.16 and 4.17 for binary

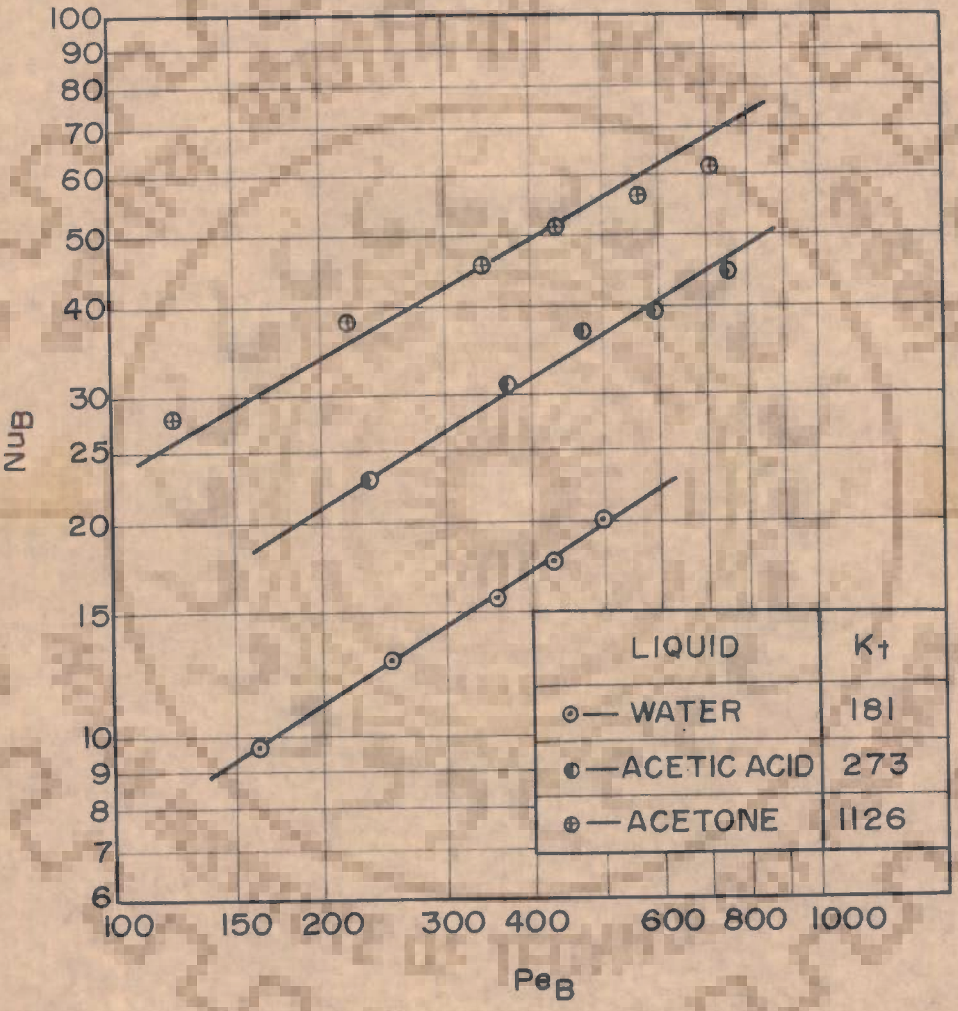


FIG. 4·8 VARIATION OF Nu_B WITH Pe_B FOR SATURATED PURE LIQUIDS.

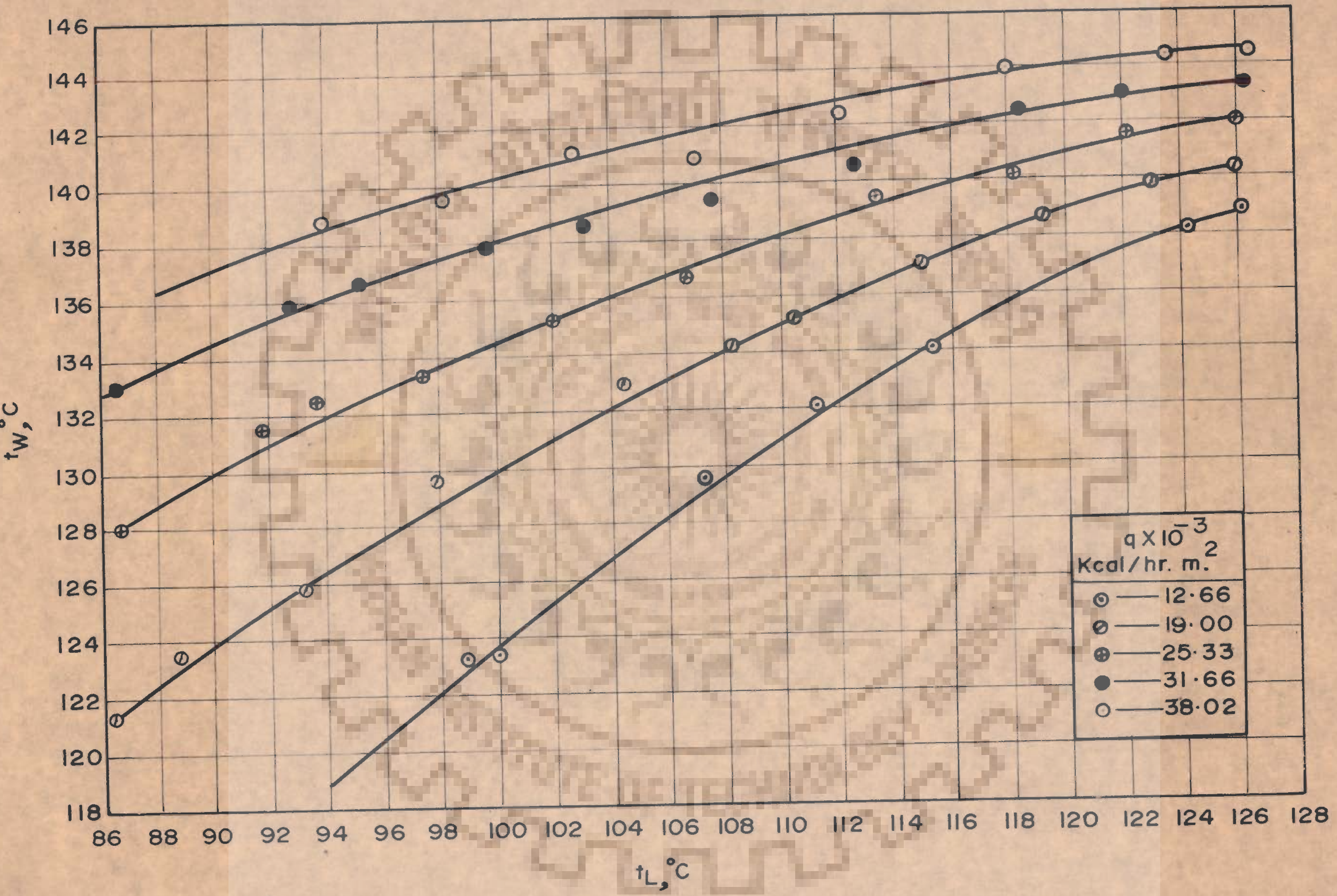


FIG. 4·9 VARIATION OF t_W WITH t_L FOR POOL BOILING OF 15 Wt. % WATER – GLYCERINE MIXTURE.

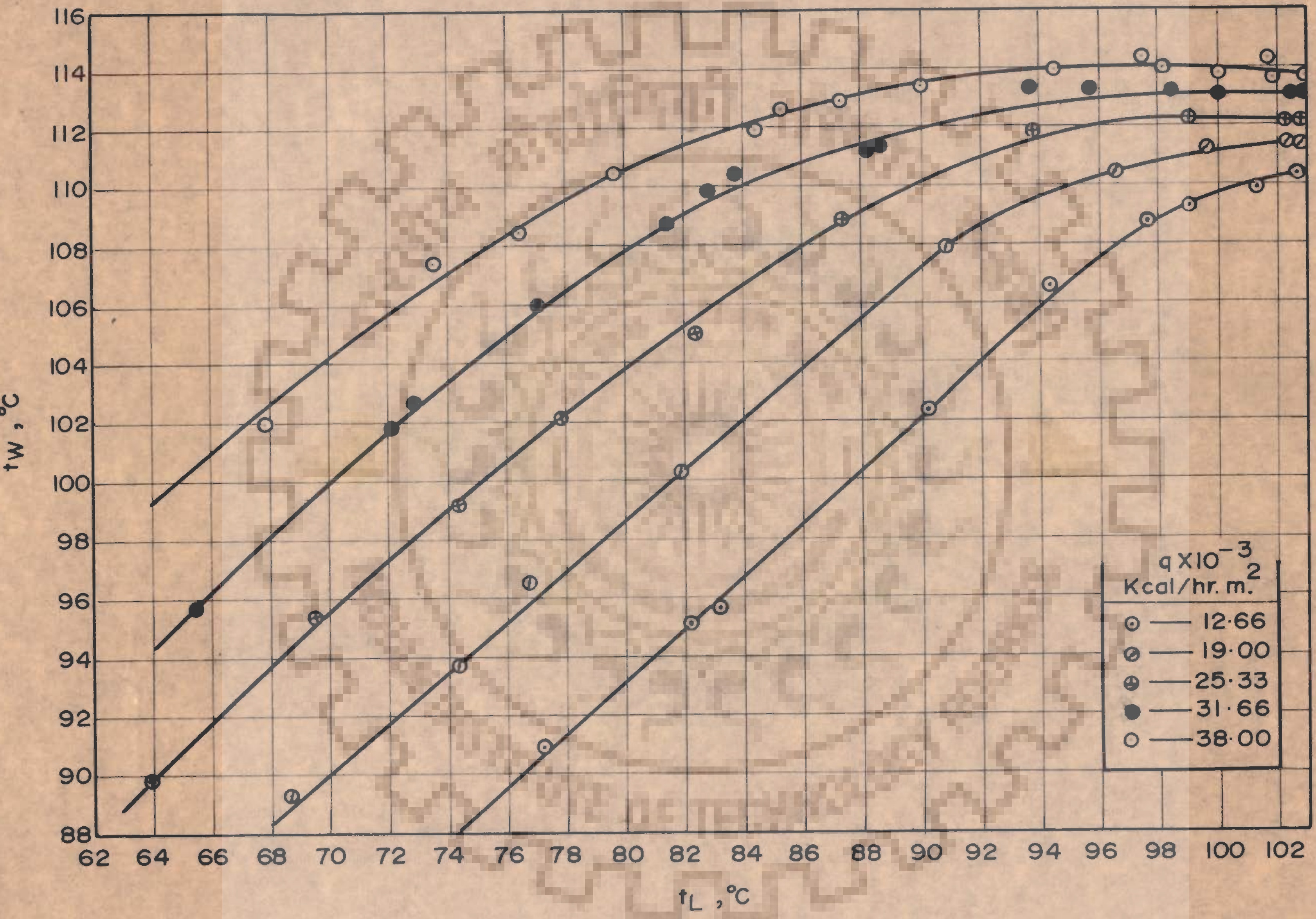


FIG.4·10 VARIATION OF tW WITH tL FOR POOL BOILING OF 65 Wt. % WATER–GLYCERINE MIXTURE.

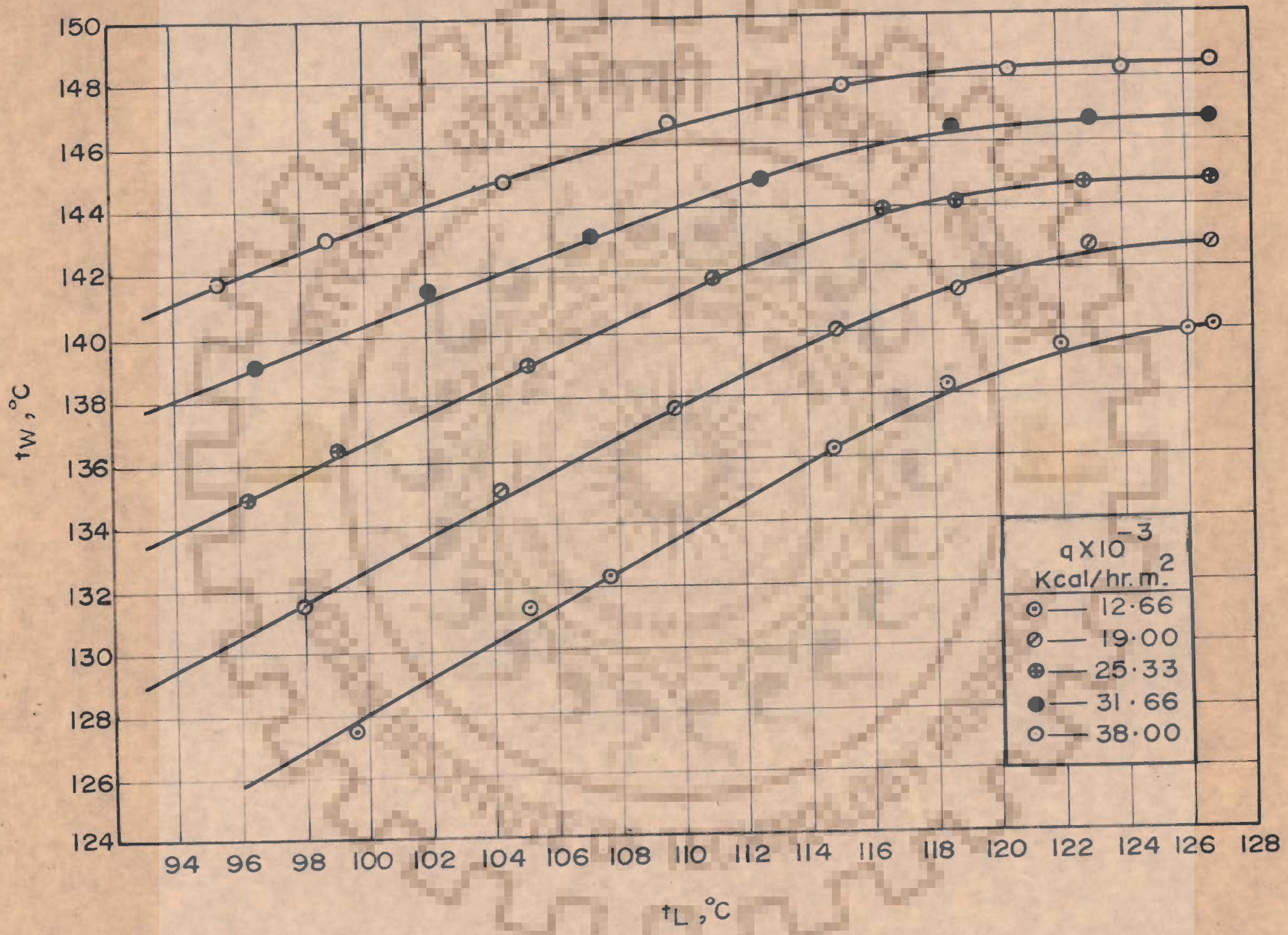


FIG. 4·11 VARIATION OF tW WITH tL FOR POOL BOILING OF 14·6 Wt. % WATER – ETHYLENE GLYCOL MIXTURE.

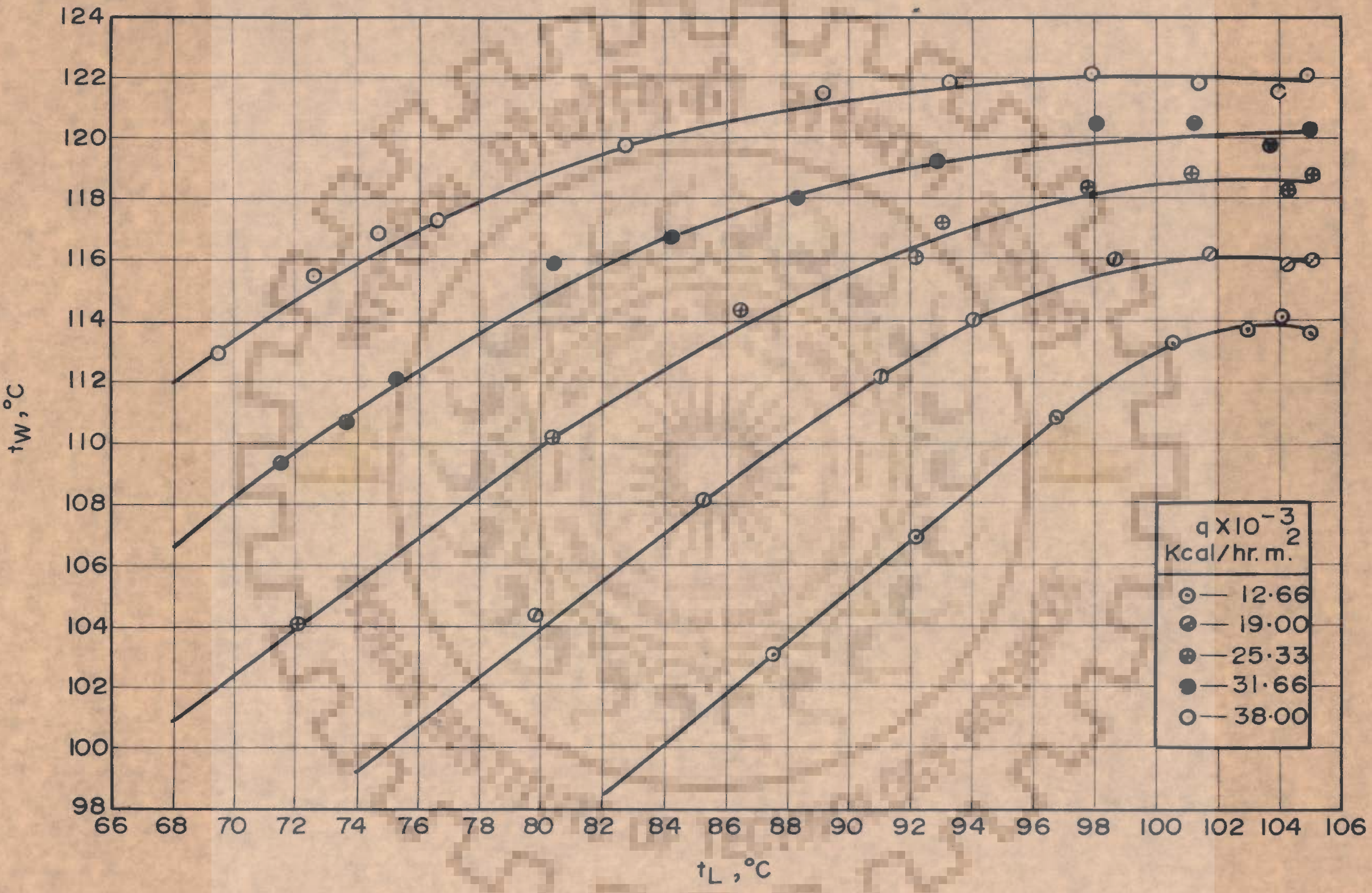


FIG. 4·12 VARIATION OF t_W WITH t_L FOR POOL BOILING OF 57·4 Wt. % WATER-ETHYLENE GLYCOL MIXTURE.

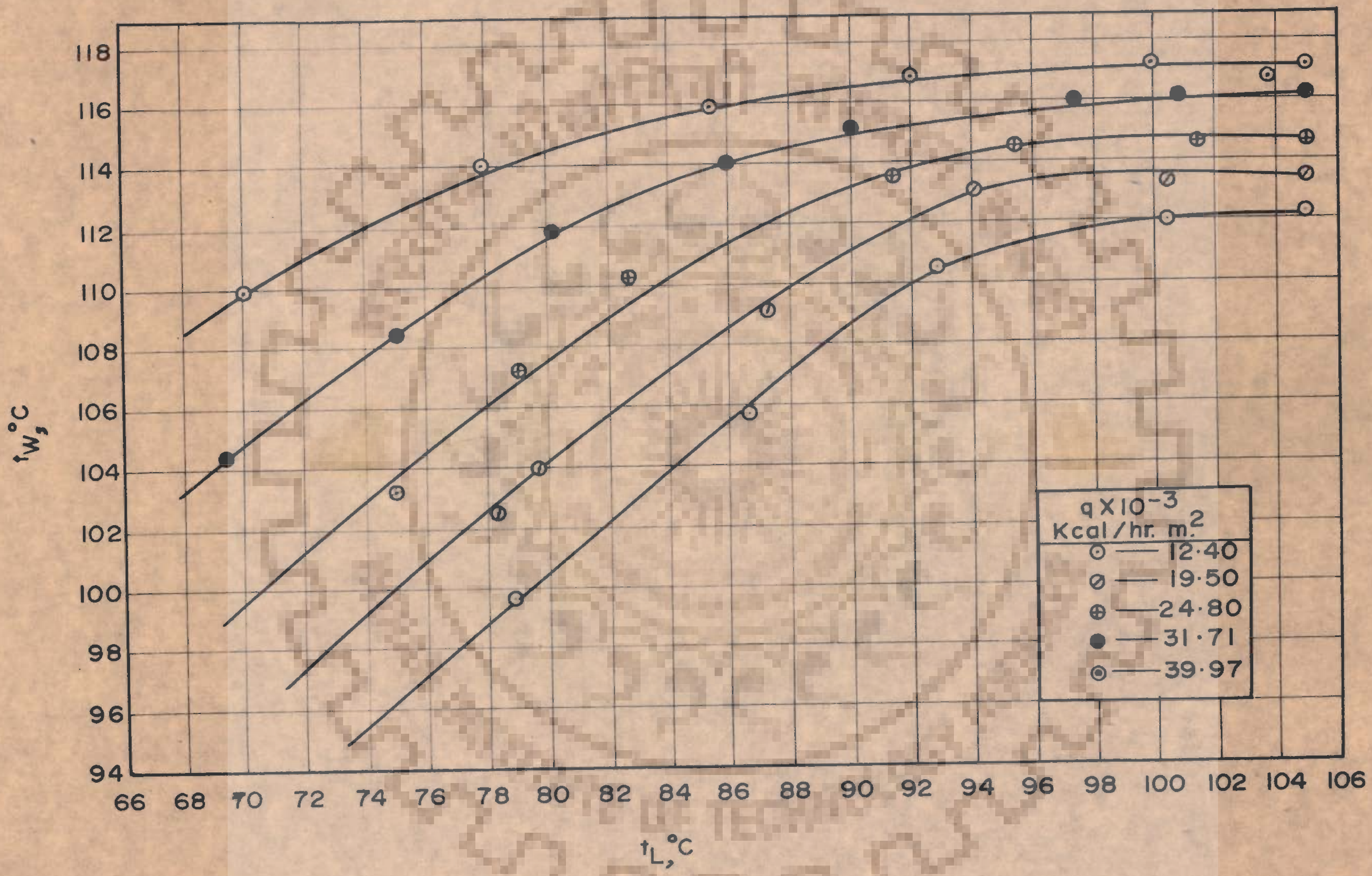


FIG. 4·13 VARIATION OF t_W WITH t_L FOR POOL BOILING OF 14·4 Wt. % WATER-ACETIC ACID MIXTURE.

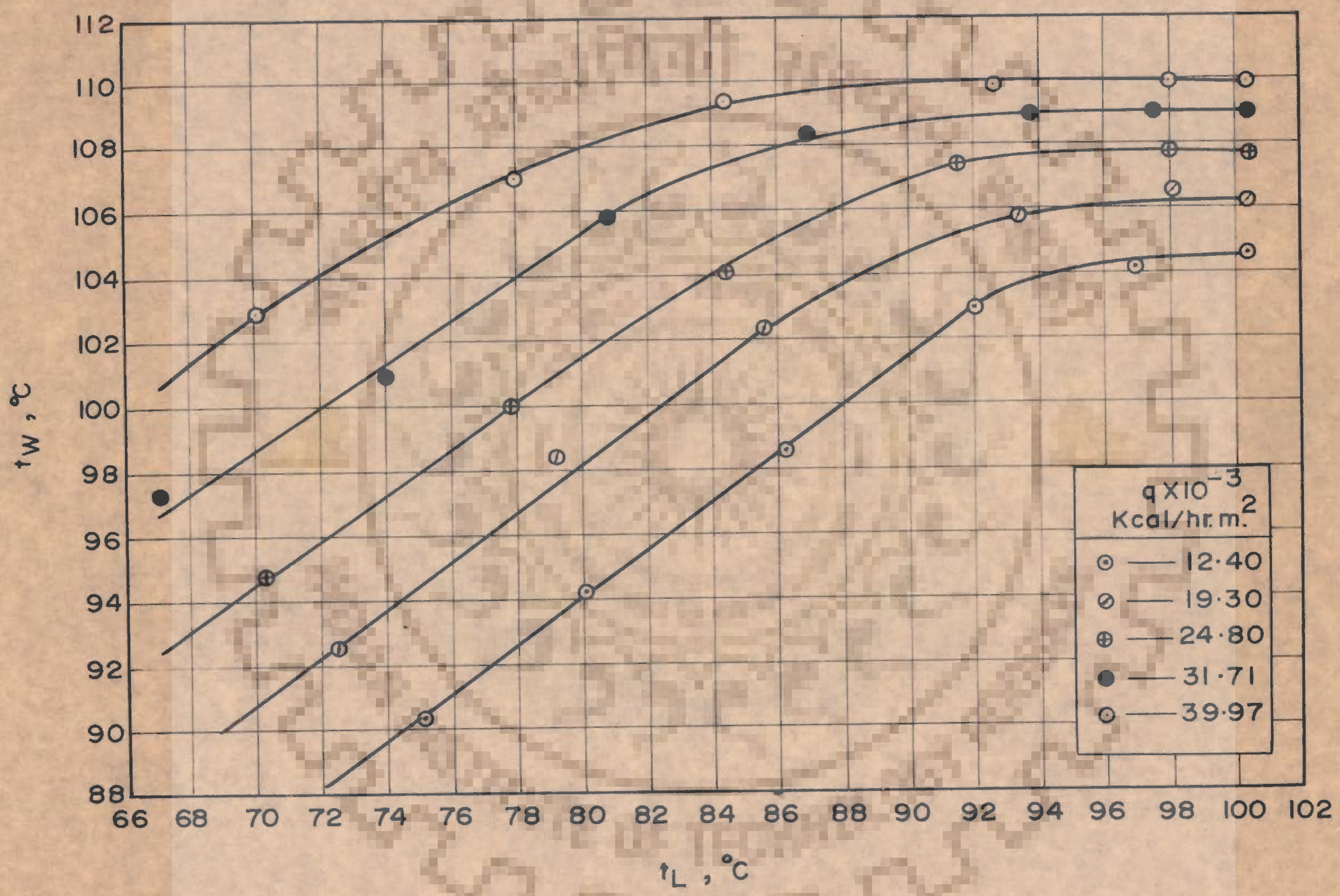


FIG. 4·14 VARIATION OF t_W WITH t_L FOR POOL BOILING OF 58·8 Wt. % WATER-ACETIC ACID MIXTURE .

mixtures; water-glycerine, water-ethylene glycol, and water-acetic acid, respectively. These figures represent the experimental data for boiling heat transfer at constant heat flux for the mixtures. The general behaviour of curves for all compositions are almost the same. However, addition of more volatile component decreases the value of wall temperature for all the mixtures studied.

4.2.2 Variation of Heat Transfer Coefficient with Heat Flux

In Figures 4.18 to 4.22 heat transfer coefficient has been represented as a function of heat flux with Δt_{sub} as parameter for some concentrations of binary liquid mixtures studied on log-log plot. These figures reveal the following characteristic features :

Boiling heat transfer coefficient for binary liquid mixtures is found to increase linearly with heat flux with average slopes of about 0.60 for water-glycerine, 0.59 for water-ethylene glycol and 0.65 for water-acetic acid. The different slopes for different systems as compared to that of water which was found to be 0.7, may be due to the effect of physical properties of the mixtures on the change in nucleation characteristics with heat flux. The value of Δt_{sub} seems to have significant influence on the value of heat transfer coefficient for binary liquid mixtures in the similar fashion as with their pure components.

4.2.3 Boiling Curves for Mixtures

Boiling curves (q versus Δt) for various concentrations

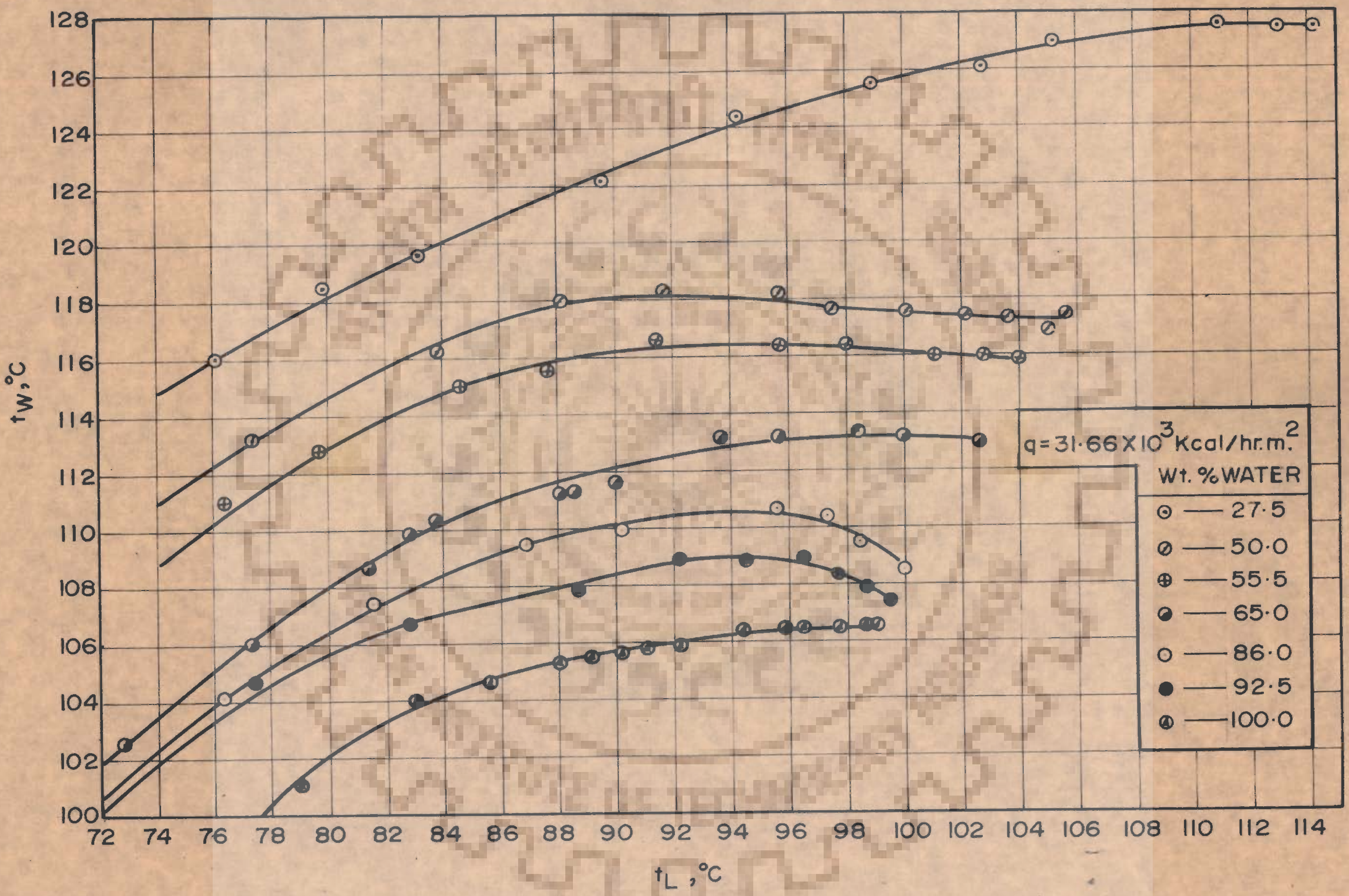


FIG. 4·15 VARIATION OF t_W WITH t_L FOR POOL BOILING OF WATER-GLYCERINE MIXTURES.

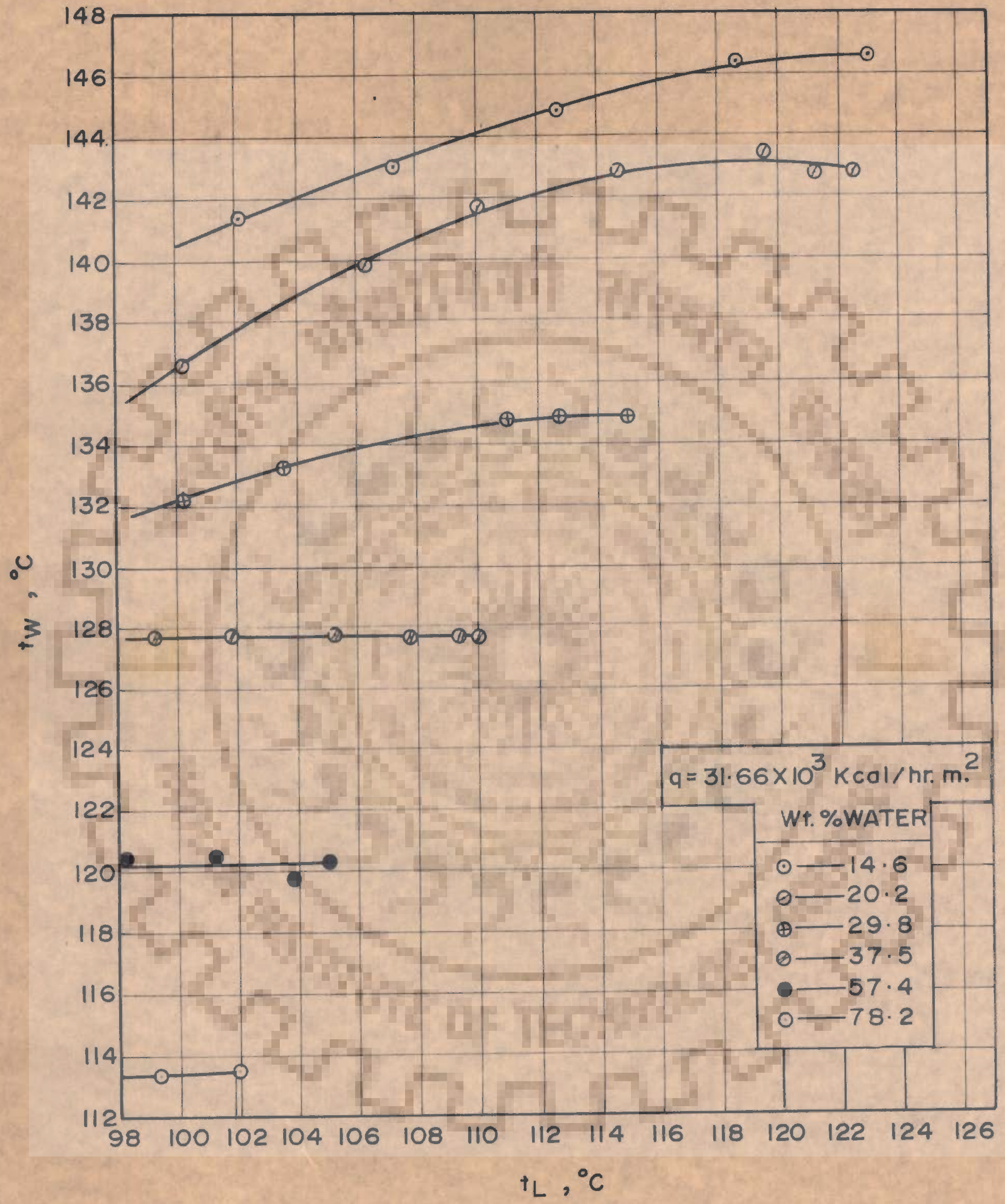


FIG. 4·16 VARIATION OF t_W WITH t_L FOR POOL BOILING OF WATER – ETHYLENE GLYCOL MIXTURES.

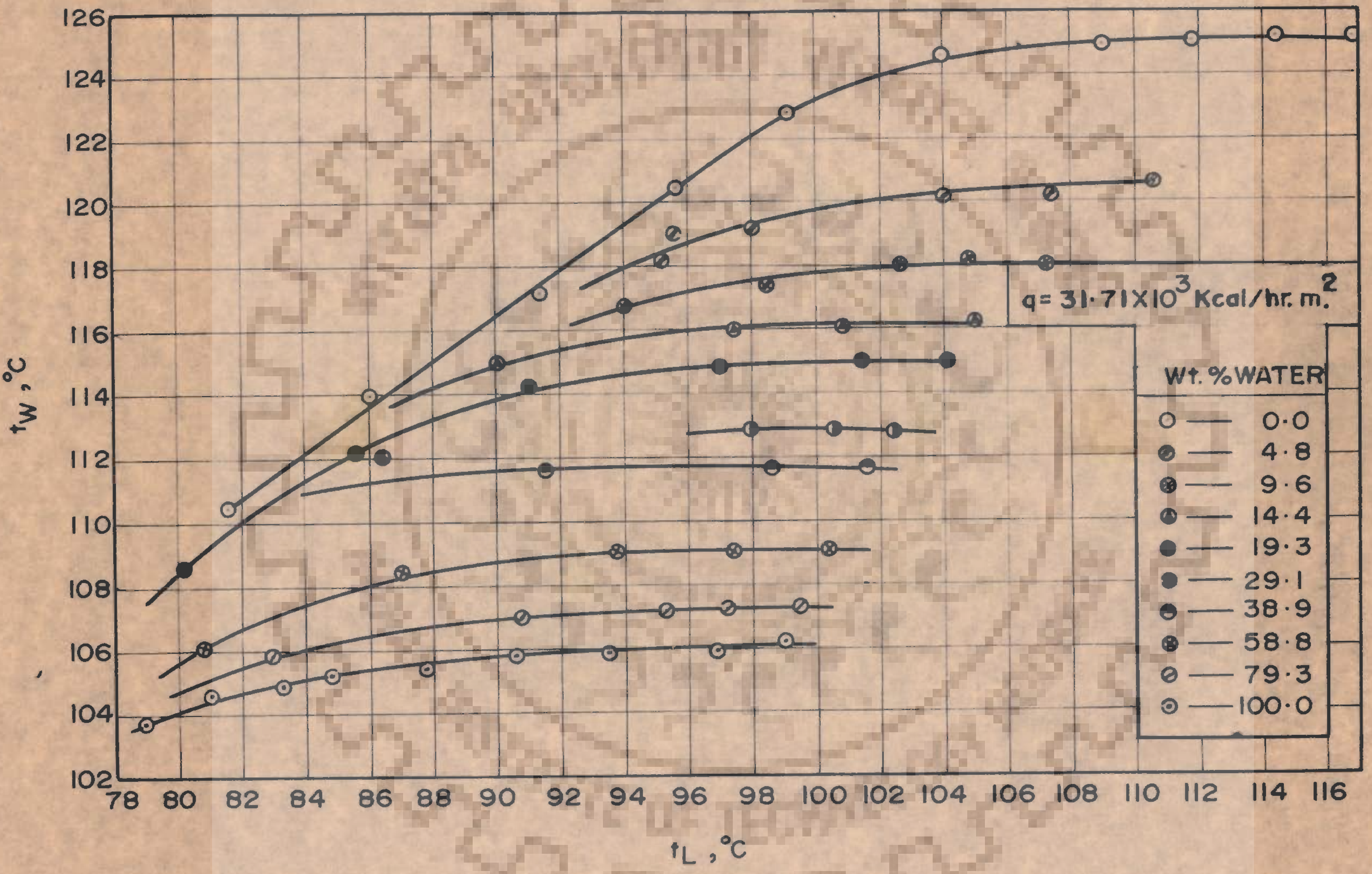


FIG. 4·17 VARIATION OF t_W WITH t_L FOR POOL BOILING OF WATER-ACETIC ACID MIXTURES.

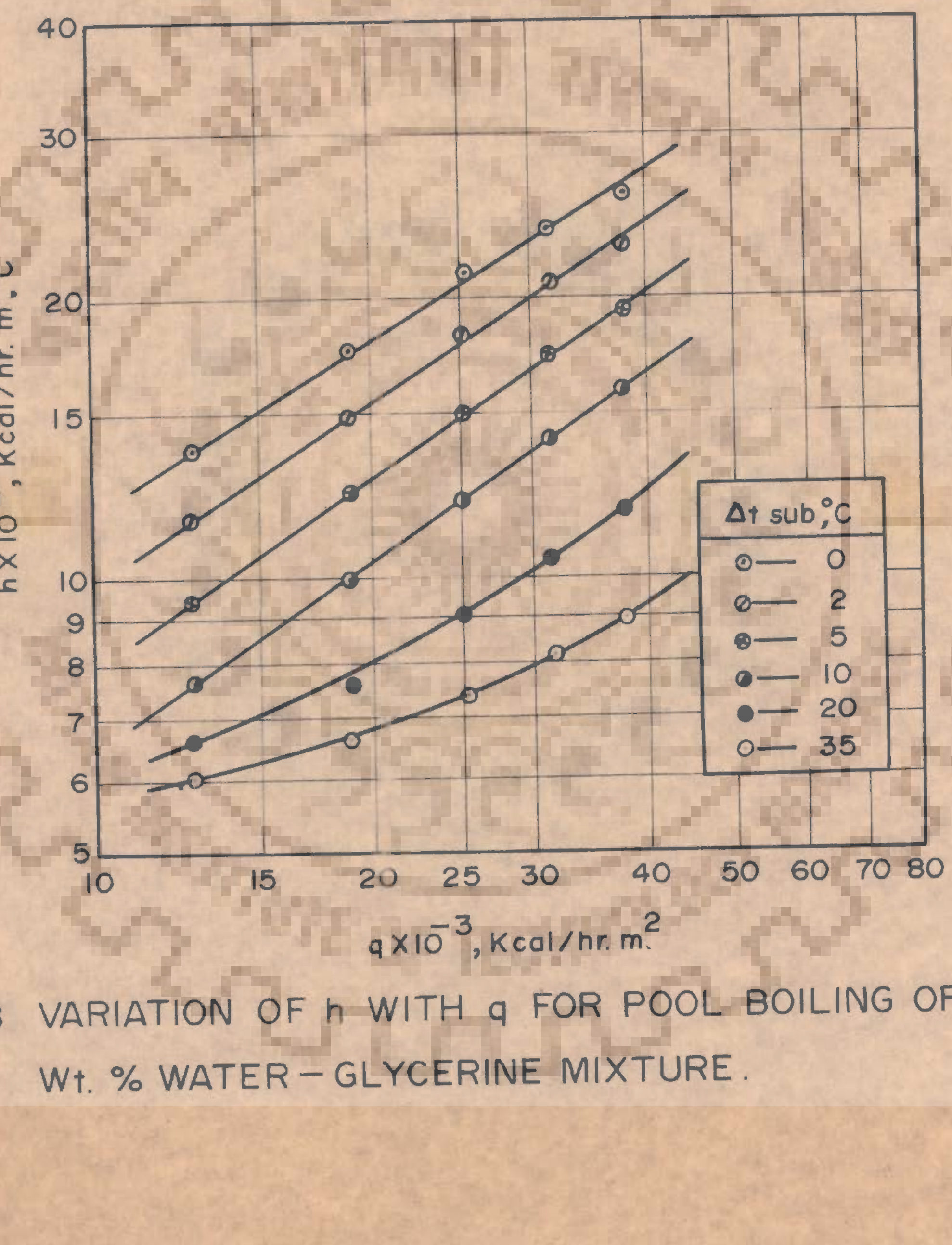


FIG.4·18 VARIATION OF h WITH q FOR POOL BOILING OF 27·5 Wt. % WATER – GLYCERINE MIXTURE.

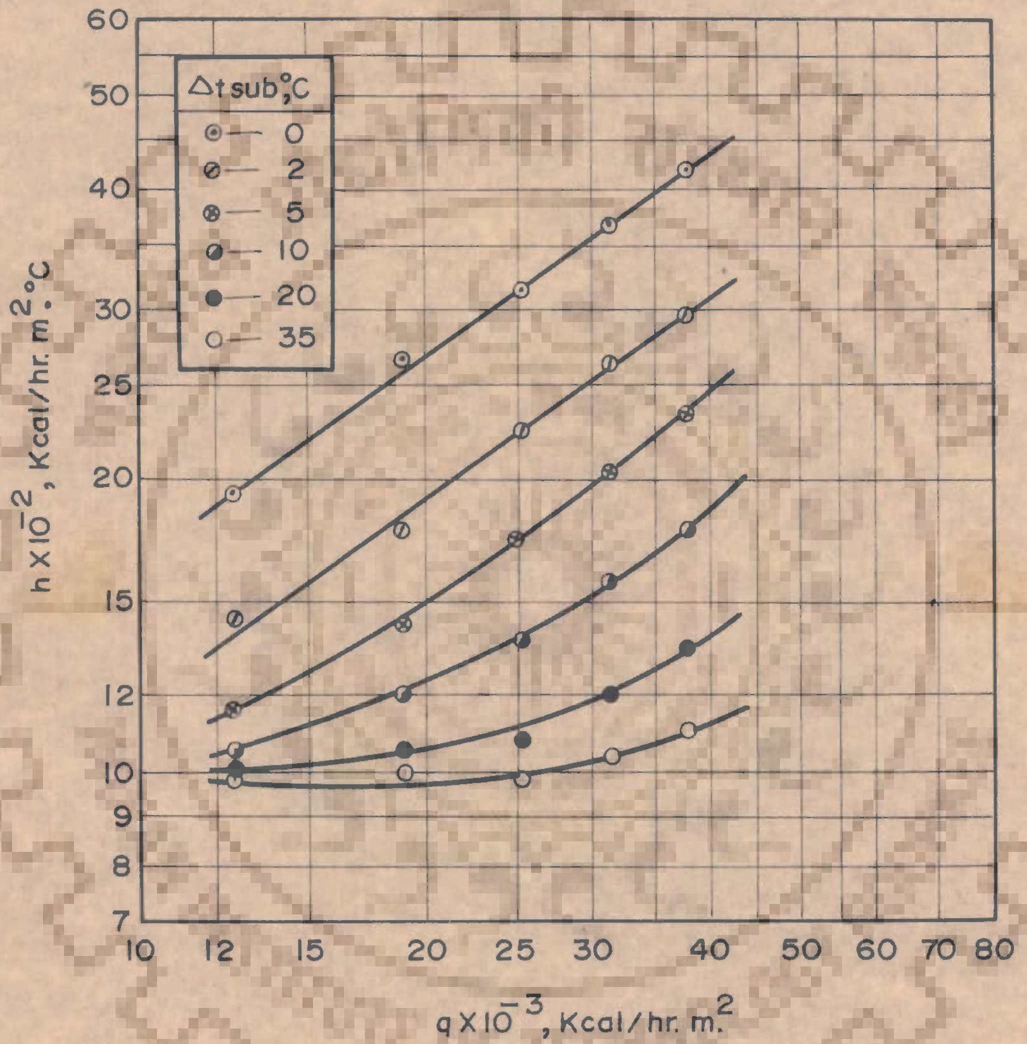


FIG. 4·19 VARIATION OF h WITH q FOR POOL BOILING OF 86 Wt. % WATER – GLYCERINE MIXTURE.

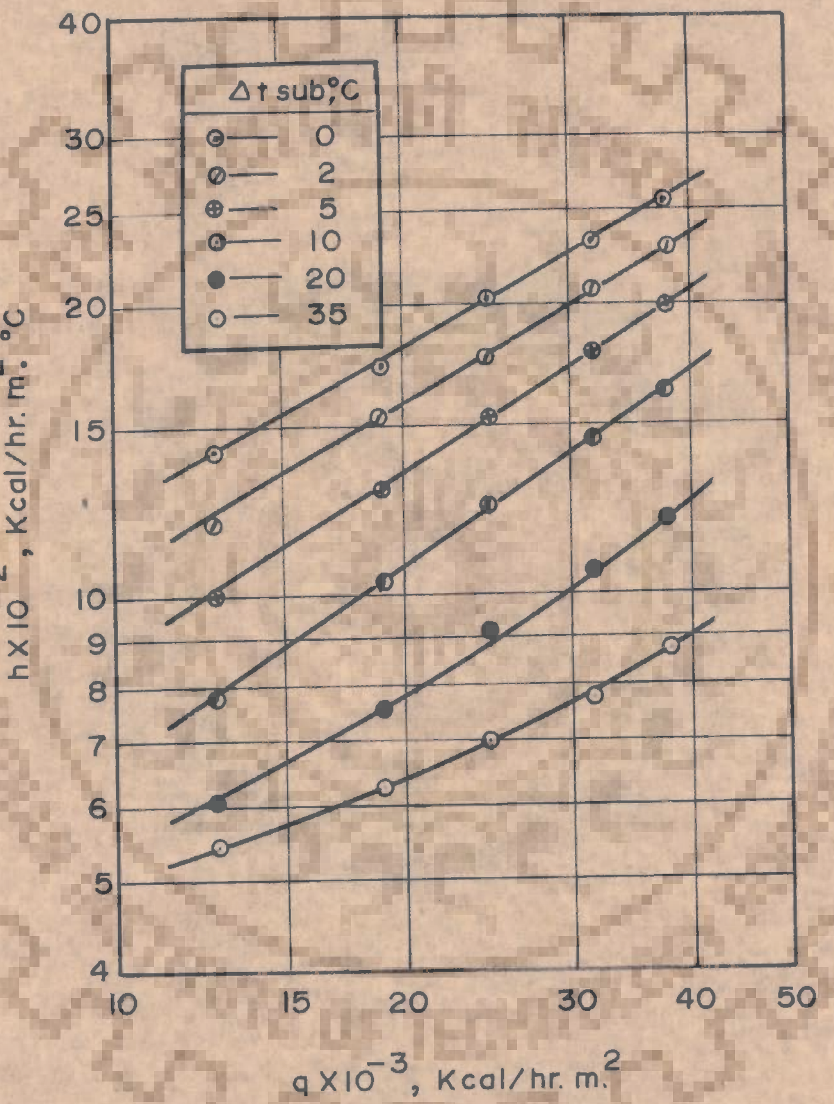


FIG.4·20 VARIATION OF h WITH q FOR POOL BOILING OF 1 Wt. % WATER-ETHYLENE GLYCOL MIXTURE.

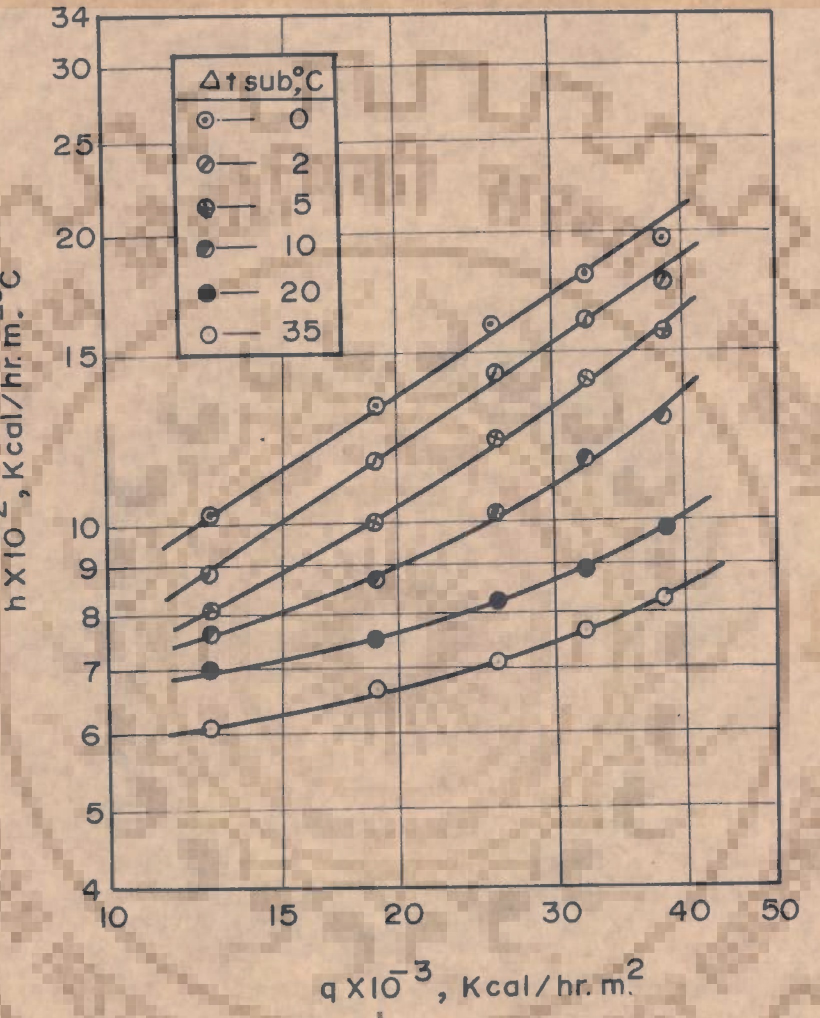


FIG.4·21 VARIATION OF h WITH q FOR POOL BOILING OF 37·5 Wt. % WATER–ETHYLENE GLYCOL MIXTURE.

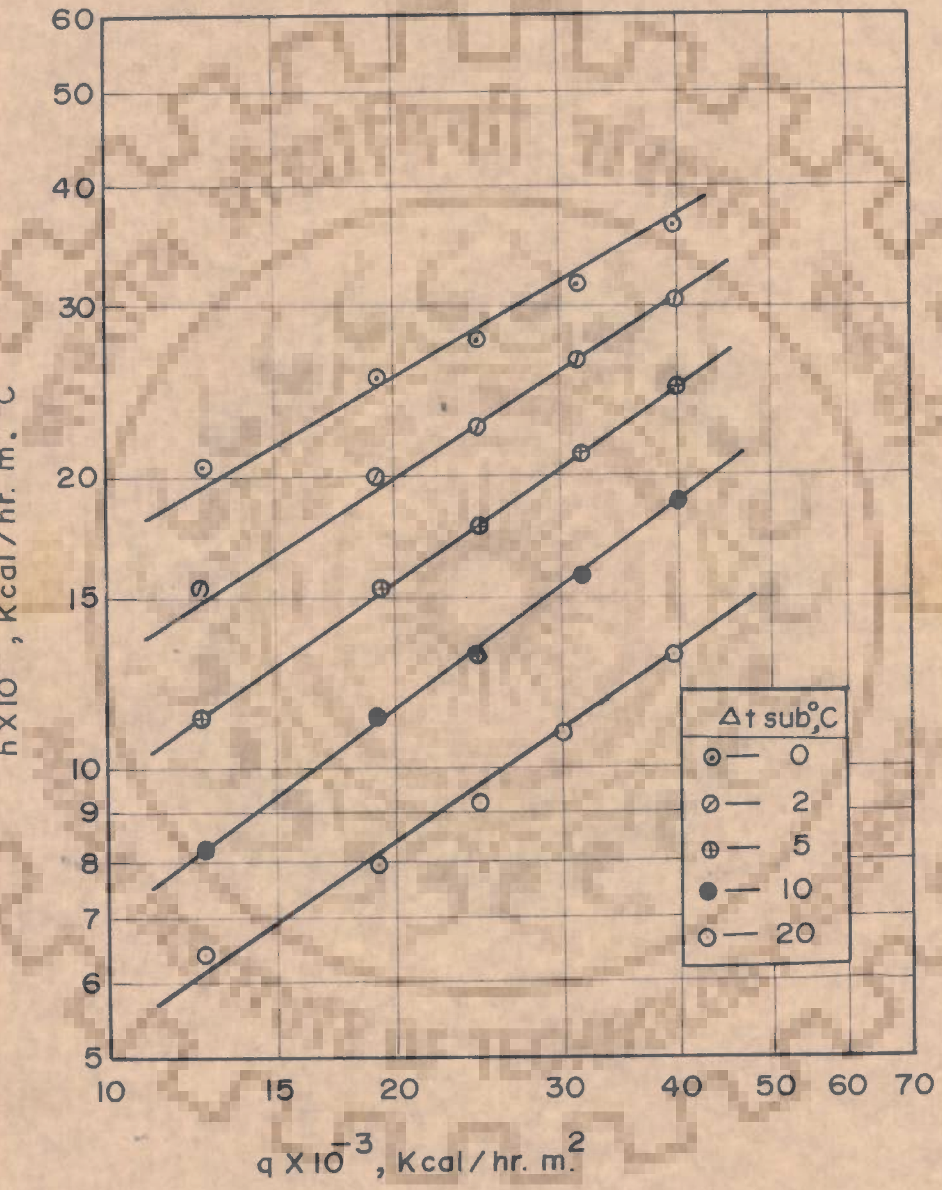


FIG. 4·22 VARIATION OF h WITH q FOR POOL BOILING OF 38·9 Wt. % WATER –ACETIC ACID MIXTURE.

of water-glycerine, water-ethylene glycol, water-acetic acid, and acetone-water have been shown in Figures 4.23, 4.24, 4.25, and 4.26, respectively. From these figures the following points may be noted :

a. The boiling curves of all the binary mixtures are straight lines similar to the pure components.

b. Except for water-glycerine system, it is clearly seen that the boiling curve shifts progressively to higher values of Δ t with the increase in concentration of more volatile component upto a certain value. Such a value of concentration is found to be 7 Wt. % water in water-ethylene glycol, 17 Wt. % water in water-acetic acid and 35 Wt. % acetone in acetone-water mixtures. When the concentration of more volatile component exceeds these respective values, the boiling curve begins to shift to lower values of Δ t until finally the boiling curve of the components constituting the mixture become close to each other.

4.2.4 Effect of Composition on Boiling Heat Transfer in Binary Liquid Mixtures

Figures 4.27 to 4.30 show the effect of concentration of more volatile component on heat transfer coefficient at various values of heat flux. All the figures, except Figure 4.27, illustrate the following points :

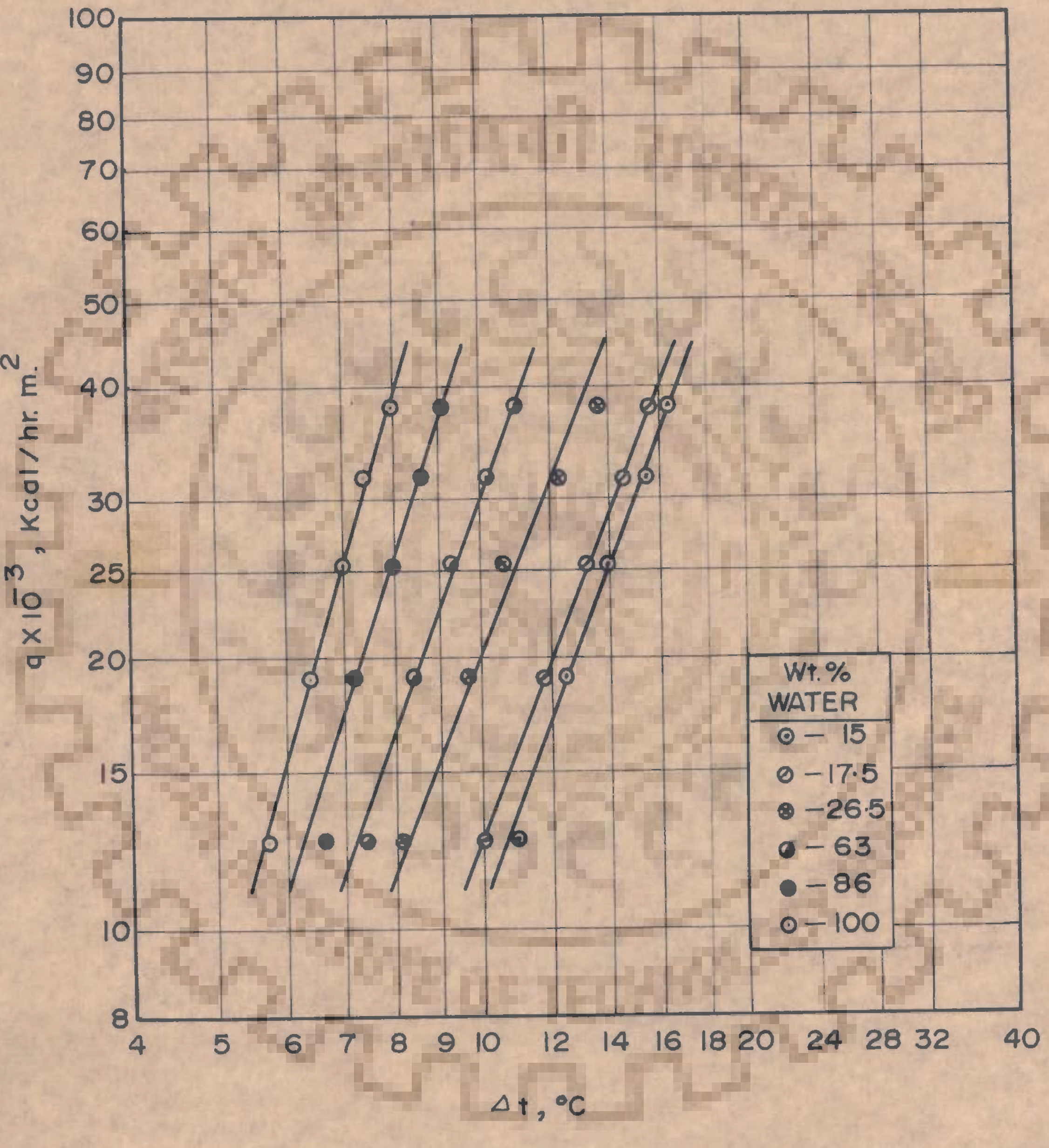


FIG.4·23 BOILING CURVES FOR SATURATED WATER – GLYCERINE MIXTURES.

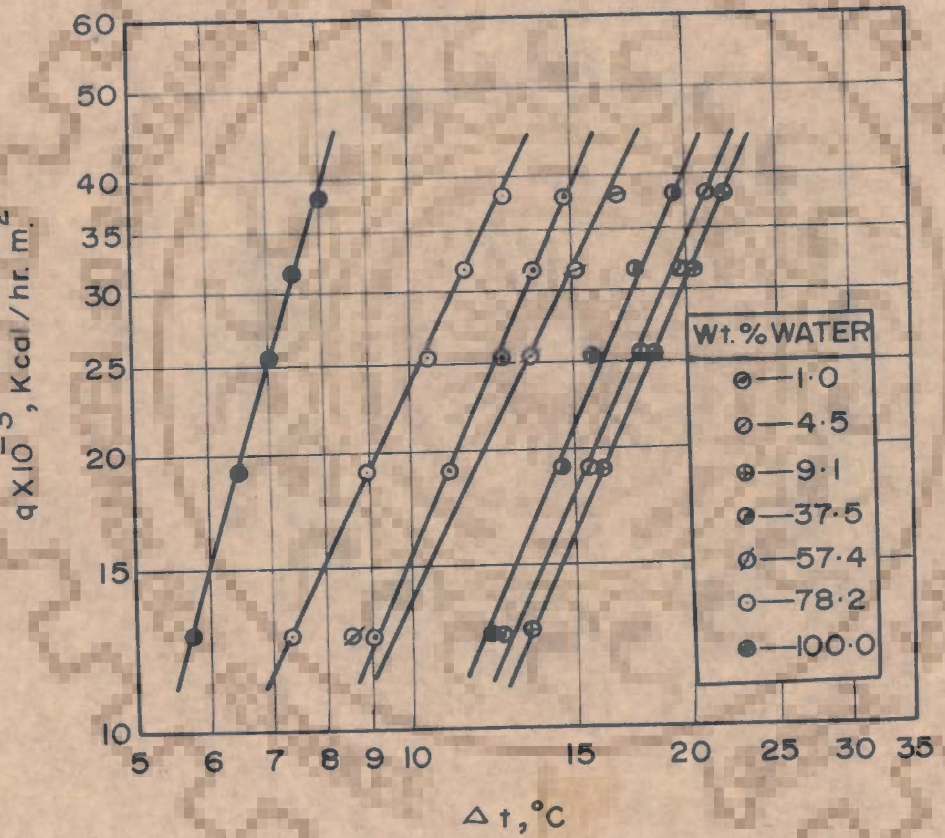


FIG. 4·24 BOILING CURVES FOR SATURATED WATER – ETHYLENE GLYCOL MIXTURES.

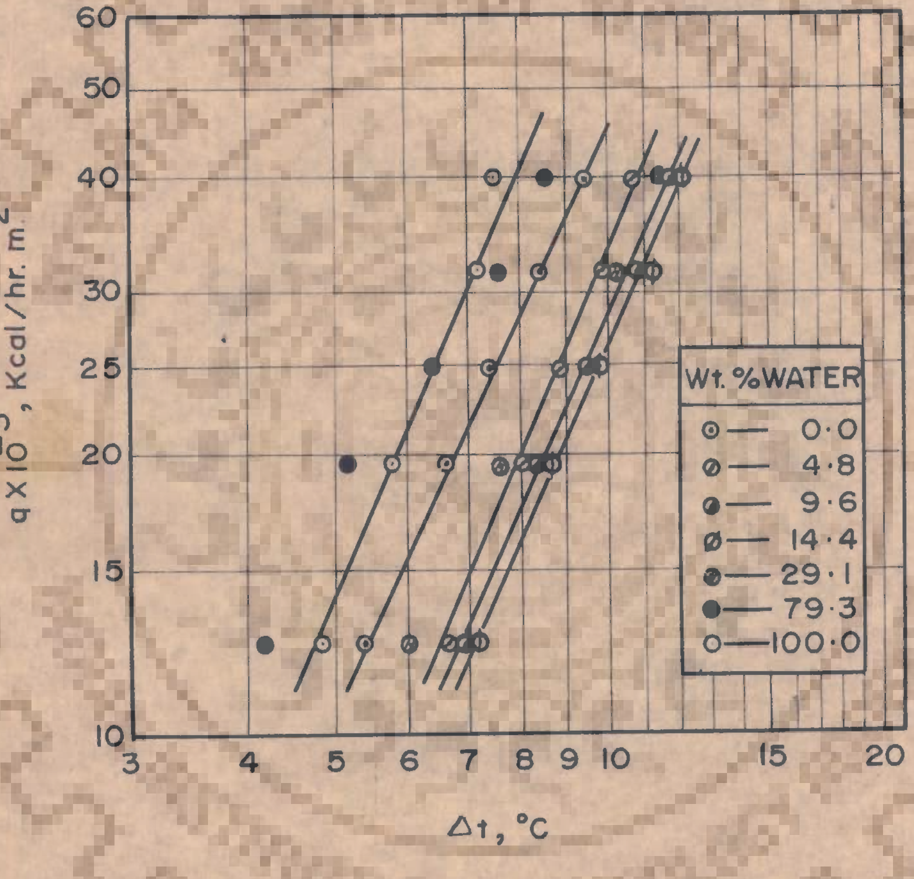


FIG.4·25 BOILING CURVES FOR SATURATED WATER–ACETIC ACID MIXTURE.

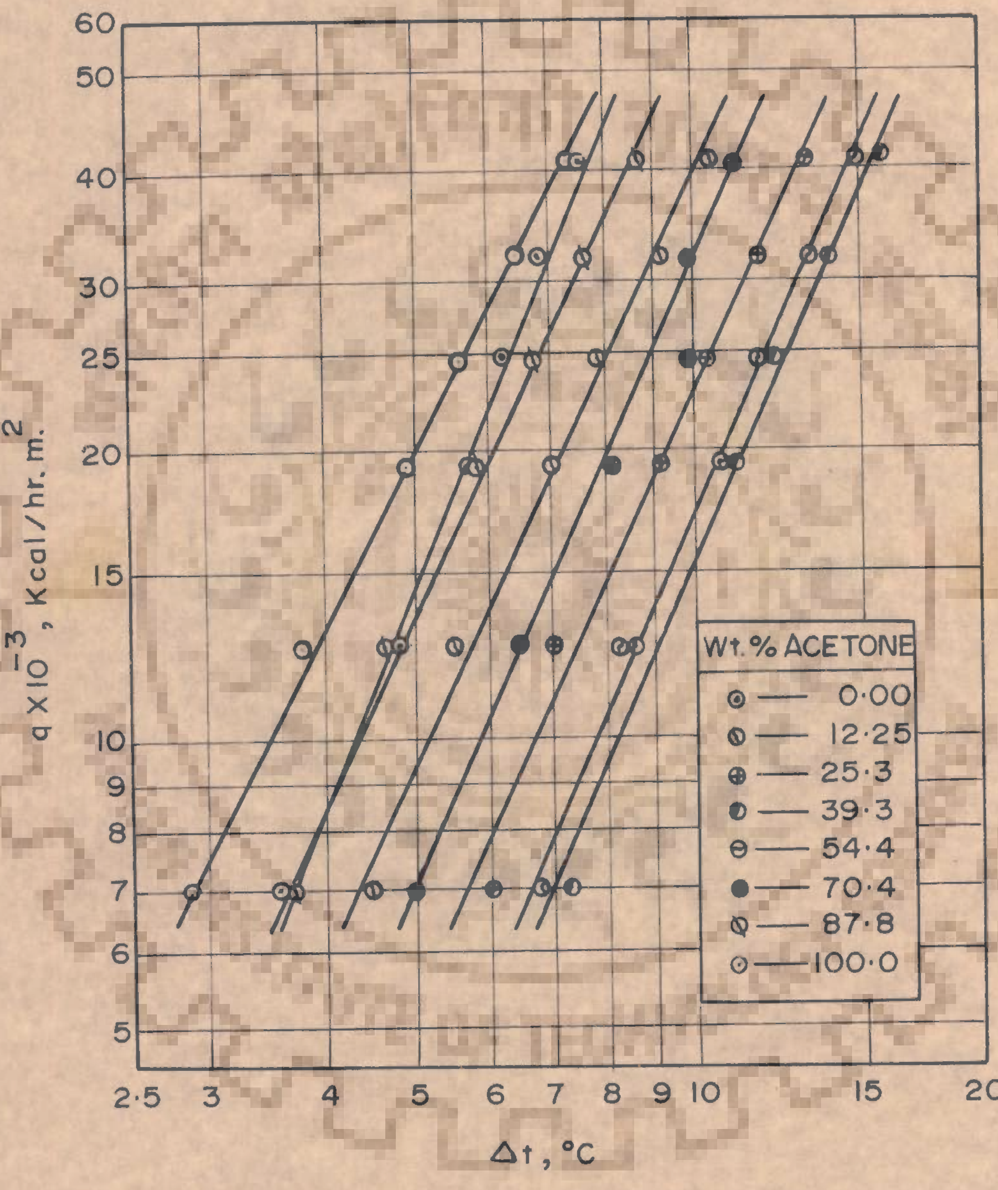


FIG. 4·26 BOILING CURVES FOR SATURATED ACETONE–WATER MIXTURES

a. Addition of more volatile component decreases the boiling heat transfer coefficient until a certain concentration of more volatile component in the mixture is reached at which h becomes minimum. Further addition of the more volatile component results in a turnaround and h continues to increase. The concentration of the more votatile component locating the turnaround in h is found to be about 7 Wt. % in water-ethylene glycol, 17 Wt. % in water-acetic acid and 35 Wt. % in acetone-water mixture.

b. Higher values of q shift the curves to higher values of heat transfer coefficient. However, qualitatively all the curves are alike and show their respective minimum at the definite concentration of the mixtures.

It is important to mention that it was not possible to conduct experiment with water-glycerine mixtures having water concentration less than 15 Wt. % because the heater temperature became quite high and it proved unsafe. However, it is clearly seen from the trend of all the curves in Figure 4.27 that they may pass through their respective turnaround points at some low concentration of water in the mixture.

c. The reduction in heat transfer coefficient becomes appreciable in all the systems at their respective turnaround points.

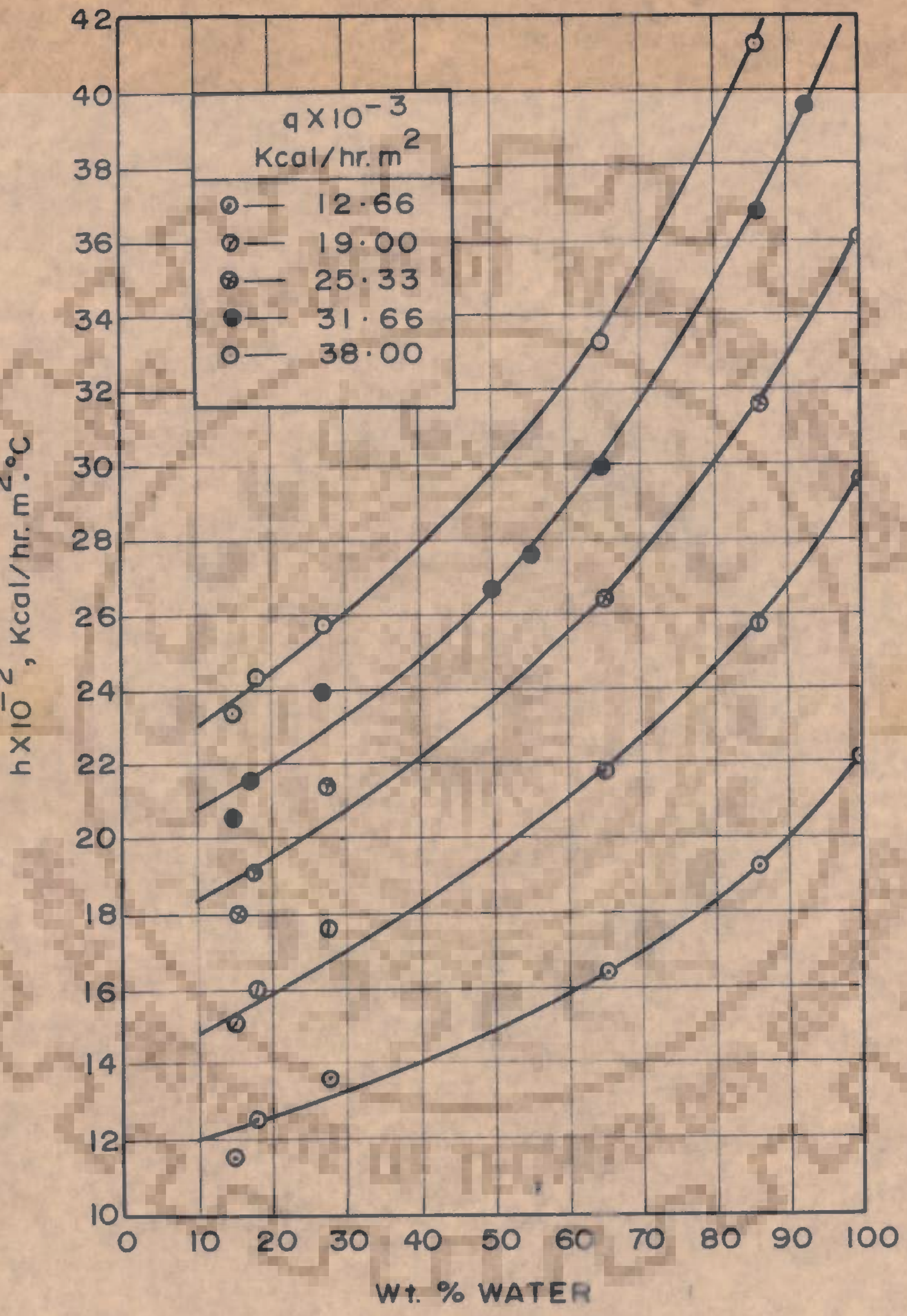


FIG.4·27 VARIATION OF h WITH Wt. % WATER IN SATURATED WATER – GLYCERINE MIXTURES AT VARIOUS VALUES OF q.

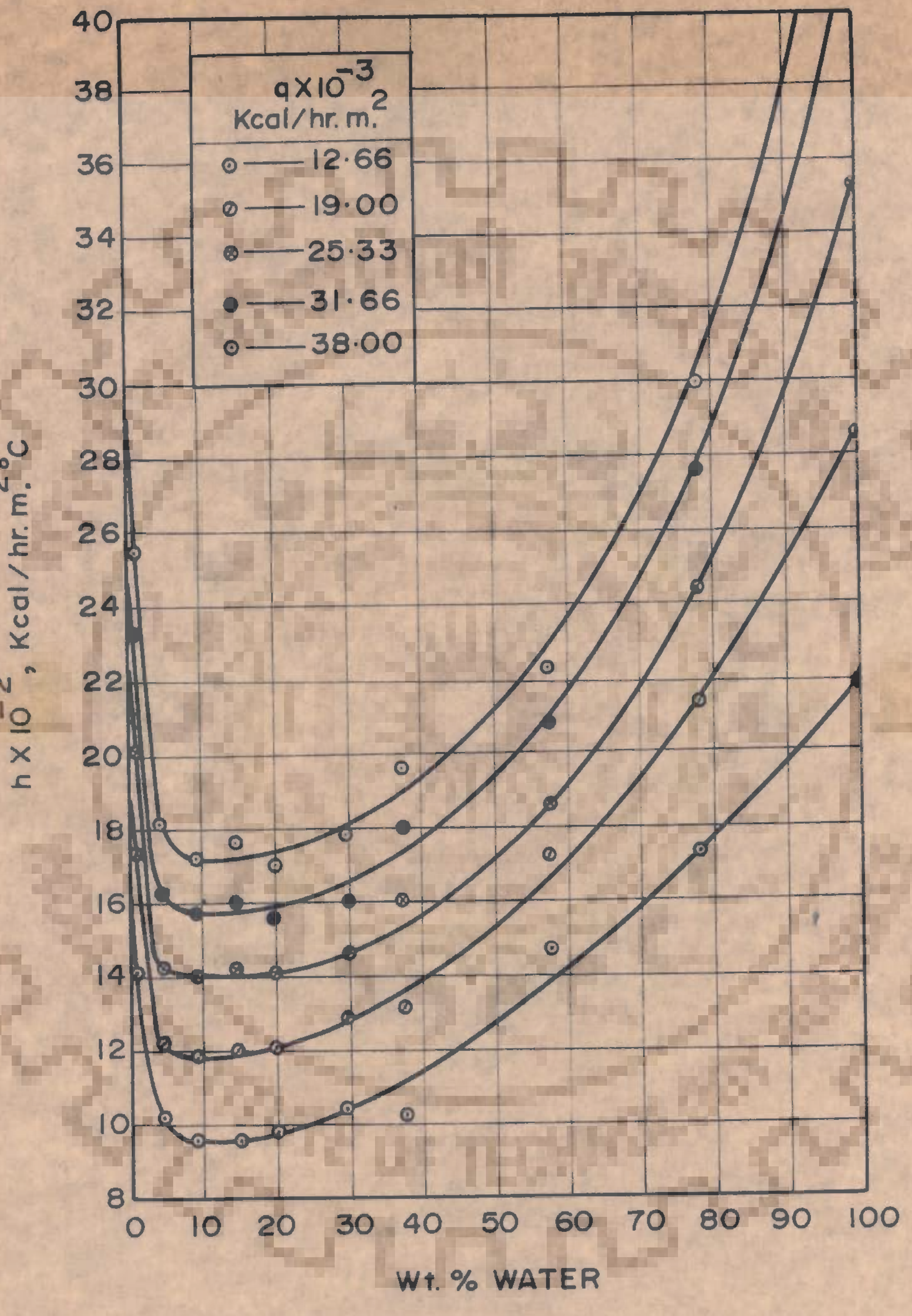


FIG.4·28 VARIATION OF h WITH Wt. % OF WATER IN SATURATED WATER-ETHYLENE GLYCOL MIXTURES AT VARIOUS VALUES OF q.

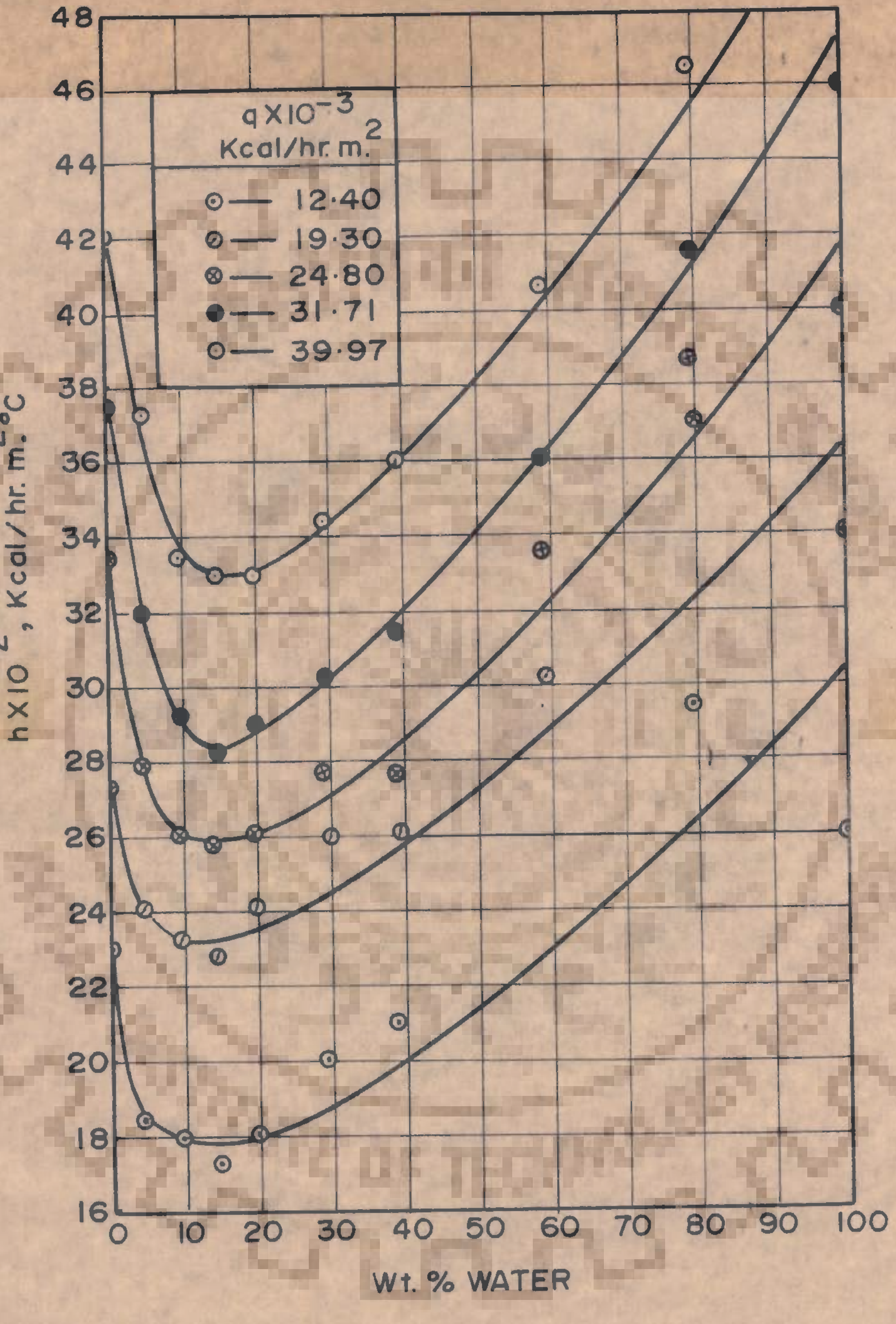


FIG. 4·29 VARIATION OF h WITH Wt. % WATER IN SATURATED WATER–ACETIC ACID MIXTURES AT VARIOUS VALUES OF q.

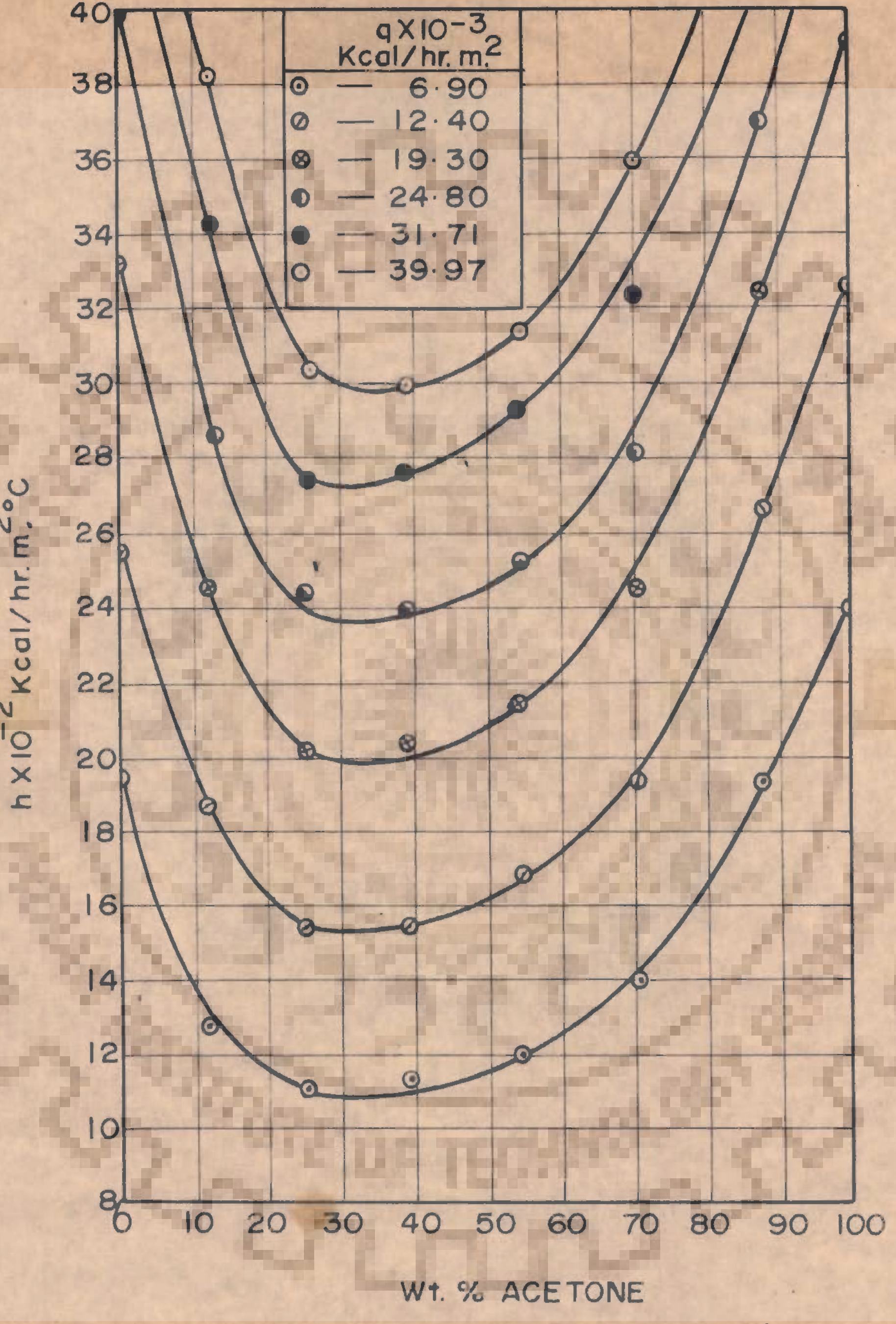


FIG. 4·30 VARIATION OF h WITH Wt. % OF ACETONE IN SATURATED ACETONE WATER MIXTURES AT VARIOUS VALUES OF q.

The behaviour of the curves with the appearance of turnarounds in Figures 4.27 to 4.30 may be attributed to the following reasons :

a. The heat transfer rate during boiling is influenced by the vapor-bubble growth rate which, besides other factors, depends on the vapor-liquid equilibrium compositions of the mixture. The dependence of bubble growth rate on the composition of binary mixture is represented by Eq. (2.33) as derived by Van Stralen (16). It is clear from the above mentioned equation that the growth rate constant C_1 attains minimum value in coincidence with a maximum in $\Delta t_x/Gd$. Figures 4.31 to 4.34 show the effect of concentration of more volatile component on the value of $\Delta t_x/G_d$. The maximum value of $\Delta t_x/G_d$ for the respective systems occurs almost at the same concentration as found experimentally and this explains the turnaround points in the curves of Figures 4.27 to 4.30.

b. The increase in the difference of vapor and liquid compositions decreases the number of nuclei for bubble formation by making the value of R_{min} greater as discussed under section 2.4. In Figures 4.31 to 4.34, the plots of (Y - X) versus composition of more volatile component show the appearance of maximum value of (Y - X) at 1.5 Wt. % in water-glycerine, 7 Wt. % in

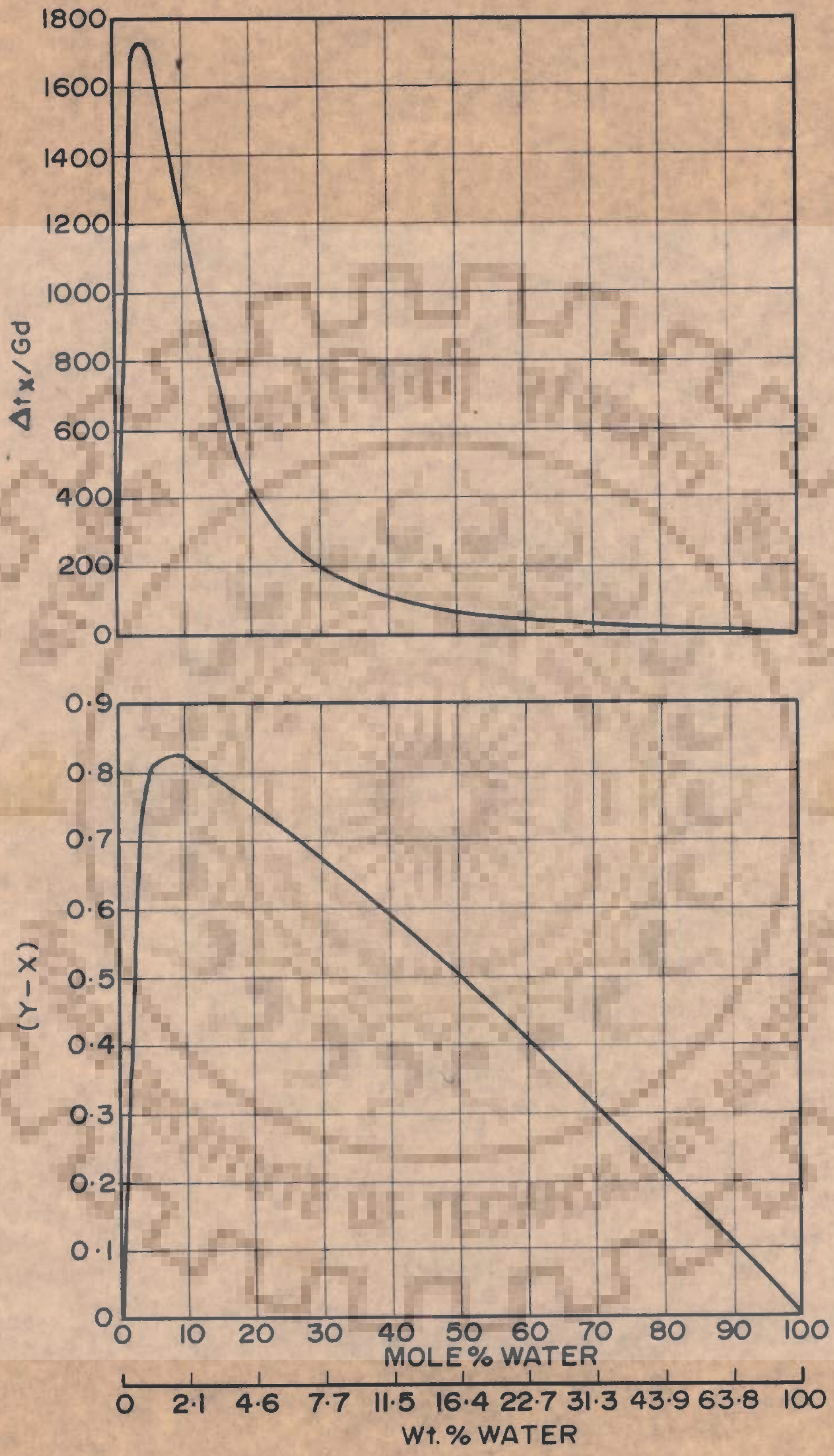


FIG. 4·31 (Y–X) AND $\Delta t_x/Gd$ VERSUS WATER CONCENTRATION IN WATER–GLYCERINE MIXTURES.

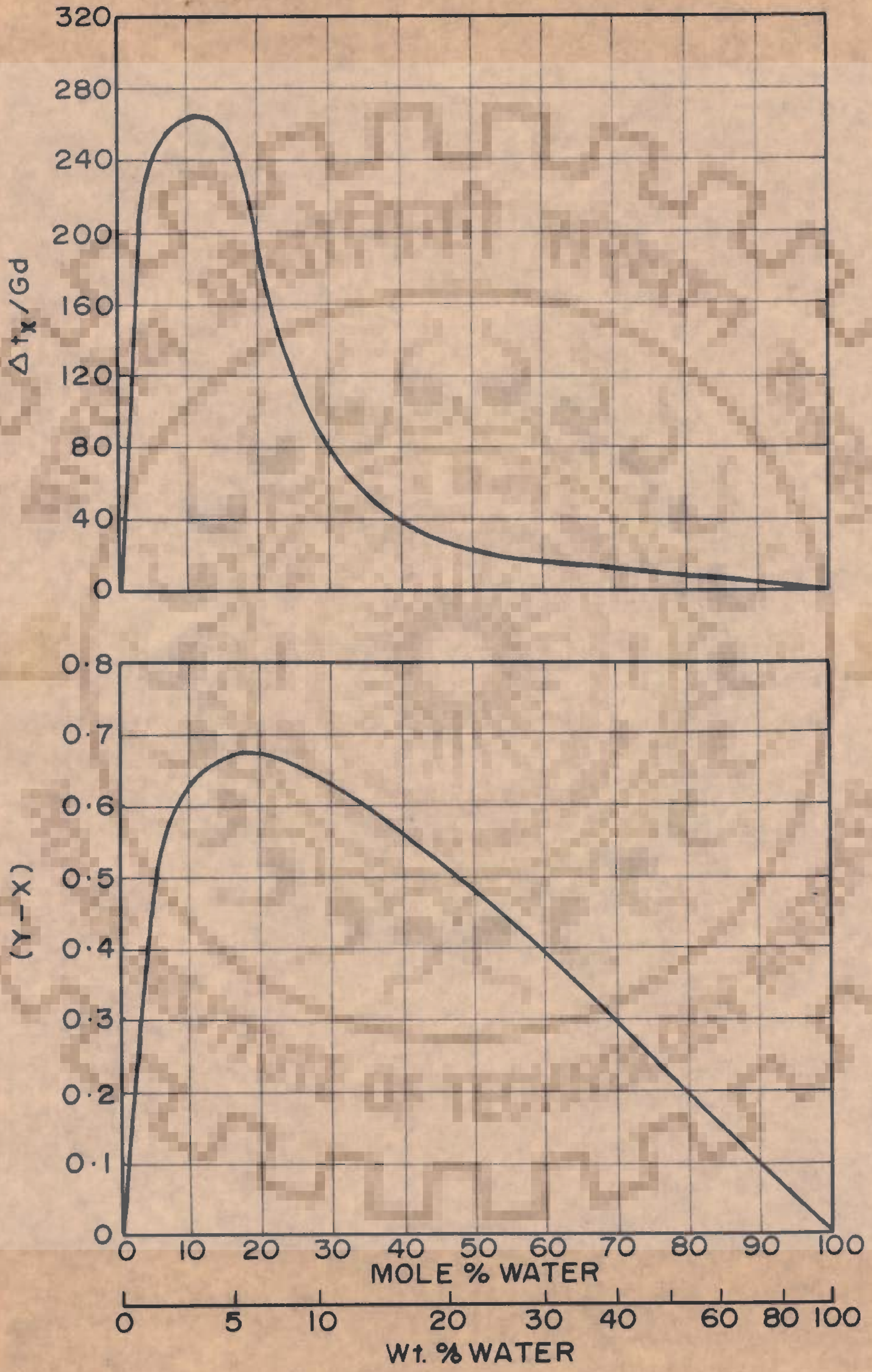


FIG. 4·32 (Y−X) AND $\Delta t_x / Gd$ VERSUS WATER CONCENTRATION IN WATER − ETHYLENE GLYCOL MIXTURES.

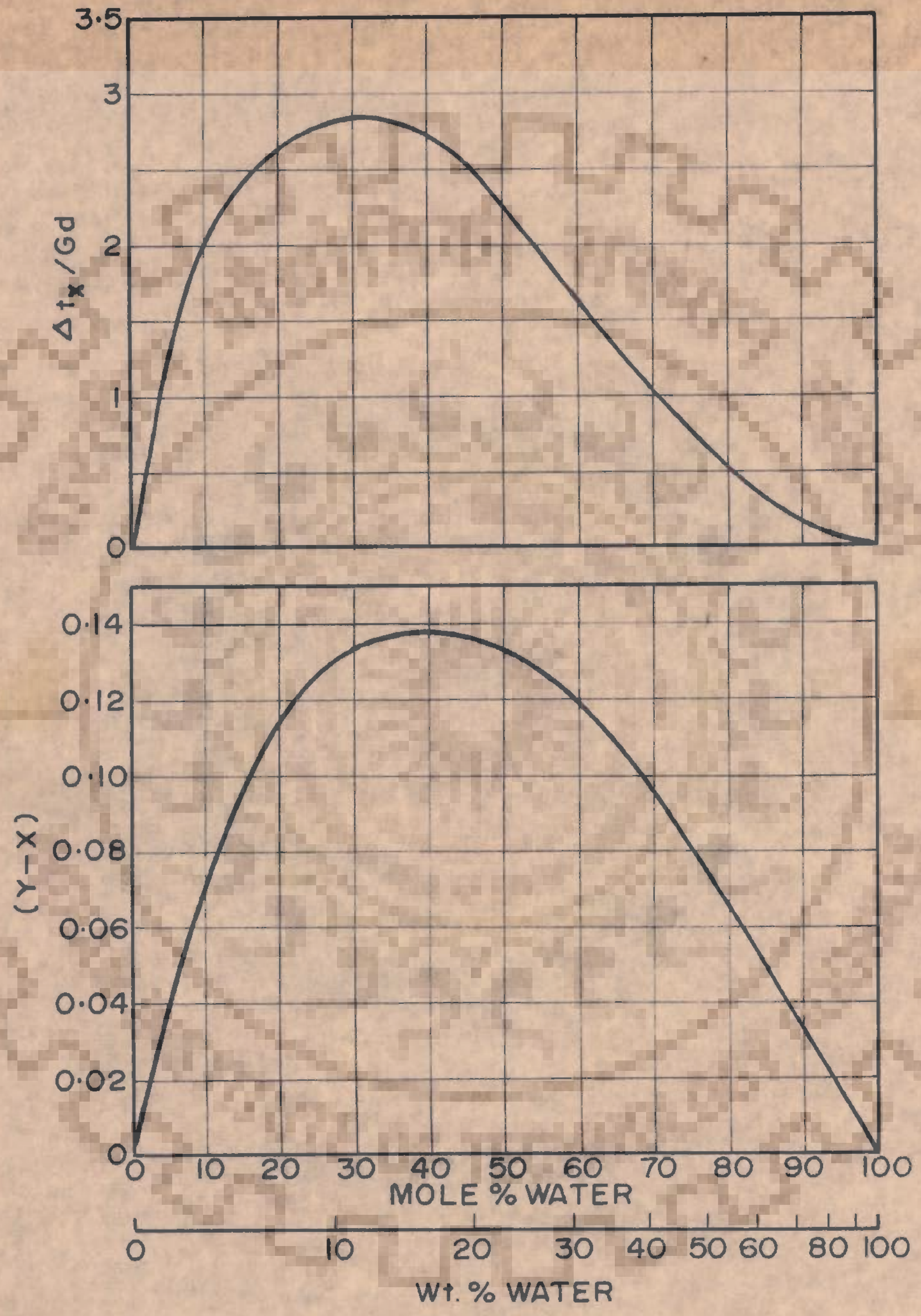


FIG.4·33 (Y−X) AND Δt_x/Gd VERSUS WATER CONCENTRATION IN WATER−ACETIC ACID MIXTURES.

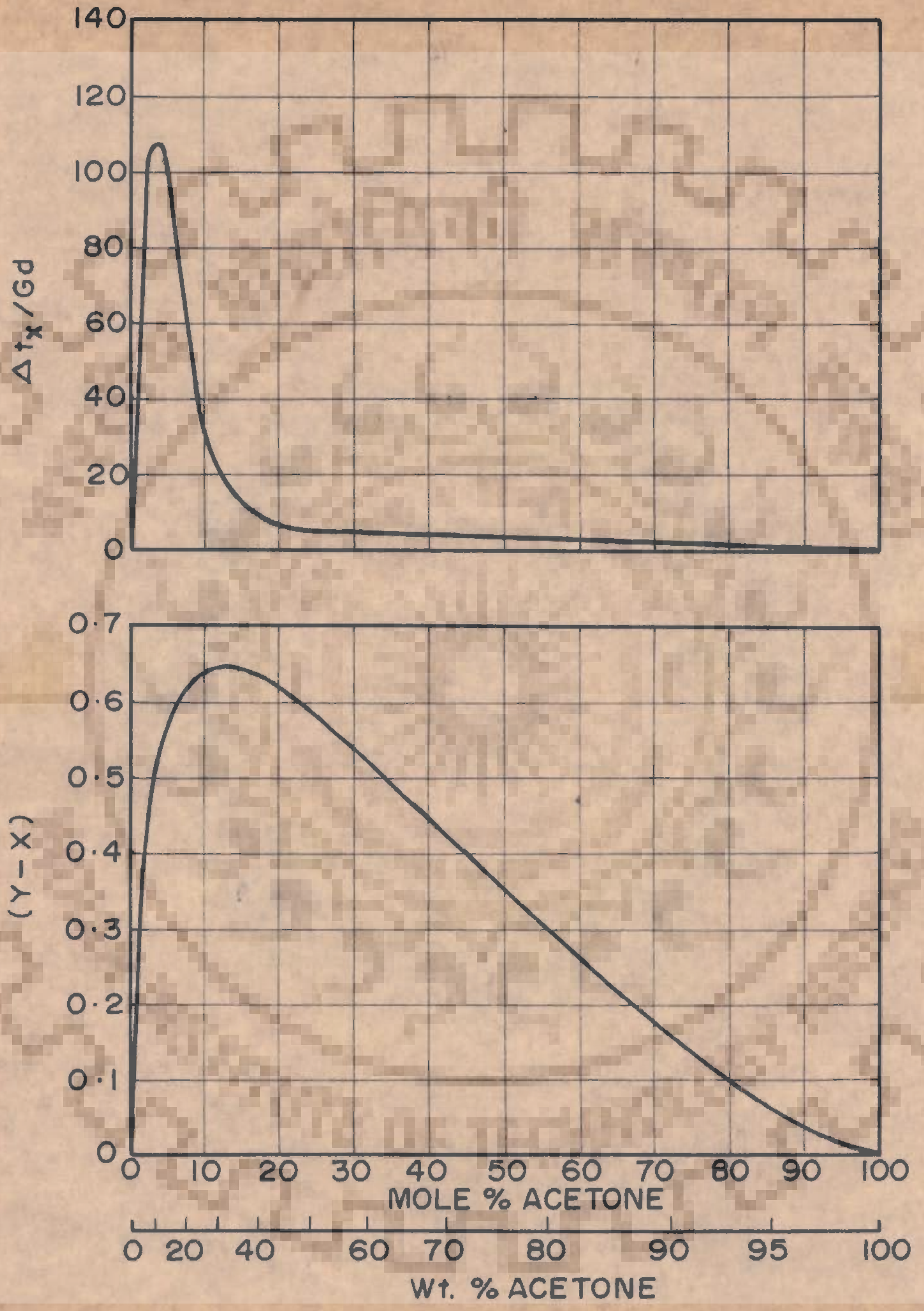


FIG. 4·34 (Y−X) AND $\Delta t_x/Gd$ VERSUS ACETONE CONCENTRATION IN ACETONE−WATER MIXTURES.

water-ethylene glycol, 17 Wt. % in water-acetic acid and 35 Wt. % in acetone-water mixtures. At these concentrations the number of nuclei for bubble formation are expected to be minimum and consequently the value of heat transfer coefficient becomes minimum. This also supports the experimental findings about the turnaround points.

The saturated nucleate boiling data for water-ethylene glycol and water-glycerine mixtures have been compared with the data of Sternling and Tichacek (45) in Figure 4.35. The data points of these authors were obtained from the faired curves which represented the cross plot of h versus q with composition as parameter.

The data points for water-ethylene glycol appear to possess indiscernible scatter. The experimental data of the present investigation as well as those of Ref. (45) exhibit a definite concentration (about 7 Wt. %) at which heat transfer coefficient becomes minimum. However there is apparent scatter with the data for water-glycerine which may be attributed to the following reasons :

a. There is obvious uncertainty in the evaluation of test points as they have been obtained from the faired curves as stated above.

b. The glycerine used in the present investigation was not extra pure quality which was the case with the data of Ref. (45). Nevertheless, the trend of the curves is similar.

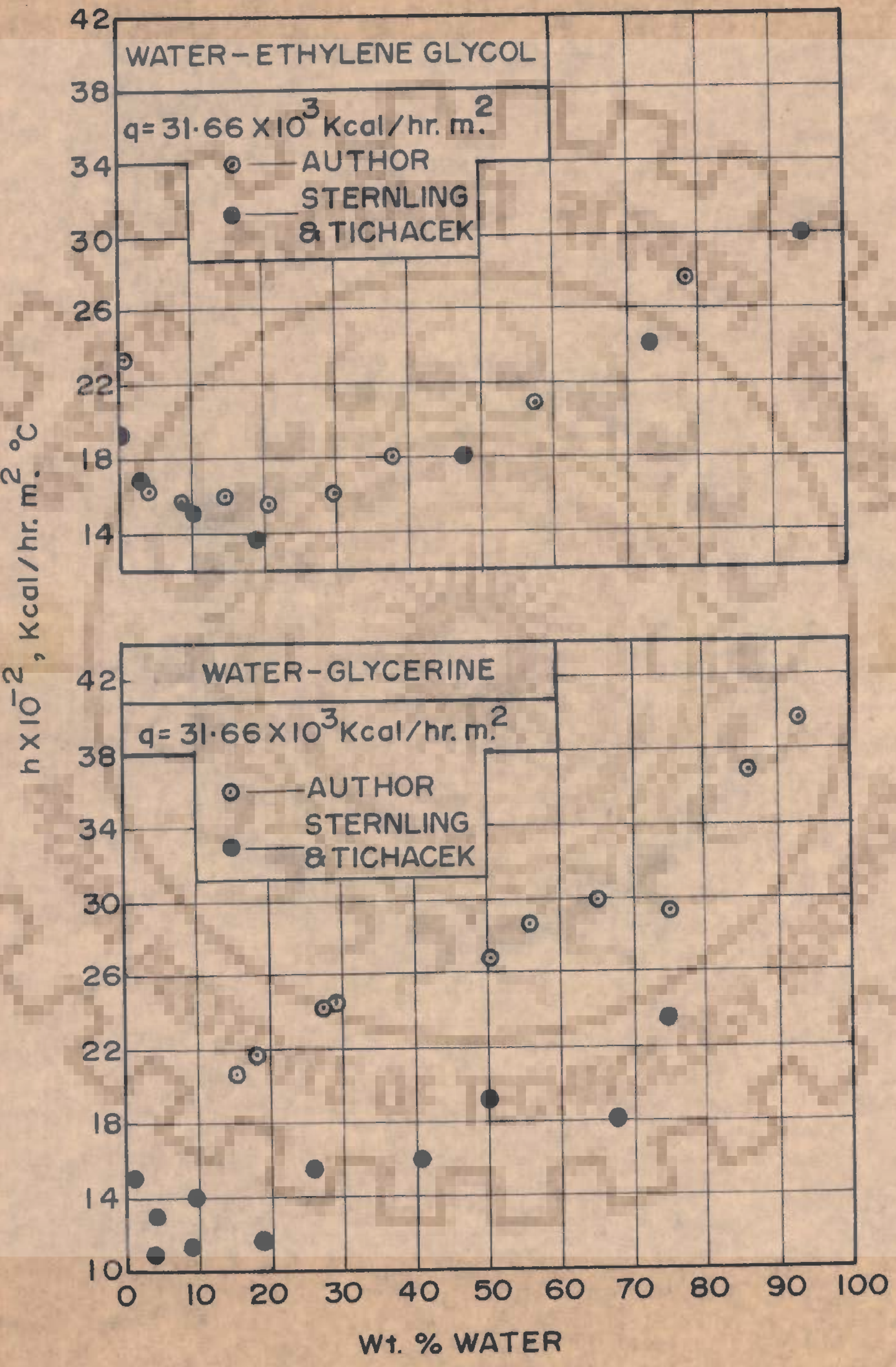


FIG. 4·35 COMPARISON BETWEEN BOILING DATA OF AUTHOR AND OF (45) FOR SATURATED BINARY MIXTURES.

4.2.5 Effect of Degree of Subcooling

The effect of liquid subcooling on the plot of heat transfer coefficient as a function of concentration of more volatile component is shown in Figures 4.36 to 4.38. The curves in these figures possess almost similar features as those observed in Figures 4.27 to 4.30 for saturated boiling. Degree of subcooling does not alter the concentrations at which the heat transfer coefficient becomes minimum. The curves with high values of Δt_{sub}, seem to become flatter. The value of heat transfer coefficient decreases markedly with the increase in the value of Δt_{sub} at a given heat flux and concentration.

Figure 4.39 shows the dependence of Nu_B on the values of K_{sub} on log-log plot for different systems. All the curves are found to possess almost same slope of about 0.5.

4.2.6 Effect of Peclet Number

Figure 4.40 represents a typical log-log plot of Nu_B as a function of Pe_B for saturated boiling of the binary liquid mixtures. All the curves are straight and parallel with a slope of about 0.6.

4.3 GENERALIZED CORRELATION

4.3.1 General Correlation for Binary Liquid Mixtures

It was argued to choose the dimensionless groups for the general correlation, which would take into account the effect of all the

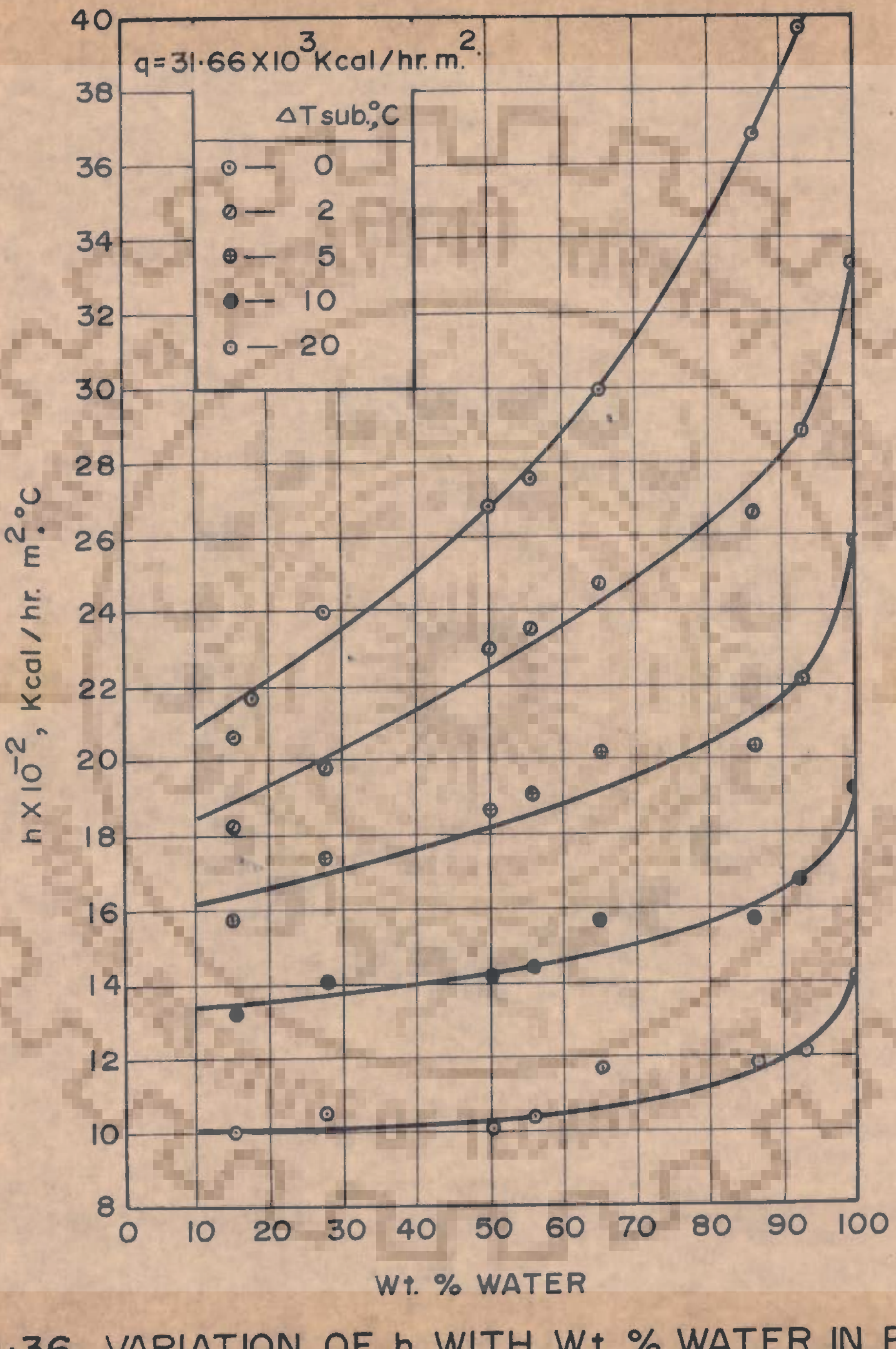


FIG. 4·36 VARIATION OF h WITH Wt. % WATER IN POOL BOILING OF WATER-GLYCERINE MIXTURES.

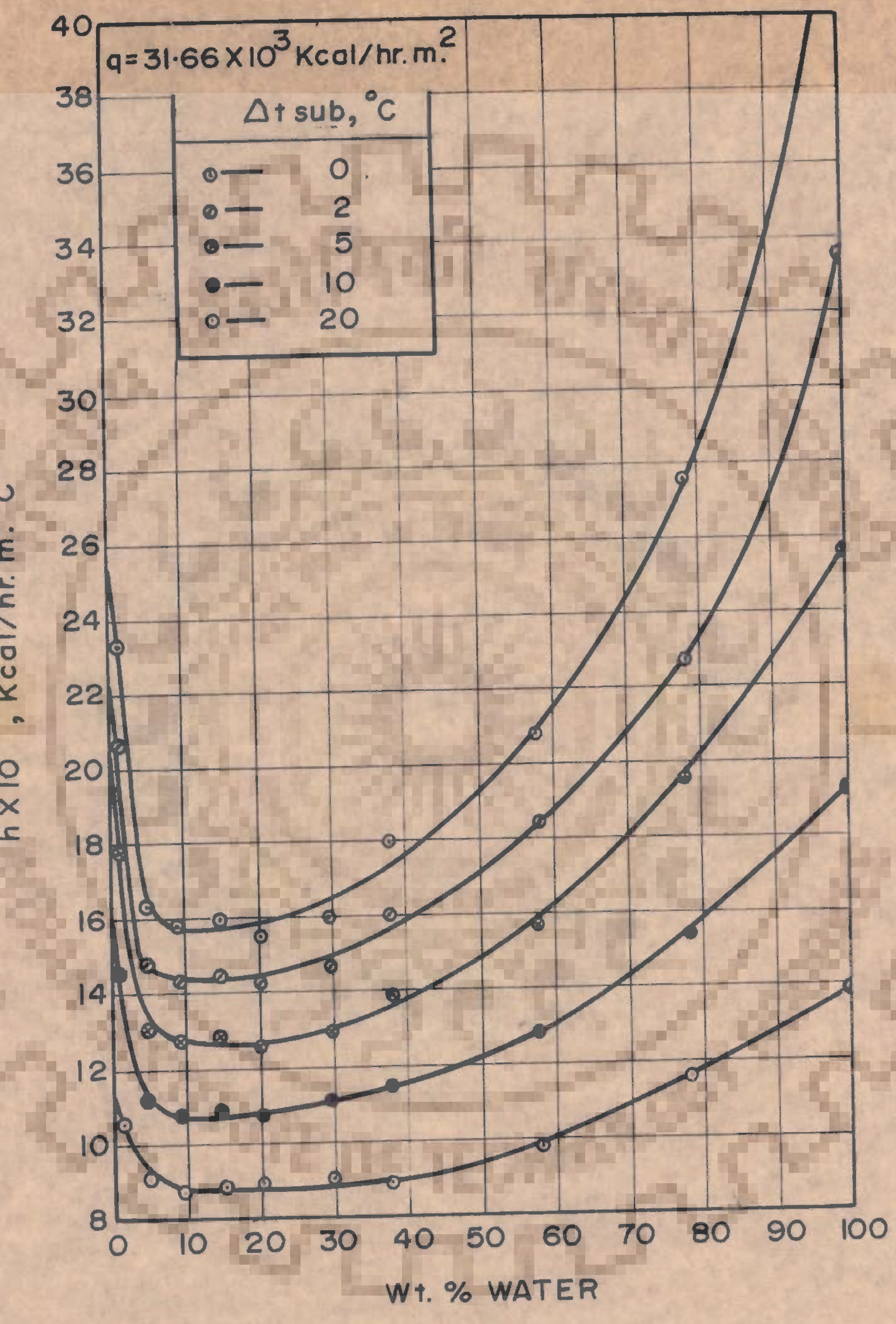


FIG.4·37 VARIATION OF h WITH Wt. % WATER IN POOL BOILING OF WATER-ETHYLENE GLYCOL MIXTURES.

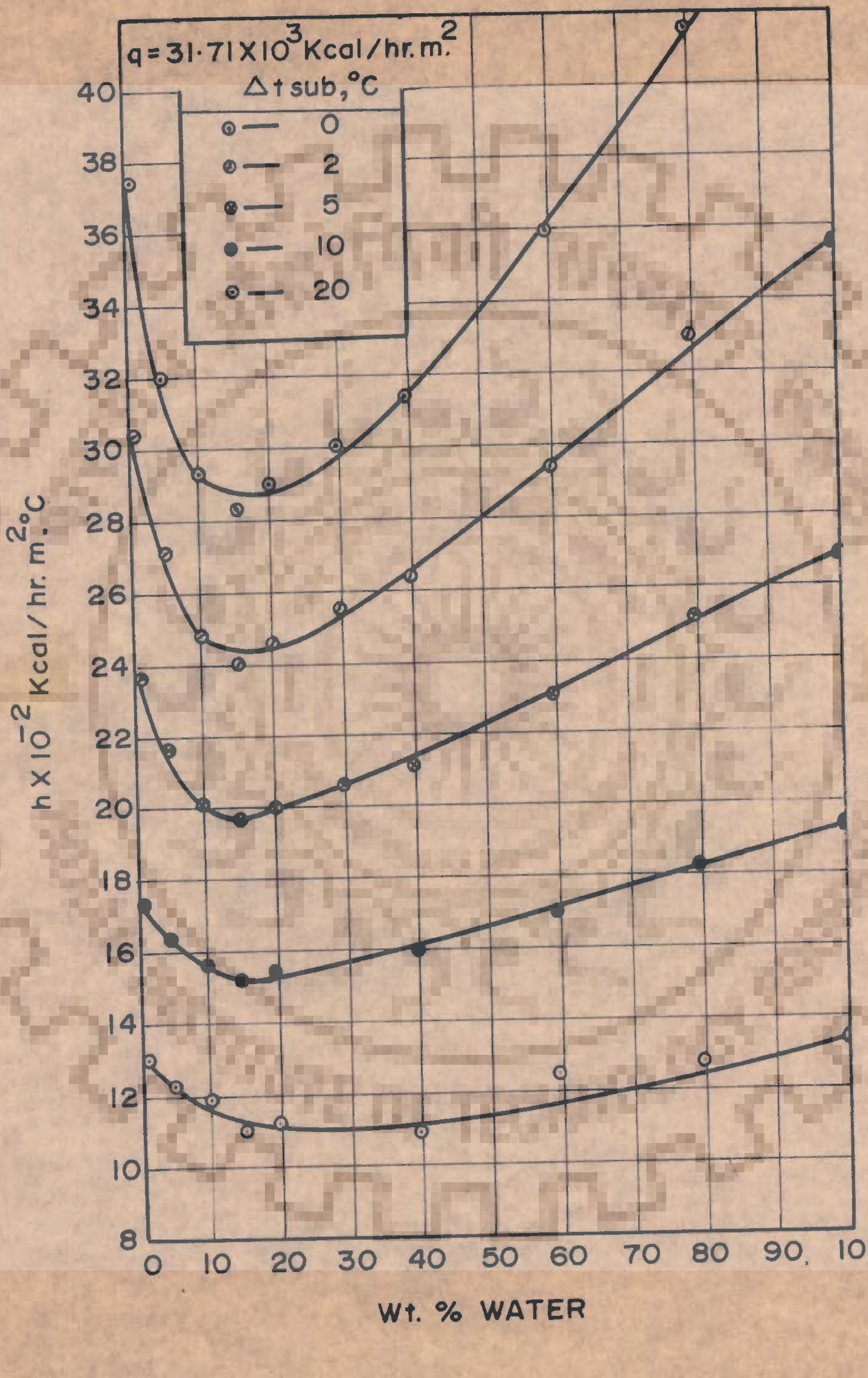


FIG. 4·38 VARIATION OF h WITH Wt. % WATER IN POOL BOILING OF WATER-ACETIC ACID MIXTURES.

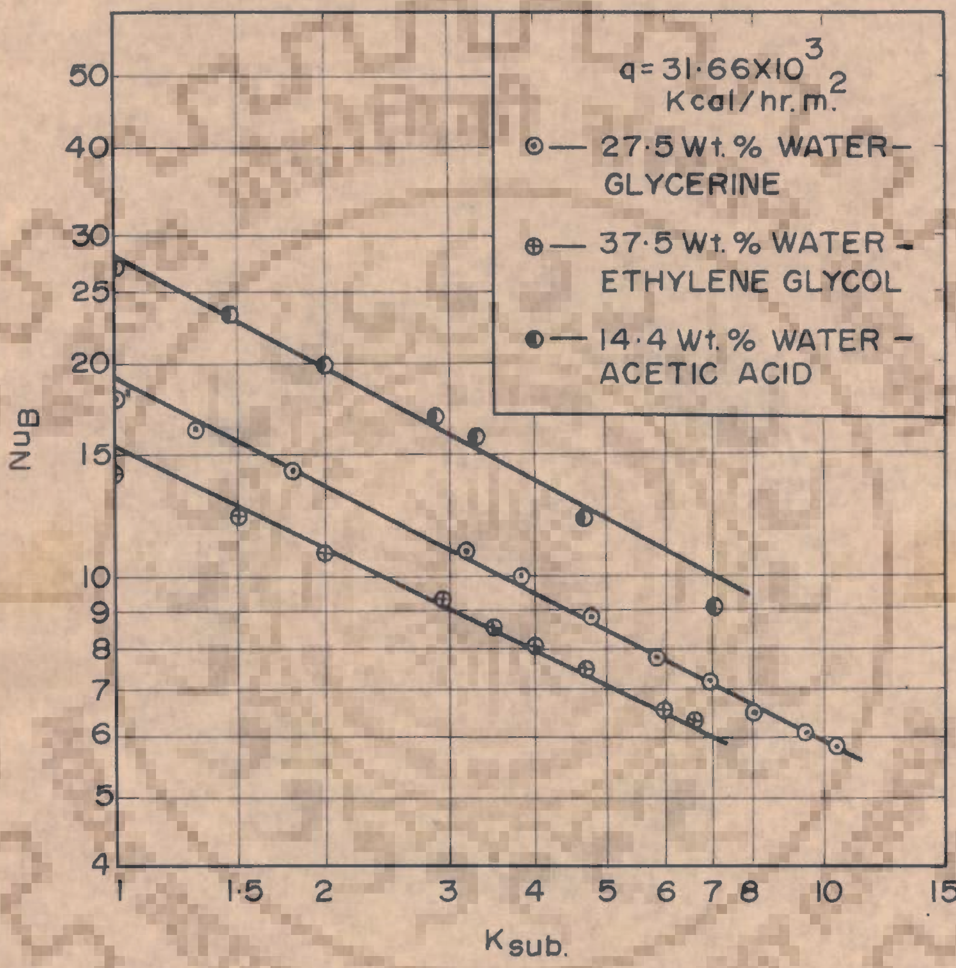


FIG. 4·39 Nu$_B$ AS A FUNCTION OF K$_{sub}$ FOR BINARY LIQUID MIXTURES.

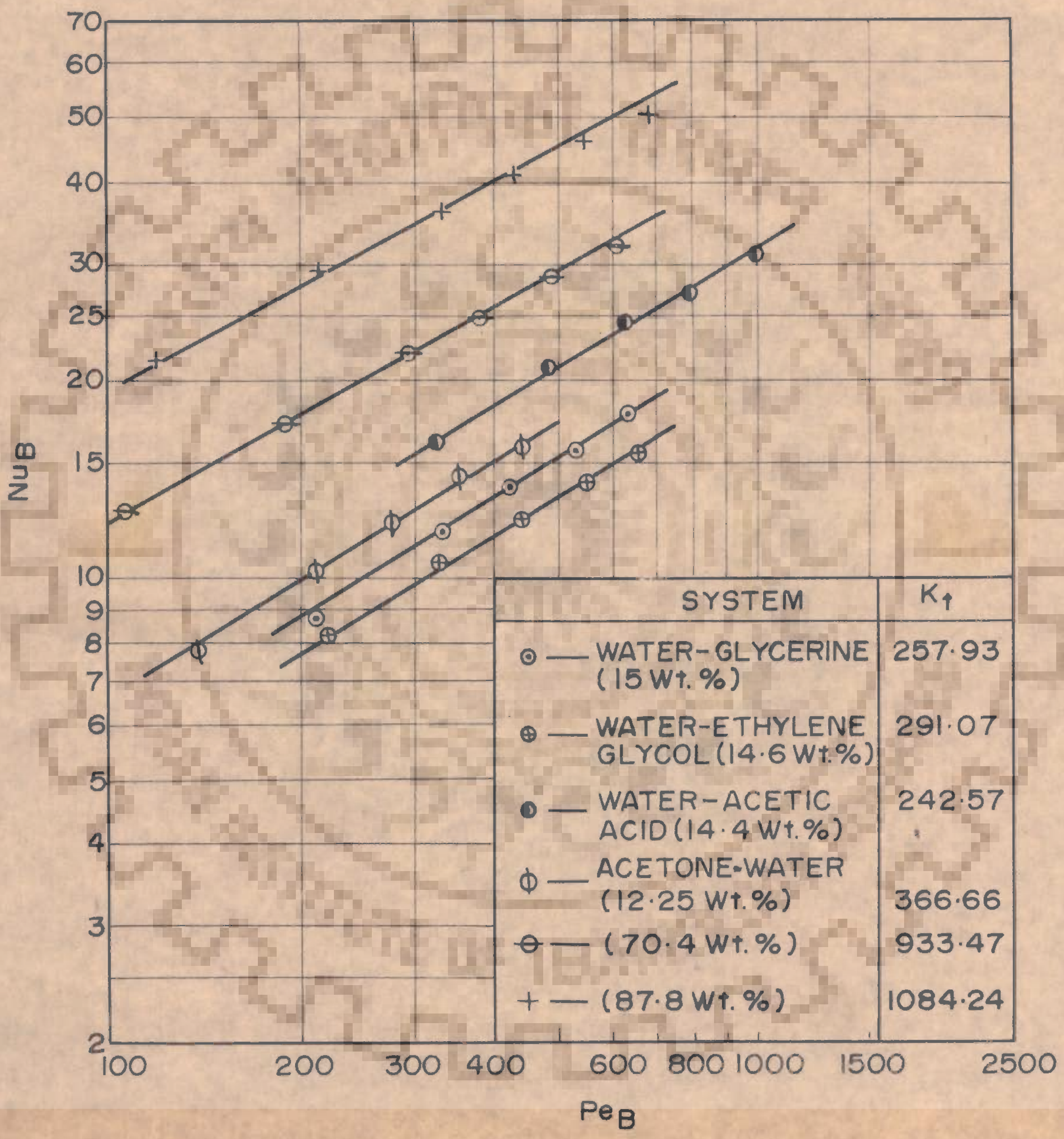


FIG. 4·40 Nu_B AS A FUNCTION OF Pe_B FOR BINARY LIQUID MIXTURES.

variables influencing the boiling process. The groups should contain such properties which could be determined easily and precisely as far as possible. Keeping this in view and considering the results of Figures 4.39 and 4.40; a generalized correlation for boiling heat transfer might be sought in the following form using dimensionless groups of earlier workers (22, 25, 30, 50, 61) alongwith a new proposed subcooling group, K_{sub} .

$$Nu_B = C \ (Pe_B)^{n_1} \ (K_{sub})^{n_2} \ (K_t)^{n_3} \qquad (4.4)$$

However, the above correlation lacks to include the effect of mass diffusion on the boiling of binary mixtures. Therefore Eq.(4.4) was considered to be inadequate to correlate the experimental data of liquid mixtures. To include the effect of mass diffusion, a dimensionless group, K_c , was chosen. This group was suggested by Grigorev (18) who extended the Kruzhilin's analysis for the boiling heat transfer of binary mixtures. Thus Eq.(4.4) assumes the following form :

$$Nu_B = C \ (Pe_B)^{n_1} \ (K_{sub})^{n_2} \ (K_t)^{n_3} \ (K_c)^{n_4} \qquad (4.5)$$

All calculations, in processing the experimental data of 4 binary mixtures, were carried out using an IBM 1620 computer. A least square curve fitting program was used to determine the values of exponents and constant, C. The program listing and results of some data points are given in Appendix G. Using the computed values of exponents n_1 , n_2 , n_3, and n_4; and constant, C , the following generalized correlation can be recommended :

$$Nu_B = 0.0576\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}\,(K_c)^{-0.034} \qquad (4.6)$$

Since the value of exponent, n_4, to which the concentration group is raised is found to be small, therefore the group, K_c , may be omitted. However, it is felt necessary to retain the group in its present form, firstly, so as to include the effect of mass transfer on the boiling of binary mixtures, secondly, the omission of the group, K_c, is likely to cause a maximum error of about 10 % for some systems.

All the physical properties of the binary liquid mixtures used in the correlation were calculated at the saturation temperature corresponding to the relevant concentration of the system. Accurate predictions of the properties of the mixtures at high temperatures are noticeably lacking. Therefore the properties were estimated by the methods as mentioned in Appendix C.

For the systems : water-glycerine and water-ethylene glocol the group, K_c was modified to the following form :

$$K_c = 1 + \frac{(Y - X)^2}{Y(1-X)}$$

The inclusion of the group, K_c, in its modified form, in Eq. (4.6) was found favourable to correlate the experimental data of these systems.

The experimental values of Nu_B of all the systems and those predicted by Eq. (4.6) have been compared in Figure 4.41. Eq. (4.6) seems to correlate most of the experimental data of the systems investigated. The standard deviation between the predicted and experimental values of Nu_B for about 697 data points on 4 different liquid mixtures varying widely in physical properties is 31.88 %. The average deviation is 31.84 %. The maximum error of ± 31 % covers 95 percent of the experimental data.

4.3.2 General Correlation for Pure Liquids - Comparison between Experimental and Predicted Values of Nu_B by Correlations of Others

The results of Figures 4.6 through 4.8 and the desirability of the correlation in the form, as discussed under section 4.3.1, suggest that all boiling heat transfer data on 3 pure liquids might also be described by the Eq. (4.4). A least square curve fitting program determined the values of exponents and constant in Eq. (4.4) and the following form of correlation resulted :

$$Nu_B = 0.084\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37} \qquad (4.7)$$

The physical properties of the liquids appearing in Eq. (4.7) were calculated at their saturation temperature.

Figure 4.42 shows the comparison between the experimental and predicted values of Nu_B by correlation (4.7). The proposed correlation (4.7) was found to best correlate 133 data points

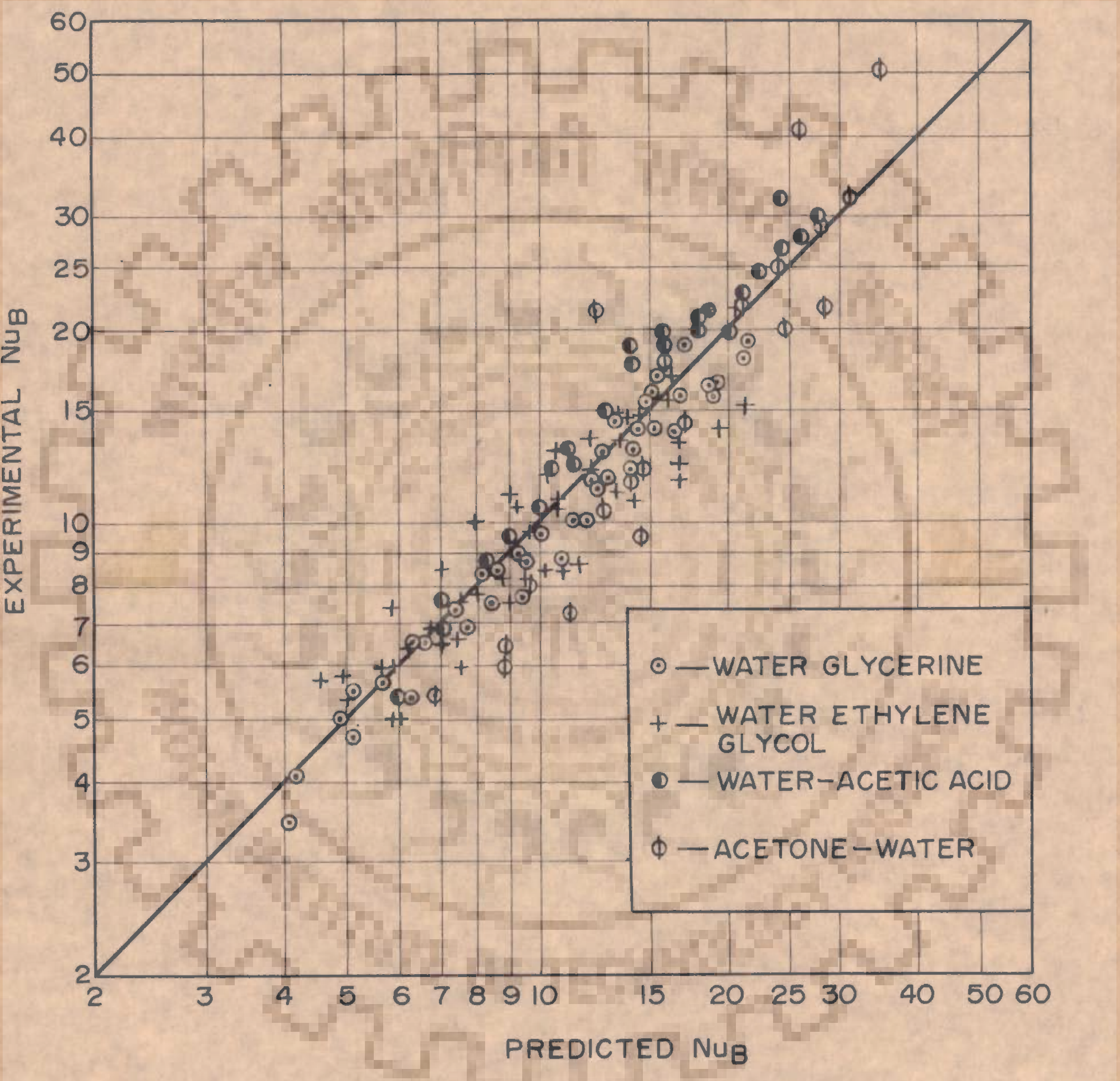


FIG. 4·41 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED Nu_B BY THE PROPOSED CORRELATION FOR BINARY MIXTURES.

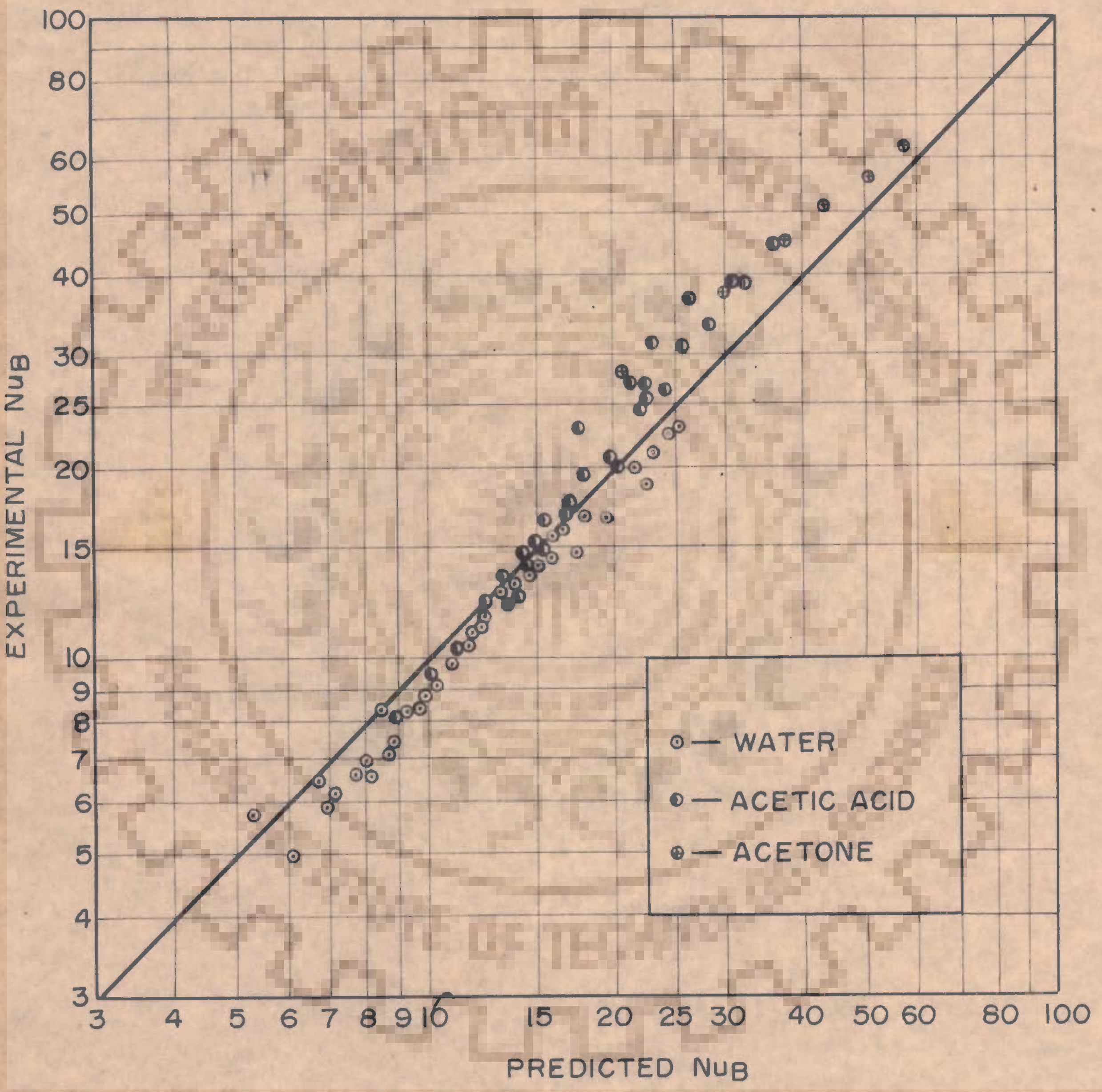


FIG.4·42 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED Nu_B BY THE PROPOSED CORRELATION FOR PURE LIQUIDS.

on water, acetic acid, and acetone with standard deviation of 20.54 % and average deviation of 20.16 %. About 95 percent of experimental data lie along the line describing the correlation within a maximum error of ± 24 %.

Referring to correlation (4.6), it can be easily noted that the correlation, if extended to the pure liquids i.e. the concentration group K_c is unity, assumes the form of Eq. (4.7). However the difference lies only in the value of constant, C.

Some of the important correlations (Table 2.3) were selected from the literature to check their validity using the saturated pool boiling heat transfer data of present investigation. The experimental values of Nu_B have been plotted against those predicted by the correlations of others in Figures 4.43, 4.44, and 4.45 for water, acetic acid, and acetone, respectively. From these figures the following points can be noted :

a. Correlations due to Borishanskii (30) and Kichigin et al (30) are found to best correlate experimental data on water with a maximum error of ± 24 %.

b. The experimental data on acetic acid are close to the predicted values by correlations due to McNelly (24) and Labuntsov (29) within a maximum error of ± 24 %.

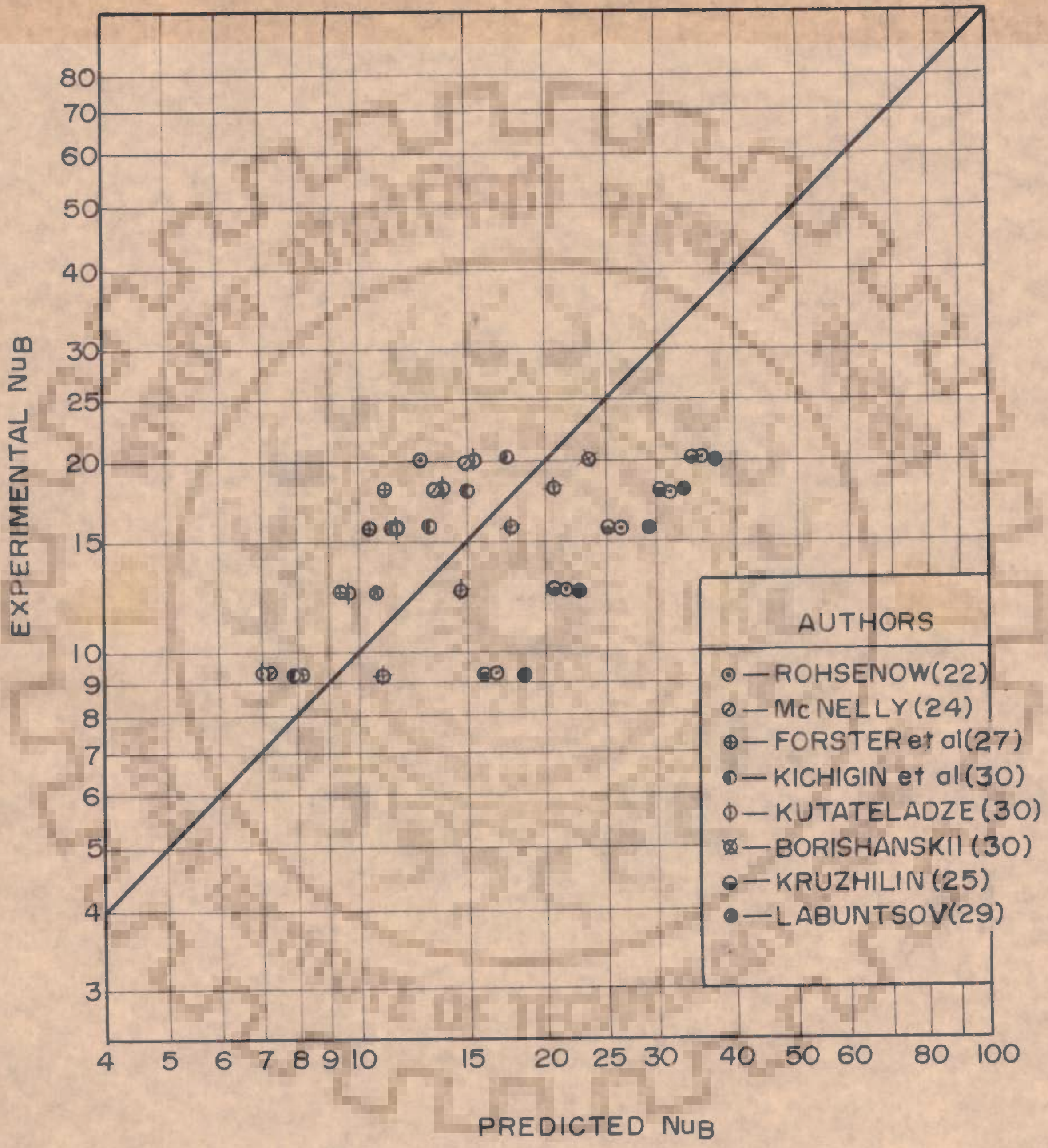


FIG. 4·43 COMPARISON OF EXPERIMENTAL Nu_B WITH THOSE PREDICTED BY DIFFERENT CORRELATIONS FOR SATURATED POOL BOILING OF WATER.

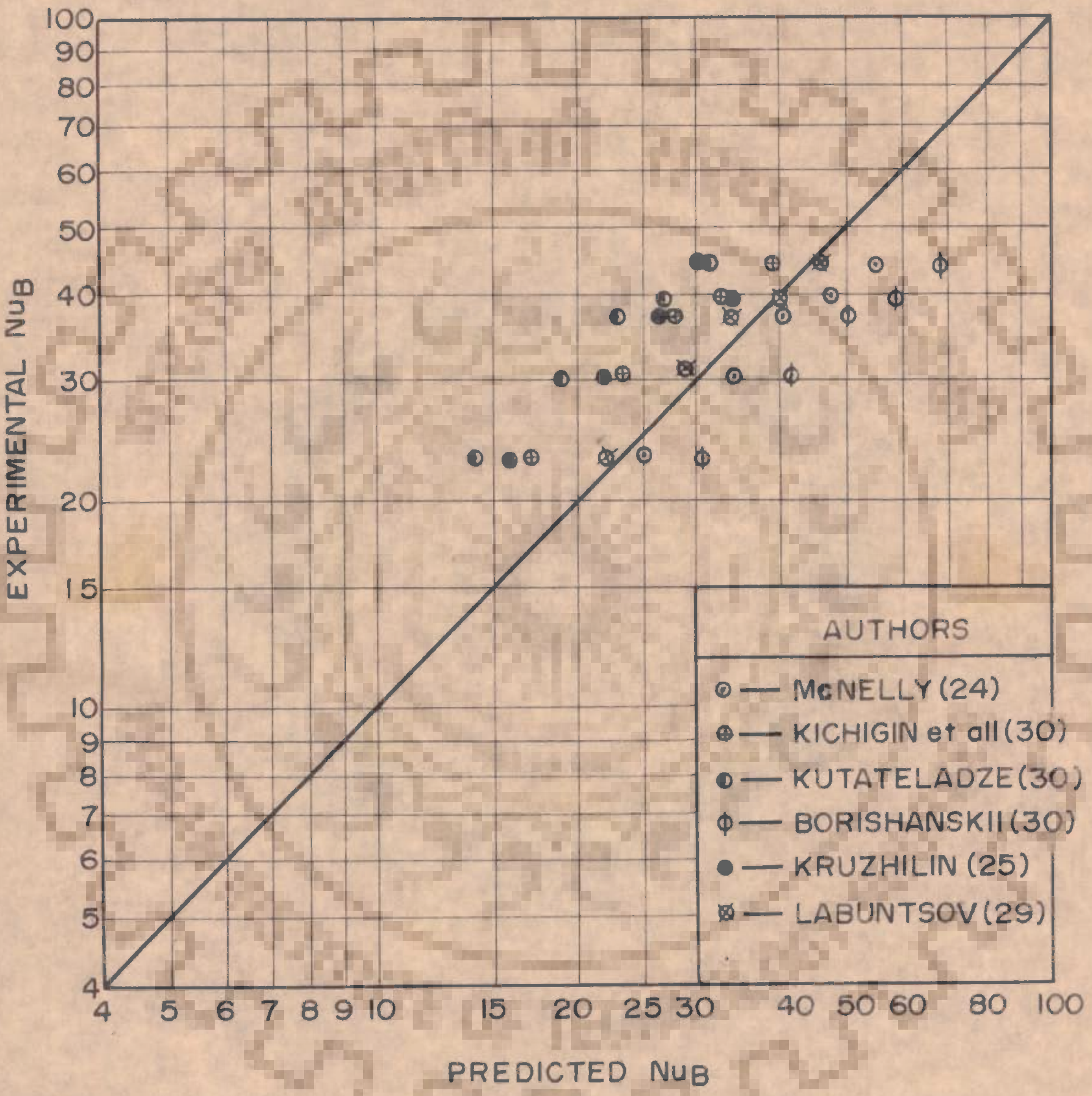


FIG. 4·44 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED Nu_B USING DIFFERENT CORRELATIONS FOR SATURATED POOL BOILING OF ACETIC ACID.

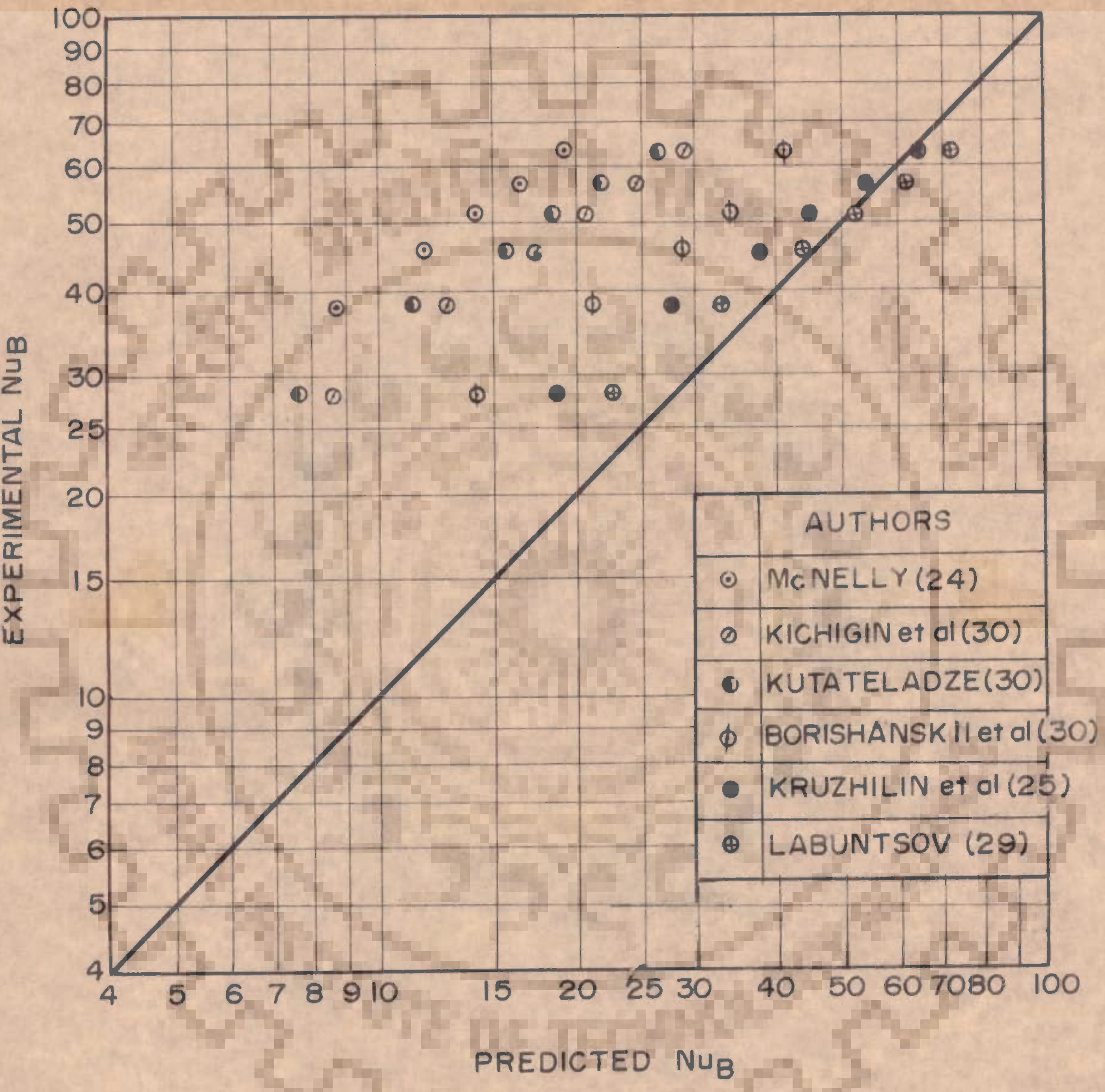


FIG. 4·45 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED Nu_B USING DIFFERENT CORRELATIONS FOR SATURATED POOL BOILING OF ACETONE.

c. Correlations due to Labuntsov (29) and Kruzhilin et al (25) predict values of Nu_B within ± 24 % of the experimental values of acetone.

d. No single correlation seems to extend the generality to the experimental data of all the 3 pure liquids within a maximum error of ± 24 %.

It may be pointed out from Figure 4.42 that the proposed equation (4.7) represents the best fit correlation for 133 data points of all the 3 pure liquids within a maximum error of ± 24 %. The correlation is applicable for both subcooled and saturated boiling of pure liquids.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

1. The experimental data of the present investigation on the pool boiling of saturated water were compared with those of other workers at 1 atmosphere pressure. It was found that the data points of the present investigation compared well with the data reported by (49, 57, 30, 58).

2. The data points on the pool boiling of saturated water - ethylene glycol mixture showed a good agreement with the data of Sternling and Tichacek (45).

3. Heat transfer coefficient in boiling of binary mixtures decreases with the increase in concentration of more volatile component until a certain concentration is reached at which the value of heat transfer coefficient becomes minimum. Beyond this concentration heat transfer coefficient begins to increase giving rise to a turnaround point. The concentration of the more volatile component corresponding to the turnaround points is found to be about 7 Wt. %, 17 Wt. %, and 35 Wt. % for the binary mixtures of water-ethylene glycol, water-acetic acid, and acetone-water, respectively.

The concentration of a binary mixture at which boiling heat transfer coefficient is minimum was predicted using the methods proposed by van Stralen (16), Tolubinskii et al (14) and Grigorev et al (18). The predicted concentrations for the above binary systems were found to be in quantitative agreement with the experimental results.

4. Experimental data on subcooled and saturated pool boiling of 4 binary liquid mixtures have been found to be correlated in the following form with a standard deviation of 31.88 % .

$$Nu_B = 0.0576\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}\,(K_c)^{-0.034}$$

A maximum error of ± 31 % covered about 95 % of the total data points.

5. A general correlation is recommended for calculating heat transfer coefficient during subcooled and saturated boiling of pure liquids; water, acetic acid, and acetone in the following form :

$$Nu_B = 0.084\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}$$

The above correlation showed a standard deviation of 20.16 %. A maximum error of ± 24 % covered about 95 % of the total data points of pure liquids.

It is easily seen that the correlation for pure liquids is a special case of the correlation meant for binary mixtures. But the value of constant, C, is different in the two correlations.

6. The generality of other correlations was tested for water, acetic acid, and acetone. It has been found that the proposed correlation yields better generality results than any other correlation (22, 24, 25, 27, 29, 30). The proposed correlation possesses one more

special feature as it can be used to calculate boiling heat transfer coefficient during subcooled and saturated boiling of liquids.

The present investigation can be extended to cover the following :

1. Addition of dimethylamine has been studied as an aid in acetic acid-water separation by normal distillation especially in the water-rich region where relative volatility is low (68). As such it would be important to collect boiling heat transfer data for the ternary system, acetic acid-water-dimethylamine.
2. Glycerine is recovered as a by-product from soap-making by means of evaporation. Thus it will have its industrial utility if boiling heat transfer studies are conducted using soap-lye system at atmospheric and subatmospheric pressures.
3. Reboilers used in process industries operate over a range of pressures. Therefore it would be useful to carry out boiling heat transfer studies of liquid mixtures at pressures other than one atmosphere and at high heat fluxes.

APPENDIX A

TABLES AND CHARTS OF CALIBRATIONS

Table A-1 Performance of Thermocouples

Standard Thermometer °C	Wall Thermocouple		Liquid Thermocouple	
	mV	°C	mV	°C
50.1	2.037	50.05	2.040	50.10
60.5	2.490	60.50	2.488	60.45
70.2	2.914	70.15	2.914	70.15
80.0	3.360	80.05	3.360	80.05
90.3	3.824	90.20	3.828	90.30
99.0	4.230	99.00	4.232	99.05

Table A-2 Calibration of Wattmeter

Readings of Wattmeter, Watt		Error
Substandard	Wattmeter	%
80	80	0
120	120	0
277	280	1.08
466	460	0.86
636	640	0.63
797.5	800	0.31
975	980	0.51

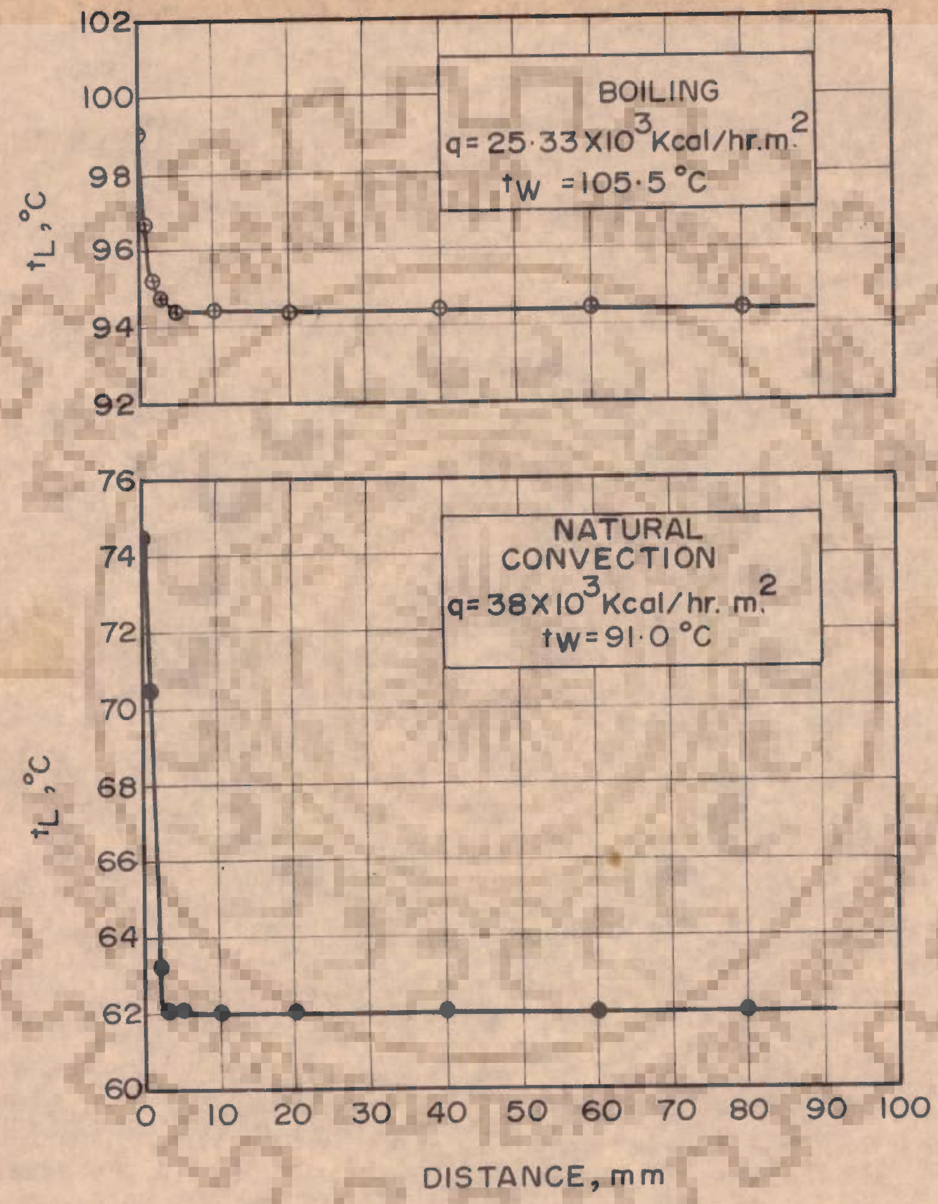


FIG. A-1 VARIATION OF t_L FOR WATER AT DIFFERENT NORMAL POSITIONS OF SIDE THERMOCOUPLE FROM TEST SURFACE .

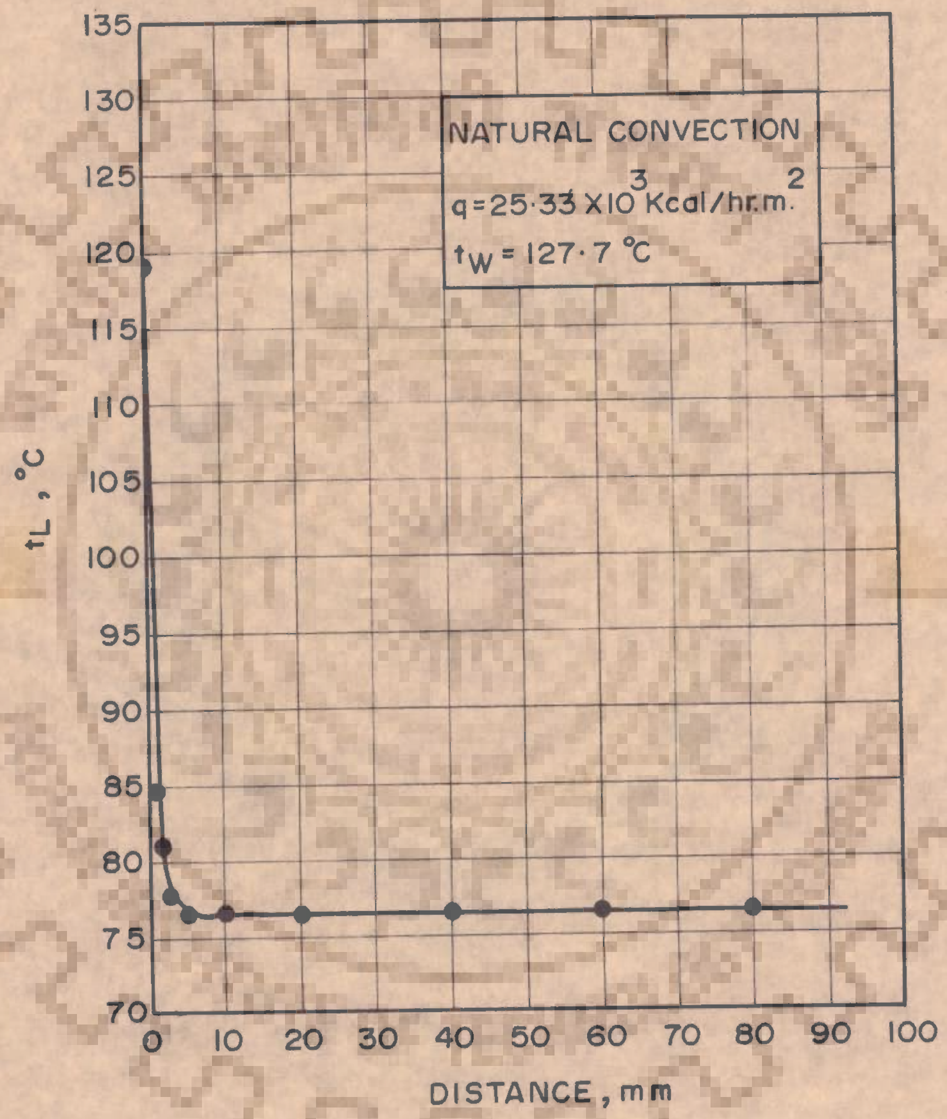


FIG. A-2 VARIATION OF t_L FOR ETHYLENE GLYCOL AT DIFFERENT NORMAL POSITIONS OF SIDE THERMOCOUPLE FROM TEST SURFACE.

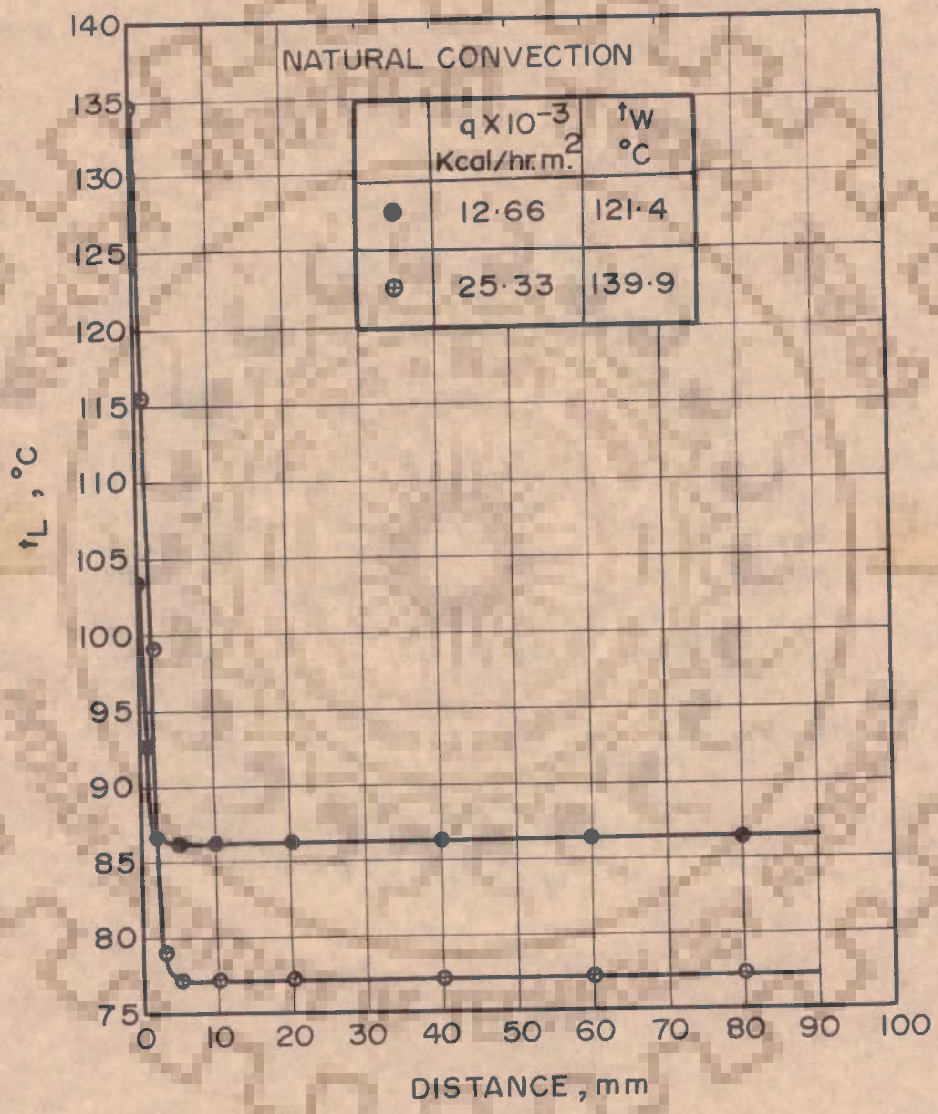
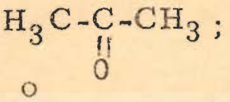


FIG. A-3 VARIATION OF t_L FOR GLYCERINE AT DIFFENT NORMAL POSITIONS OF SIDE THERMOCOUPLE FROM TEST SURFACE.

APPENDIX B

TABLES OF PHYSICAL PROPERTIES OF PURE LIQUIDS

Table B-1 Physical Properties of Acetone

Formula : 
$H_3C-\underset{\underset{O}{\|}}{C}-CH_3$; Molecular Weight = 58.1

$t_{MP} = -93.2\,^{o}C$; $t_B = 56.1\,^{o}C$; $t_c = 235.0\,^{o}C$ $P_c = 48.6\,kg/cm^2$

1. Density, Viscosity, Surface tension, Specific heat and Latent heat of Vaporization (62, 65)

t °C	ρ_L g/cm^3	$\mu \times 10^2$ g/cm.sec	$\sigma \times 10^4$ kg/m	C Kcal/kg.°C	λ Kcal/kg
20	0.7905	0.325	24.2	0.516	132
30	0.7788	0.296	-	0.523	-
40	0.7674	0.271	21.6	0.530	128
50	0.7564	0.249	-	0.538	-
52.2	-	0.2405	-	-	-
53.86	-	0.2377	-	-	-
56.1	-	-	-	-	125
60	0.7446	-	19.0	-	123.5
70	0.7326	-	-	-	-
80	0.7205	-	16.5	-	118.3
100	-	-	-	-	112.8

2. Thermal conductivity (62)

t, °C	25	50	75	100
k $\frac{Kcal}{m.hr.^{o}C}$	0.145	0.140	0.135	0.130

Table B-2 Physical Properties of Acetic acid

Formula : CH_3COOH ; Molecular Weight = 60

t_{MP} = 16.7°C ; t_B = 118°C ; t_c = 321.6°C P_c = 59.1 kg/cm^2

1. Density, Viscosity, surface tension and Latent heat of Vaporization(62)

t °C	ρ_L g/cm^3	$\mu \times 10^2$ g/cm.sec	$\sigma \times 10^4$ kg/m	λ Kcal/kg
20	1.0491	-	28.4	84.1
30	1.0392	0.79	27.35	85.7
40	1.0284	0.69	26.3	87.2
50	1.0175	0.62	25.3	88.4
60	1.0060	0.55	24.3	89.6
70	0.9948	-	23.25	90.6
80	0.9835	0.453	22.2	91.6
90	0.9718	-	21.2	92.4
100	0.9599	0.377	20.2	93.1
110	0.9483	-	19.2	93.4
120	0.9362	0.320	18.25	93.2
130	0.9265	0.297	17.2	92.7

2. Thermal conductivity (62, 65)

t, °C	25	50	75
$\frac{Kcal}{hr.m.°C}$	0.147	0.143	0.139

3. Specific heat (65)

$C = 0.4688 + 0.000909\, t$, Kcal/kg.°C

Table B-3 Physical Properties of Ethylene glycol

Formula : $CH_2OH\ CH_2OH$ Molecular Weight = 62.07

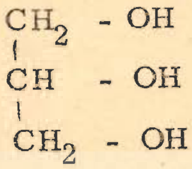
1. Density, Viscosity, Heat Capacity and Thermal Conductivity (66)

t °C	ρ_L g/cm^3	$\mu \times 10^2$ g/cm.sec	C Kcal/kg. °C	k Kcal/m.hr °C
20	1.112	19.6	0.578	0.228
40	1.100	9.5	0.604	0.228
60	1.087	5.25	0.626	0.226
80	1.073	5.23	0.644	0.226

2. Surface tension (65)

t, °C	20	50	80	130
$\sigma \times 10^4$ kg/m	48.6	46.5	43.5	37.4

Table B-4 Physical Properties of Glycerine

Molecular Formula 

$$\begin{array}{l} CH_2 - OH \\ \vert \\ CH - OH \\ \vert \\ CH_2 - OH \end{array}$$

; Molecular Weight = 92.1

1. Density, Viscosity and Surface tension (62).

t °C	ρ_L g/cm³	μx10² g/cm.sec	σ x10⁴ kg/m	t °C	ρ_L g/cm³	μx10² g/cm.sec	σ x10⁴ kg/m
20	1.2594	1480	60.7	110	1.1976	-	54.4
30	1.2547	600	60.2	120	1.1876	5.2	53.3
40	1.2500	330	59.7	130	1.1765	-	52.1
50	1.2438	180	59.2	140	1.1628	1.8	51.0
60	1.2376	102	58.5	150	1.1468	-	49.8
70	1.2315	59	57.8	160	1.1261	1.0	-
80	1.2239	35	57.0	180	-	0.45	-
90	1.2165	21	56.1	200	-	0.22	-
100	1.2077	13	55.3	-	-	-	-

2. Thermal Conductivity (62)

t, °C	25	50	75	100	125	150
$\frac{K\,cal}{m.hr.^{\circ}C}$	0.240	0.243	0.246	0.248	0.251	0.254

3. Specific heat (62, 35)

t, °C	0	20	50	100
C, $\frac{K\,cal}{kg-^{\circ}C}$	0.54	0.58	0.60	0.67

4. Vapor pressure (62)

t, °C	P_v, mmH_g	t, °C	P_v, mmH_g	t, °C	P_v, mmH_g
125.5	1	198.0	40	240.0	200
153.8	5	208.0	60	263.0	400
167.2	10	220.1	100	290	760
132.2	20	-	-	-	-

*Table B-5 Constants for Physical Properties of Ethylene glycol and Glycerine (45)

Formulae :

$$\rho = \rho_o - aT \qquad C = C_o + b_1T$$

$$k = k_o + K_1T \qquad \lambda = \lambda_o - J_1T$$

$$P_v = P_1 \exp\left(-\frac{a_1}{T}\right) \qquad \sigma = \sigma_o\left(1 - \frac{T}{T_c}\right)$$

Symbol	Units	Compound Ethylene glycol	 Glycerine
t_{MP}	°C	-15.6	18.0
t_B	°C	197.4	290
T_c	°K	705	970
ρ_o	g/cm^3	1.451	1.445
a	g/cm^3, °K	0.00115	0.000625
C_o	K cal/kg, °C	0.244	0.122
b_1	K cal/kg. °C . °K	0.00108	0.00144
k_o	Kcal/m.hr. °C	0.226	0.244
K_1	K cal/m.hr. °C. °K	0	0
λ_o	K cal/kg	353	284
J_1	K cal/kg. °K	0.3	0.2
$P_1 \times 10^{-5}$	atm.	29.8	193.8
a_1	°K	7100	9450
σ_o	kg/m	94.0×10^{-4}	106×10^{-4}

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* Some of the properties of Ethylene glycol and Glycerine were not available for the experimental temperature range. They have been calculated by the formulae as obtained by Sternling and Tickacek (45).

APPENDIX C

PHYSICAL PROPERTIES OF BINARY LIQUID MIXTURES

Table C-1 Physical Properties of Water-Glycerine Mixture

1. Density (70)

Wt. % Water	Density, kg/m^3 15°C	20°C	25°C	30°C	Wt.% Water	Density, kg/m^3 15°C	20°C	25°C	30°C
0	1264.15	1261.08	1258.02	1254.95	60	1101.45	1099.30	1097.10	1094.75
10	1238.10	1235.10	1232.00	1228.90	70	1074.55	1072.70	1070.70	1068.55
20	1211.60	1208.50	1205.45	1202.40	80	1048.40	1046.90	1045.25	1043.50
30	1184.15	1181.25	1178.40	1175.65	90	1023.25	1022.10	1020.70	1019.05
40	1156.50	1153.80	1151.05	1148.30	100	999.13	998.23	997.08	995.68
50	1128.70	1126.30	1123.75	1121.10					

2. Surface tension (64)

$t = 18°C$

Wt.% Water	0	2	15	50	70	80	85	90	95	100
$\sigma \times 10^4$, kg/m	61.63	62.04	64.59	69.28	72.14	73.21	73.67	73.88	73.93	74.5

3. Viscosity (62)

Wt. % Water	$\mu \times 10^2$ gm/cm.sec 20°C	25°C	30°C	Wt. % Water	$\mu \times 10^2$ gm/cm.sec. 20°C	25°C	30°C
0	1499	945	624	60	3.750	3.181	2.731
10	234.6	163.6	115.3	70	2.501	2.157	1.873
20	62.0	45.86	34.92	80	1.769	1.542	1.360
30	22.94	17.96	14.32	90	1.311	1.153	1.024
40	10.96	8.823	7.312	100	1.005	0.893	0.800
50	6.050	5.041	4.247				

4. Specific heat (70)

Mole % Water	Wt. % Water	C, Kcal/kg.°C 15°C	C, Kcal/kg.°C 32°C	Mole % Water	Wt.% Water	C, Kcal/kg.°C 15°C	C, Kcal/kg.°C 32°C
0	0	0.555	0.576	88.5	60	0.851	0.841
56.1	20	0.67	0.672	95.34	80	0.929	0.924
77.3	40	0.765	0.758	97.88	90	0.961	0.960

5. Thermal conductivity (62)

Wt. % Water	k, K cal/m.hr.°C 0°C	20°C	40°C	60°C	80°C	100°C
0	-	0.243	0.245	0.247	0.250	0.252
20	0.279	0.284	0.289	0.294	0.299	0.304
40	0.323	0.333	0.343	0.353	0.361	-
60	0.373	0.389	0.405	0.420	0.432	-
80	0.427	0.449	0.470	0.489	0.503	-
100	0.486	0.515	0.540	0.561	0.576	0.585

Table C-2 Physical Properties of Water-Ethylene glycol Mixtures

1. Surface tension (64)

$t = 15\,^{o}C$

Moles of Glycol/litre	1.0	0.5	0.25	0.125	0.0
$\sigma \times 10^{4}$, kg/m	72.3	73.8	74.5	74.75	74.85

2. Viscosity (65)

$t = 25\,^{o}C$

Wt.% Water	0	24.36	30.48	39.16	50.45	54.87	66.89	85.89	100
$\mu \times 10^{2}$, gm/cm.sec	18.09	92.4	62.54	45.08	32.12	28.7	16.28	12.64	8.95

3. Specific heat (65)

$t = 20\,^{o}C$

Wt.% water	0	10	20	30	40	50	60	70	80	90
C, $\frac{Kcal}{kg.^{o}C}$	0.562	0.628	0.674	0.72	0.76	0.808	0.855	0.896	0.946	0.991

4. Thermal conductivity (62)

Wt. % Water	k, Kcal/m.hr.°C					
	0°C	20°C	40°C	60°C	80°C	100°C
0	0.217	0.219	0.221	0.223	0.225	0.227
20	0.252	0.256	0.260	0.264	0.268	0.272
40	0.298	0.306	0.314	0.322	0.330	0.336
60	0.351	0.364	0.377	0.390	0.403	0.410
80	0.417	0.437	0.457	0.473	0.488	0.496
100	0.486	0.515	0.540	0.561	0.576	0.585

Table C-3 Physical Properties of Water-Acetic acid Mixtures

1. Density (70)

Wt. % Water	$\rho_L \times 10^{-4}$ kg/m^3						
	0°C	10°C	15°C	20°C	25°C	30°C	40°C
0	1.0697	-	1.0545	1.0498	1.0440	1.0380	1.0271
10	1.0865	1.0766	1.0708	1.0661	1.0605	1.0549	1.0445
20	1.0895	1.0798	1.0747	1.0700	1.0647	1.0596	1.0495
30	1.0869	1.0779	1.0732	1.0685	1.0637	1.0590	1.0493
40	1.0813	1.0728	1.0684	1.0642	1.0597	1.0552	1.0462
50	1.0729	1.0654	1.0613	1.0575	1.0534	1.492	1.0408
60	1.0621	1.0557	1.0522	1.0468	1.0450	1.0416	1.0338
70	1.0491	1.0440	1.0411	1.0384	1.0350	1.0320	1.0253
80	1.0343	1.0305	1.0283	1.0263	1.0235	1.0210	1.0153
90	1.0177	1.0156	1.0141	1.0125	1.0107	1.0089	1.0042
100	0.9999	0.997	0.9991	0.9982	0.9971	0.9957	0.9922

2. Surface tension (64)

Wt. % Water	$\sigma \times 10^{4}$ kg/m		Wt. % Water	$\sigma \times 10^{4}$ kg/m	
	25°C	35°C		25°C	35°C
0.0	27.87	26.82	58.51	41.0	40.05
6.47	28.44	27.45	80.75	48.9	48.0
8.63	29.45	28.6	89.01	52.8	53.25
16.92	31.77	30.9	94.06	60.3	59.3
34.75	35.33	34.8	97.33	66.7	65.5
48.16	38.6	37.8	100	73.35	71.8

3. Viscosity (62)

Wt. % Water	$\mu \times 10^2$, gm/cm. sec								
	20°C	30°C	40°C	50°C	60°C	70°C	80°C	90°C	100°C
0	1.22	1.04	0.90	0.79	0.70	0.63	0.56	0.51	0.46
5	1.89	1.52	1.26	1.07	0.92	0.78	0.69	0.59	0.52
10	2.43	1.87	1.49	1.22	1.04	0.89	0.77	0.65	0.57
20	2.75	2.09	1.69	1.35	1.12	0.94	0.81	0.69	0.59
30	2.66	2.05	1.63	1.33	1.10	0.91	0.78	0.67	0.58
40	2.43	1.89	1.48	1.23	1.03	0.84	0.73	0.63	0.54
50	2.21	1.70	1.35	1.11	0.92	0.76	0.65	0.57	0.50
60	1.96	1.52	1.20	0.99	0.82	0.68	0.59	0.51	0.45
70	1.70	1.33	1.05	0.87	0.73	0.61	0.52	0.46	0.40
80	1.45	1.15	0.92	0.76	0.64	0.54	0.47	0.41	0.36
90	1.22	0.97	0.78	0.65	0.56	0.47	0.41	0.36	0.32

4. Specific heat (65)

t = 38°C

Mole % Water	0.0	45.5	69.1	83.3	93.02	96.77	100.0
C, K cal/kg. °C	0.533	0.627	0.725	0.816	0.905	0.955	0.99

Table C-4 Physical Properties of Acetone-Water Mixtures

1. Surface tension (64)

Wt. % Acetone	$\sigma \times 10^4$ kg/m 0°C	25°C	45°C	Wt. % Acetone	$\sigma \times 10^4$ kg/m. 0°C	25°C	45°C
0	77.25	73.4	70.3	50	34.2	31.0	28.4
5	60.8	56.5	53.6	75	30.1	27.3	25.0
10	54.3	49.95	46.8	85	29.1	26.1	23.8
20	46.14	42.0	38.9	90	28.5	25.6	23.1
25	43.2	39.1	36.0	95	27.8	24.7	22.2
30	40.9	36.7	33.8	100	26.6	23.5	21.0
40	37.0	33.4	30.6				

2. Viscosity (65)

Vol. % Acetone	$\mu \times 10^2$ gm/cm. sec. 0°C	15°C	25°C	35°C	45°C
0	1.794	1.145	0.895	0.721	0.597
12.5	-	1.445	1.090	0.855	0.696
25	2.96	1.720	1.276	0.981	0.783
37.5	-	1.643	1.368	1.037	0.826
50	3.06	1.788	1.335	1.026	0.818
62.5	-	1.529	1.182	0.913	0.738
75	1.72	1.126	0.894	0.726	0.602
100	0.41	-	0.324	-	-

3. Specific heat (65)

t = 17°C

Wt.% Acetone	10	20	30	40	50	60	70	80	90	100
C, Kcal/kg. °C	0.991	0.975	0.95	0.925	0.895	0.86	0.795	0.72	0.635	0.524

4. Thermal conductivity (62)

Wt. % Acetone	k, K cal/m. hr. °C			
	0°C	20°C	40°C	60°C
0	0.486	0.515	0.540	0.561
20	0.382	0.399	0.414	0.426
40	0.295	0.303	0.310	0.317
60	0.226	0.228	0.229	0.230
80	0.177	0.173	0.169	0.165
100	0.146	0.139	0.132	0.126

C-1 PROPERTY ESTIMATION METHODS FOR MIXTURES

Mixture properties were available for a limited range of temperatures. However, in the correlations, properties have been also used beyond the available range of temperatures. Therefore it was felt necessary to devise methods for their estimation. Only those methods which were tested successfully with the available properties of the mixtures have been used for property prediction.

1. Density

The liquid density was calculated at the saturation temperature of the mixture assuming no change in their volumes on mixing.

The vapor density was obtained by using equation of state for ideal gases. The composition of the gaseous mixture was taken as that of liquid at its saturation temperature.

2. Surface tension

The surface tension of liquid mixtures were available at low temperatures. These values were extrapolated for higher temperatures by using the equation of Meissner and Michaels (71) as reproduced below :

$$\sigma = \sigma_o \left(\frac{T_c - T}{T_c - T_o}\right)^{1.2}$$

The value of T_c in the above equation was calculated by Kay's rule for mixtures. σ_o is the surface tension available at T_o .

However, the surface tension of Water-Ethylene glycol mixtures was available for a very small range of concentration, and was estimated as molal average of the surface tensions of pure components at saturation temperature of the mixture.

3. Specific heat

The specific heat of liquid -mixtures were calculated using linear mixing rule based on pure component values at the saturation temperature of the mixture.

4. Thermal conductivity

The thermal conductivity of the mixtures was estimated by using the equation of Filippov and Novoselova (72)

$$k_m = k_2 x_2 + k_1 x_1 - 0.72 (k_2 - k_1) (x_2 - x_1)$$

where x_2 refers to the component having larger value of k. Thermal conductivity of pure components were used at the saturation temperature of the mixture. The calculated values compared well with the extrapolated experimental values available in the literature.

5. Latent heat of vaporization

The latent heat of vaporization of mixtures was estimated as weighted average of the latent heats of the pure components at their normal boiling points.

APPENDIX D

TABLES OF VAPOR LIQUID EQUILIBRIA

Table D-1 Vapor Liquid Equilibrium for Acetone-Water at P = 1 atm(69)

t	Wt. % Acetone		Mole % Acetone	
°C	Liquid	Vapor	Liquid	Vapor
100.0	0.0	0.0	0.0	0.0
92.0	3.2	55.5	1.0	27.9
84.2	7.7	74.0	2.5	47.0
75.6	14.5	84.6	5.0	63.0
66.9	25.2	91.0	10.0	75.4
62.4	45.6	93.2	20.0	81.3
61.1	58.0	94.0	30.0	83.2
60.3	67.5	94.4	40.0	84.2
59.8	76.5	95.0	50.0	85.1
59.2	83.0	95.5	60.0	86.3
58.8	88.5	96.0	70.0	87.5
58.2	92.0	96.5	80.0	89.7
57.4	96.5	98.2	90.0	93.5
56.9	98.0	99.0	95.0	96.2
56.7	99.4	99.6	97.5	97.9
56.5	100.0	100.0	100.0	100.0

Table D-2 Vapor Liquid Equilibrium for Water-Acetic acid at P=1 atm(68)

t °C	Wt. % Water Liquid	 Vapor	Mole % Water Liquid	 Vapor
118.1	0.0	0.0	0.0	0.0
107.90	10.0	16.7	27.0	40.0
104.7	20.0	30.1	45.5	59.2
103.2	30.0	42.3	59.0	71.0
102.1	40.0	52.9	69.0	79.0
101.3	50.0	62.2	77.0	84.5
100.9	60.0	70.0	83.4	88.8
100.7	70.0	77.4	88.8	92.0
100.2	80.0	85.1	93.0	95.0
100.1	90.0	92.5	97.0	98.0
100.0	100.0	100.0	100.0	100.0

Table D-3 Vapor-Liquid Equilibrium for Water-Ethylene glycol at P = 747 mm Hg (67)

t	Wt. % Water		Mole % Water	
°C	Liquid	Vapor	Liquid	Vapor
196.7	0.0	0.0	0.0	0.0
196.6	0.1	1.0	0.354	3.36
182.6	1.3	19.0	4.33	44.7
171.6	2.1	34.0	7.0	64.0
168.6	2.6	38.8	8.4	68.5
151.2	5.8	62.0	17.5	85.0
140.8	9.9	76.0	27.5	91.5
136.5	12.0	79.9	32.3	93.5
133.0	13.0	83.0	34.0	94.5
127.9	16.4	87.2	40.4	96.0
125.0	18.7	89.4	44.0	96.1
120.6	26.3	93.2	55.3	97.6
112.0	38.7	97.2	68.5	99.3
110.5	40.2	98.0	70.0	99.5
103.7	72.7	99.7	88.4	99.9
99.6	100.0	100.0	100	100

*Table D-4 Vapor Liquid Equilibrium for Water-Glycerine at P=1atm(45, 62)

t °C	Wt. % Water Liquid	Wt. % Water Vapor	Mole % Water Liquid	Mole % Water Vapor
290	0.00	0.00	0.00	0.00
249	0.398	18.2	2.00	53.34
223	1.019	51.0	5.00	84.12
193	2.127	64.5	10.00	90.28
173.5	3.337	73.0	15.00	93.31
162	4.66	80.75	20.00	95.54
145	7.74	84.65	30.00	97.52
133	11.54	96.83	40.00	99.36
125	16.36	100.0	50.00	100.0
117.5	22.69	100.0	60.00	100.0
112	31.34	100.0	70.00	100.0
107	43.90	100.0	80.00	100.0
103	63.77	100.0	90.00	100.0
100	100.00	100.0	100.00	100.0

* The vapor-liquid equilibrium data have been calculated by using experimental boiling points and derived Van Laar Coefficients (45).

APPENDIX E

TABLES OF EXPERIMENTAL DATA

Table E-1 Experimental Data of Heat Transfer to Pure Liquids

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m.^{2} °C
Tube-1, O.D = 25.6 mm, A = 1.248×10^{-2} m^2			
WATER			
q = 6.9×10^3 Kcal/hr. m^2			
1	102.54	99.00	1949
2	102.01	97.50	1530
3	100.20	95.10	1352
q = 12.4×10^3 Kcal/hr. m^2			
4	103.80	99.00	2583
5	103.60	97.20	1937
6	103.40	95.8	1632
7	102.95	94.35	1442
8	102.40	91.65	1153
9	101.30	89.45	1045
10	93.25	86.00	1012
11	94.95	81.50	923
12	90.8	77.00	900
q = 16.54×10^3 Kcal/hr.m^2			
13.	104.20	99.00	3181
14	104.20	97.75	2564
15	104.10	95.80	1993
16	103.70	93.00	1546
17	103.6	91.75	1396
18	102.12	86.5	1040
19	96.40	80.35	1032
20	90.70	73.60	967
q = 19.3×10^3 Kcal/hr. m^2			
21	104.70	98.95	3357
22	104.50	97.40	2718
23	104.50	93.50	1755
24	104.10	90.05	1374
25	103.80	87.50	1184
26	101.80	83.80	1070
27	99.20	80.90	1055
28	95.20	75.85	1000
q = 23.43×10^3 Kcal/hr. m^2			
29	105.00	99.00	3905
30	105.10	97.00	2892
31	105.00	94.82	2302
32	105.00	93.00	1953
33	104.90	89.60	1531
34	104.55	85.95	1260
35	102.20	81.55	1135
36	98.70	77.45	1100
37	94.40	72.45	1070
q = 24.8×10^3 Kcal/hr. m^2			
38	105.25	98.90	3906
39	105.30	94.95	2396
40	105.05	90.65	1722
41	104.60	85.00	1265
42	102.50	81.05	1156
q = 27.57×10^3 Kcal/hr.m^2 °C			
43	105.55	98.90	4146
44	105.50	96.45	3046
45	105.40	92.50	2137
46	105.10	88.80	1691
47	104.57	82.95	1275
48	102.65	78.50	1142
49	97.80	73.20	1165
50	93.70	68.40	1097
q = 31.71×10^3 Kcal/hr. m^2			
51	105.85	99.00	4629
52	105.80	96.90	3563
53	105.80	93.50	2578
54	105.70	90.60	2100
55	105.50	86.5	1669
56	105.05	82.00	1373
57	102.85	77.40	1246
58	99.85	72.12	1143
59	95.10	66.65	1113

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
	$q = 35.84 \times 10^{3}$ Kcal/hr. m^{2}		
60	106.30	99.00	4910
61	106.35	96.00	3463
62	106.35	91.65	2438
63	106.00	84.80	1691
64	105.60	79.95	1397
65	103.80	75.00	1244
66	101.10	71.05	1175
67	97.35	66.30	1155
68	95.05	63.70	1145
	$q = 39.97 \times 10^{3}$ Kcal/hr. m^{2}		
69	106.60	99.00	5259
70	106.77	96.00	3711
71	106.65	91.65	2664
72	106.50	86.07	1956
73	106.20	79.95	1523
	$q = 41.35 \times 10^{3}$ Kcal/hr. m^{2}		
74	106.80	99.00	5301
75	106.80	94.25	3294
76	106.80	90.25	2498
77	106.75	85.80	1974
78	106.50	80.60	1597
79	104.75	74.20	1350
80	102.20	69.05	1245
81	97.40	64.00	1236
	Tube-2, O.D = 27 mm, A= 1.358×10^{-2} m^{2}		
	WATER		
	$q = 12.66 \times 10^{3}$ Kcal/hr. m^{2}		
82	104.70	99.00	2220
83	104.70	97.40	1735
84	104.70	96.60	1565
85	103.40	93.95	1340
86	100.70	90.40	1229
87	99.35	88.05	1120
88	97.00	85.50	1100
89	93.25	82.25	1150
90	90.45	79.45	1150
91	85.00	74.20	1172
92	83.20	72.25	1165
93	79.45	68.40	1126

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
	$q = 19.00 \times 10^{3}$ Kcal/hr. m^{2}		
94	105.55	99.00	2900
95	105.40	98.10	2603
96	105.55	97.65	2400
97	105.35	95.55	1939
98	104.30	93.65	1704
99	104.45	90.95	1407
100	103.20	89.60	1400
101	102.20	88.50	1337
102	101.25	86.60	1300
103	99.40	84.60	1284
104	95.25	80.30	1271
105	91.60	76.65	1271
106	84.50	69.05	1230
107	80.05	64.10	1191
	$q = 25.33 \times 10^{3}$ Kcal/hr. m^{2}		
108	105.90	99.00	3670
109	105.90	98.60	3470
110	105.90	97.10	2878
111	105.80	95.80	2533
112	105.60	93.65	2120
113	104.80	90.00	1710
114	104.35	88.55	1603
115	103.50	86.00	1445
116	102.60	84.05	1365
117	94.20	75.05	1320
118	92.10	72.00	1260
119	86.60	66.45	1257
	$q = 31.66 \times 10^{3}$ Kcal/hr. m^{2}		
120	106.55	99.00	4193
121	106.55	98.60	3932
122	106.55	97.65	3557
123	106.55	96.45	3135
124	106.55	95.80	2950
125	106.45	94.35	2617
126	105.9	92.25	2319
127	105.8	91.00	2140
128	105.6	90.15	2049
129	105.5	89.30	1955
130	105.35	88.00	1825
131	104.65	85.65	1666
132	104.00	83.00	1508

Run No.	Temperature, °C		h
	t_W	t_L	Kcal/hr.m^{2}°C
133	101.10	79.00	1433
134	99.10	76.20	1380
135	97.30	73.75	1344
136	94.8	70.70	1315
137	91.80	68.10	1336

$q = 38.00 \times 10^{3}$ Kcal/hr.m^{2}

Run No.	t_W	t_L	h
138	107.01	99.00	4750
139	107.00	98.50	4470
140	107.00	97.50	4000
141	106.80	95.15	3262
142	106.75	93.20	2804
143	106.55	91.00	2444
144	106.25	88.70	2165
145	106.15	86.50	1935
146	105.40	84.70	1836
147	104.80	82.05	1670
148	104.00	79.00	1520
149	102.15	76.10	1459
150	99.40	73.00	1439
151	97.10	70.05	1405
152	94.10	66.40	1372
153	92.60	64.15	1330
154	89.10	60.35	1322

Tube-1, O.D = 25.6mm, A=1.248×10^{-2} m^{2}

ACETIC ACID

$q = 12.4 \times 10^{3}$ Kcal/hr.m^{2}

Run No.	t_W	t_L	h
155	122.25	116.60	2194
156	122.40	112.55	1258
157	122.05	111.40	1164
158	119.95	106.10	895
159	117.45	101.30	767
160	113.40	95.70	700
161	115.05	93.45	574
162	110.00	91.35	665
163	100.20	79.90	810

$q = 19.3 \times 10^{3}$ Kcal/hr.m^{2}

Run No.	t_W	t_L	h
164	123.50	116.8	2880
165	123.50	115.95	2556
166	123.40	112.35	1829

Run No.	Temperature, °C		h
	t_W	t_L	Kcal/hr.m^{2}°C
167	122.75	110.35	1556
168	122.55	108.55	1378
169	120.60	104.20	1176
170	119.45	99.75	979
171	114.65	93.60	915
172	111.30	89.15	872
173	106.00	83.35	850

$q = 24.8 \times 10^{3}$ Kcal/hr.m^{2}

Run No.	t_W	t_L	h
174	123.80	116.70	3493
175	124.10	114.45	2570
176	124.20	113.60	2340
177	123.30	108.85	1659
178	122.30	103.60	1326
179	121.20	99.55	1145
180	116.85	93.75	1070
181	113.65	89.70	1035
182	109.50	85.55	1035

$q = 31.71 \times 10^{3}$ Kcal/hr. m^{2}

Run No.	t_W	t_L	h
183	125.25	116.75	3730
184	125.40	114.30	2856
185	125.10	111.85	2393
186	125.10	109.00	1970
187	124.65	104.15	1540
188	121.40	99.35	1438
189	122.60	95.60	1174
190	117.20	91.45	1285
191	112.05	86.40	1235
192	106.75	78.80	1115

$q = 39.97 \times 10^{3}$ Kcal/hr.m^{2}

Run No.	t_W	t_L	h
193	126.25	116.80	4230
194	126.35	115.40	3650
195	126.30	113.60	3147
196	126.30	110.35	2506
197	126.35	105.50	1917
198	124.45	98.80	1558
199	122.00	93.45	1400
200	114.15	83.65	1310
201	109.15	77.30	1250

Tube -1, O.D.=25.6 mm, $A=1.248\times10^{-2}\ m^2$

ACETONE

Run No.	Temperature, °C t_W	Temperature, °C t_L	h $Kcal/hr.m^2.°C$
	$q = 6.9 \times 10^3\ Kcal/hr.m^2$		
202	58.38	55.5	2400
	$q = 12.4 \times 10^3\ Kcal/hr.m^2$		
203	59.3	55.5	3260
	$q= 19.3 \times 10^3\ Kcal/hr.m^2$		
204	60.42	55.5	3920
	$q = 24.8 \times 10^3\ Kcal/hr.m^2$		
205	61.15	55.5	4420
	$q = 31.71 \times 10^3\ Kcal/hr.m^2$		
206	62.05	55.5	4870
	$q = 39.97 \times 10^3\ Kcal/hr.m^2$		
207	63.07	55.5	5230

Table E-2 Experimental Data of Heat Transfer to Water-Glycerine Mixtures

Tube-2, O.D = 27 mm, A = 1.358 x 10^{-2} m^2

Run No.	Temperature, ^{o}C t_W	Temperature, ^{o}C t_L	h Kcal/hr.m^2.°C
15 Wt. % WATER			
q = 12.66 x 10^3 Kcal/hr.m^2			
1	139.10	128.00	1141
2	138.70	127.40	1120
3	138.90	126.25	1007
4	138.20	124.30	911
5	134.15	115.30	672
6	132.00	111.20	609
7	129.55	107.20	567
8	123.35	100.00	542
9	123.20	98.80	519
10	116.80	93.20	536
q = 19.00 x 10^3 Kcal/hr.m^2			
11	140.6	128.1	1520
12	140.6	126.05	1305
13	139.95	123.10	1127
14	138.65	119.25	979
15	137.00	115.00	864
16	135.15	110.45	769
17	134.25	108.35	734
18	132.90	104.50	669
19	129.65	97.85	598
20	125.65	93.25	586
21	123.40	88.75	548
q = 25.33 x 10^3 Kcal/hr.m^2			
22	142.10	128.00	1797
23	142.00	126.00	1583
24	141.55	122.25	1312
25	140.25	118.25	1151
26	139.70	113.46	965
27	139.40	113.30	970
28	136.60	106.70	847
29	135.25	102.00	762
30	133.25	97.40	707
31	132.30	93.70	656
32	131.50	91.70	636
33	127.95	86.65	614
q = 31.66 x 10^3 Kcal/hr.m^2			
34	143.50	128.00	2043
35	143.50	126.35	1847
36	143.15	122.05	1500
37	142.35	118.50	1327
38	140.50	112.65	1137
39	139.30	107.60	999
40	138.50	103.15	895
41	137.90	99.70	829
42	136.60	95.25	766
43	135.80	92.85	737
44	133.00	86.60	682
q = 38.00 x 10^3 Kcal/hr.m^2			
45	144.40	128.10	2331
46	144.40	126.50	2123
47	144.35	123.50	1823
48	144.00	118.00	1462
49	142.40	112.15	1256
50	140.95	107.00	1119
51	141.10	102.65	988
52	139.50	98.25	921
53	138.70	94.00	850
54	136.90	85.15	734
17.5 Wt. % WATER			
q = 12.66 x 10^3 Kcal/hr. m^2			
55	134.00	124.00	1266
56	133.65	122.65	1150
q = 19.00 x 10^3 Kcal/hr.m^2			
57	135.90	124.00	1597
58	135.50	121.95	1402
q = 25.33 x 10^3 Kcal/hr.m^2			
59	137.20	124.10	1934
60	137.20	123.60	1863
61	137.30	121.95	1650

Run No.	Temperature, °C		h Kcal/hr.m.^{2} °C
	t_W	t_L	
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
62	138.60	124.00	2168
63	138.70	121.85	1879
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
64	139.60	124.10	2452
65	139.60	122.05	2165
	27.5 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
66	123.30	114.25	1399
67	123.40	113.50	1279
68	123.10	111.00	1046
69	121.95	107.75	891
70	120.70	104.10	763
71	119.00	101.45	721
72	117.35	98.85	684
73	116.15	97.30	672
74	113.25	93.10	628
75	106.90	87.10	640
76	102.00	81.15	607
	$q = 19.00 \times 10^3$ Kcal/hr.m^2		
77	124.95	114.20	1767
78	124.95	113.20	1617
79	124.85	110.25	1301
80	123.60	105.25	1035
81	122.90	102.45	929
82	121.15	98.20	828
83	118.85	93.65	754
84	115.20	88.25	705
85	110.80	83.00	684
86	106.40	77.05	650
	$q = 25.33 \times 10^3$ Kcal/hr.m^2		
87	126.02	114.20	2142
88	126.02	112.80	1916
89	126.50	110.30	1564
90	125.35	104.75	1230
91	124.65	102.40	1138
92	123.60	98.40	1905
93	122.10	93.85	897
94	119.55	89.40	840
95	116.40	83.80	777
96	114.25	79.75	735
97	112.35	78.00	738
98	109.30	73.50	690
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
99	127.40	114.20	2398
100	127.50	113.00	2183
101	127.60	111.00	1907
102	127.00	105.30	1459
103	126.15	102.75	1360
104	125.50	98.90	1190
105	124.40	94.30	1052
106	122.25	89.60	970
107	119.65	83.20	869
108	118.50	79.95	821
109	116.00	76.15	794
110	113.60	72.00	760
111	111.70	68.45	733
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
112	128.95	114.25	2576
113	128.85	113.0	2397
114	129.15	112.00	2215
115	128.55	106.55	1727
116	127.80	105.00	1666
117	127.00	99.85	1400
118	126.50	95.40	1222
119	124.90	88.20	1035
120	122.70	82.70	950
121	121.35	75.80	834
122	120.00	74.75	830
123	118.00	71.00	809
124	115.55	67.45	790
	50 Wt. % WATER		
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
125	116.65	105.60	2814
126	117.35	103.75	2328
127	227.55	100.10	1814
128	117.65	97.55	1575

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2°C
129	118.25	95.70	1403
130	118.40	91.75	1188
131	118.05	88.25	1062
132	116.20	83.90	980
133	113.20	77.40	884
134	109.65	72.10	843
135	105.30	66.30	813
	55.5 Wt. % WATER		
	q = 31.66 x 10^3 Kcal/hr.m^2		
136	115.80	104.50	2800
137	115.95	102.95	2438
138	115.90	100.10	2000
139	116.40	98.00	1720
140	116.50	95.75	1530
141	116.65	91.45	1255
142	115.50	87.75	1140
143	115.05	84.70	1045
144	112.90	79.60	950
145	111.00	76.40	915
146	106.80	71.50	900
147	105.60	69.85	886
148	103.60	66.35	850
	65 Wt. % WATER		
	q = 12.66 x 10^3 Kcal/hr.m^2		
149	110.40	102.65	1634
150	109.95	101.25	1455
151	109.30	99.00	1229
152	108.90	97.75	1135
153	107.70	94.30	945
154	102.40	90.20	1038
155	101.70	88.55	965
156	95.70	83.15	1007
	q = 19.00 x 10^3 Kcal/hr.m^2		
157	111.30	102.60	2184
158	111.50	102.20	2043
159	111.30	99.65	1631
160	110.40	96.55	1372

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2 °C
161	107.90	90.80	1111
162	100.30	81.90	1030
163	96.60	76.65	954
164	93.75	74.35	980
165	89.30	68.60	920
166	83.50	62.60	910
	q = 25.33 x 10^3 Kcal/hr.m^2		
167	112.35	102.60	2598
168	112.15	102.25	2559
169	112.35	99.00	1897
170	11.90	93.85	1403
171	108.80	87.05	1165
172	105.30	82.50	1110
173	102.25	77.80	1035
174	99.30	74.30	1001
175	95.40	69.45	978
	q = 31.66 x 10^3 Kcal/hr.m^2		
176	113.00	102.65	3059
177	113.10	102.50	2987
178	113.70	101.80	2661
179	113.20	100.00	2398
180	113.40	98.40	2111
181	113.25	95.75	1809
182	113.35	93.60	1603
183	111.60	90.00	1466
184	111.05	88.95	1433
185	110.40	83.75	1188
186	108.75	81.45	1160
187	106.10	77.30	1099
188	102.65	72.85	1065
189	97.75	68.70	1090
190	95.75	65.55	1050
	q = 38.00 x 10^3 Kcal/hr.m^2		
191	113.50	102.65	3502
192	114.45	101.70	2930
193	113.35	100.00	2744
194	113.90	98.15	2418
195	114.00	94.40	1939
196	113.40	90.00	1624

Run No.	Temperature, °C		h
	t_W	t_L	Kcal/hr.m^2.°C
197	112.85	87.30	1487
198	112.65	85.35	1392
199	111.90	84.35	1379
200	110.55	79.65	1230
201	108.55	76.40	1182
202	107.40	73.50	1121
203	102.00	67.80	1110

86 WT. % WATER

q = 12.66 x 10^3 Kcal/hr.m^2

Run No.	t_W	t_L	h
204	106.70	99.80	1835
205	106.85	98.50	1516
206	106.85	97.75	1391
207	105.95	95.00	1156
208	104.20	92.60	1091
209	102.70	90.90	1073
210	101.45	89.20	1033
211	95.95	83.75	1040
212	93.00	80.70	1030
213	87.85	75.40	1015
214	85.05	72.30	994

q = 19.00 x 10^3 Kcal/hr.m^2

Run No.	t_W	t_L	h
215	107.40	99.75	2484
216	108.80	97.80	1727
217	108.90	96.15	1490
218	108.25	94.05	1338
219	107.30	92.25	1262
220	105.90	90.00	1195
221	104.35	88.00	1162
222	101.50	84.30	1104
223	99.95	82.20	1070
224	94.75	76.60	900
225	89.10	70.20	1000

q = 25.33 x 10^3 Kcal/hr.m^2

Run No.	t_W	t_L	h
226	107.95	100.00	3186
227	108.50	99.00	2666
228	110.00	97.20	1979
229	109.40	95.10	1771
230	108.70	91.50	1473
231	107.65	87.75	1273
232	106.85	85.70	1198
233	104.70	81.95	1113
234	101.35	77.20	1050
235	98.00	73.35	1025
236	94.75	69.70	1010

q = 31.66 x 10^3 Kcal/hr.m^2

Run No.	t_W	t_L	h
237	108.50	100.00	3725
238	109.10	99.10	3166
239	109.50	98.45	2865
240	110.45	97.30	2407
241	110.75	95.65	2097
242	109.90	92.85	1857
243	110.00	90.25	1603
244	109.50	86.90	1401
245	108.35	83.70	1284
246	105.70	79.45	1206
247	104.65	75.90	1101
248	98.65	68.80	1060

q = 38.00 x 10^3 Kcal/hr.m^2

Run No.	t_W	t_L	h
249	109.10	100.00	4176
250	109.50	99.75	3897
251	109.95	99.00	3470
252	111.40	97.65	2764
253	111.10	96.20	2550
254	111.55	94.25	2197
255	111.55	91.05	1854
256	111.50	88.40	1645
257	111.90	85.40	1434
258	108.85	80.10	1322
259	106.85	75.10	1197
260	103.60	70.90	1162
261	99.10	64.25	1090

Table E-3 Experimental Data of Heat Transfer to Water-Ethylene glycol Mixtures

Tube-2, O.D = 27 mm, A = 1.358 x 10^{-2} m^2

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
	1 Wt. % WATER		
	q = 12.66 x 10^3 Kcal/hr.m^2		
1	194.00	185.15	1431
2	193.85	184.09	1297
3	193.00	179.31	925
4	191.67	175.37	777
5	188.90	167.8	600
6	187.47	166.00	590
7	182.40	161.10	594
8	177.00	154.00	550
	q = 19.00 x 10^3 Kcal/hr.m^2		
9	196.00	185.25	1767
10	194.90	180.170	1290
11	194.04	177.48	1147
12	193.00	173.60	979
13	190.40	166.06	781
14	184.58	155.45	654
15	177.77	146.54	608
16	171.14	139.00	593
	q = 25.33 x 10^3 Kcal/hr.m^2		
17	197.60	185.06	2020
18	197.32	183.00	1769
19	196.70	180.75	1588
20	195.14	174.77	1243
21	194.00	170.48	1077
22	192.00	163.23	880
23	190.60	157.61	767
24	187.77	152.44	717
25	185.21	149.30	705
26	182.60	143.90	655
27	179.43	139.25	630
	q = 31.66 x 10^3 Kcal/hr.m^2		
28	198.72	185.15	2330
29	197.62	180.63	1862
30	197.11	177.00	1573
31	195.70	170.48	1254
32	194.60	163.10	1004
33	193.20	156.20	855
34	191.45	150.00	763
35	185.54	141.10	715
36	183.05	136.30	692
37	179.00	131.00	660
	q = 38.00 x 10^3 Kcal/hr.m^2		
38	199.95	185.15	2568
39	199.95	184.38	2440
40	199.95	182.38	2163
41	199.50	179.00	1854
42	198.62	175.24	1625
43	197.25	171.02	1449
44	196.40	163.00	1138
45	195.00	156.05	976
46	194.00	149.34	851
47	192.10	143.35	780
48	189.6	139.15	753
49	186.5	132.85	708
	4.5 Wt. % WATER		
	q = 12.66 x 10^3 Kcal/hr.m^2		
50	165.00	152.00	974
51	164.20	149.00	833
52	162.17	144.00	697
53	160.00	138.20	581
	q = 19.00 x 10^3 Kcal/hr.m^2		
54	168.10	152.50	1218
55	167.00	146.65	934
56	166.08	145.64	930
57	164.08	138.40	740
	q = 25.33 x 10^3 Kcal/hr.m^2		
58	170.30	152.40	1415

Run	Temperature, °C		h
No.	t_W	t_L	Kcal/hr.m^2.°C
59	169.44	146.85	1121
60	68.10	142.64	995
61	166.80	137.10	853
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
62	172.21	152.50	1606
63	172.21	148.05	1310
64	171.20	142.00	1084
65	169.80	140.00	1062
66	169.44	137.00	976
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
67	173.50	152.50	1810
68	173.21	148.24	1522
69	172.27	142.00	1255
70	171.20	135.00	1050
	9.1 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
71	153.57	142.00	1094
72	153.57	140.50	969
73	153.84	137.20	761
74	152.00	133.55	786
	$q = 19.00 \times 10^3$ Kcal/hr.m^2		
75	155.82	141.95	1370
76	155.00	139.55	1230
77	156.61	137.00	969
78	155.00	132.55	846
	$q = 25.3 \times 10^3$ Kcal/hr.m^2		
79	157.80	140.10	1429
80	158.37	139.60	1348
81	158.47	136.80	1168
82	157.80	132.90	1016
83			
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
83	160.00	140.00	1583
84	160.08	139.20	1516
85	160.34	137.20	1368
86	160.00	132.90	1168

Run	Temperature, °C		h
No.	t_W	t_L	Kcal/hr.m^2.°C
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
87	162.12	140.05	1722
88	162.22	138.90	1630
89	162.31	137.00	1501
90	162.00	132.90	1306
	14.6 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
91	140.05	126.8	955
92	139.95	126.05	911
93	139.50	122.05	726
94	138.20	118.55	644
95	136.20	114.85	593
96	132.30	107.70	515
97	131.10	105.00	485
	$q = 19.00 \times 10^3$ Kcal/hr.m^2		
98	143.05	125.55	1086
99	142.60	126.80	1203
100	142.65	122.90	962
101	141.25	118.75	844
102	140.05	114.90	755
103	137.45	109.70	685
104	135.00	104.20	617
105	131.5	98.00	567
	$q = 25.33 \times 10^3$ Kcal/hr.m^2		
106	144.60	126.80	1423
107	144.60	122.75	1159
108	144.00	118.75	1008
109	143.35	116.40	923
110	141.65	111.00	826
111	139.00	105.10	747
112	136.40	99.10	679
113	134.80	96.20	656
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
114	146.60	126.80	1599
115	146.60	123.10	1347
116	146.40	118.70	1143
117	144.85	112.65	983

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
118	143.00	107.20	884
119	141.40	102.10	806
120	139.00	96.60	747
	q = 38.00 x 10^3 Kcal/hr.m^2		
121	148.40	126.8	1759
122	148.20	124.1	1577
123	148.20	120.5	1372
124	147.74	115.2	1168
125	146.60	109.6	1027
126	144.85	104.5	942
127	143.00	98.80	860
128	141.65	95.40	822
	20.2 Wt. % WATER		
	q = 12.66 x 10^3 Kcals/hr.m^2		
129	135.40	122.50	981
130	134.60	120.95	927
131	133.85	118.40	819
132	132.95	117.65	827
133	130.40	114.00	772
134	125.00	106.00	666
135	120.40	98.50	580
	q = 19.00 x 10^3 Kcal/hr.m^2		
136	138.20	122.50	1210
137	138.40	120.65	1070
138	137.10	119.35	1070
139	137.80	117.65	943
140	136.40	116.15	938
141	133.20	111.85	890
142	128.25	102.75	745
143	122.50	92.35	630
144	121.40	88.85	585
	q = 25.33 x 10^3 Kcal/hr.m^2		
145	140.40	122.50	1415
146	140.00	120.70	1312
147	140.10	121.20	1340
148	140.00	117.45	1123

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
149	139.85	114.65	1005
150	137.40	110.80	952
151	135.30	105.55	851
152	131.25	99.10	788
153	128.50	92.10	696
154	127.30	86.10	615
	q = 31.66 x 10^3 Kcal/hr.m^2		
155	142.80	122.5	1560
156	142.80	121.25	1469
157	143.45	119.55	1325
158	142.80	114.70	1127
159	141.40	110.00	1008
160	139.85	106.35	945
161	136.50	100.20	872
162	133.95	94.05	793
163	132.30	89.15	734
	q = 38.00 x 10^3 Kcal/hr.m^2		
164	145.00	122.50	1689
165	145.00	119.55	1493
166	144.8	114.95	1273
167	144.60	110.00	1099
168	143.60	105.00	1008
169	141.75	101.05	934
170	140.60	98.00	892
171	138.90	94.05	847
172	135.60	87.15	764
	29.8 Wt. % WATER		
	q = 12.66 x 10^3 Kcal/hr.m^2		
173	127.30	115.05	1033
174	127.30	113.80	938
175	127.10	112.05	841
176	125.75	108.80	747
177	121.80	102.75	665
178	116.85	94.60	575
	q = 19.00 x 10^3 Kcal/hr.m^2		
179.	130.05	115.05	1267
180	129.75	112.85	1124

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
181	129.75	109.85	955
182	128.80	106.20	841
183	125.80	101.40	779
184	123.85	96.25	688
185	121.65	93.30	670
186	121.20	92.30	657
	$q = 25.33 \times 10^3$ Kcal/hr.m^2		
187	132.50	114.90	1439
188	132.50	112.75	1283
189	132.65	110.00	1118
190	131.60	106.00	989
191	129.65	101.25	892
192	126.30	94.40	794
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
193	134.85	115.05	1599
194	134.85	112.75	1433
195	134.75	111.00	1333
196	133.35	103.50	1061
197	132.20	100.20	989
198	129.75	94.70	903
199	129.05	92.20	859
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
200	136.60	115.05	1763
201	136.50	113.10	1624
202	136.50	111.10	1496
203	134.25	105.70	1331
204	134.80	100.40	1105
205	133.45	97.10	1045
206	132.85	93.85	974
	37.5 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
207	122.45	110.00	1017
208	122.45	109.10	948
209	122.55	107.95	867
210	121.40	105.60	801
211	118.90	102.85	789
212	116.20	99.75	770
213	113.70	97.20	766
214	107.30	88.90	690
	$q = 19.00 \times 10^3$ Kcal/hr.m^2		
215	124.45	110.00	1315
216	124.50	108.35	1176
217	124.35	105.60	1013
218	123.30	102.65	920
219	121.05	99.00	862
220	119.95	96.70	817
221	114.75	90.60	787
222	111.80	85.30	717
223	107.40	80.00	694
	$q = 25.33 \times 10^3$ Kcal/hr.m^2		
224	125.85	110.00	1598
225	125.75	107.95	1423
226	125.70	105.20	1236
227	125.20	101.45	1067
228	124.65	99.00	988
229	123.70	96.80	942
230	121.85	92.85	873
231	121.05	90.05	817
232	119.15	86.30	771
233	116.00	82.00	745
234	112.20	77.50	730
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
235	127.65	110.00	1794
236	127.60	107.70	1591
237	127.70	105.20	1407
238	127.70	101.30	1222
239	127.70	99.20	1111
240	127.20	97.00	1048
241	127.20	94.30	962
242	125.55	88.60	857
243	122.25	84.00	828
244	118.20	78.20	791
245	116.00	75.55	783
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
246	129.45	110.00	1954
247	129.45	109.40	1895
248	129.55	107.75	1743

Run No.	Temperature, °C		h
	t_W	t_L	Kcal/hr.m^2.°C
249	129.65	105.50	1573
250	129.55	101.80	1369
251	128.40	97.40	1226
252	129.65	94.40	1078
253	128.95	89.50	963
254	127.60	87.00	936
255	125.55	82.40	881
256	122.35	76.30	825
	57.4 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
257	114.15	104.50	1312
258	113.70	103.05	1189
259	113.20	100.50	997
260	110.80	96.70	898
261	106.90	92.20	861
262	102.05	87.50	870
263	95.55	79.30	780
264	90.70	73.20	724
	$q = 19.00 \times 10^3$ Kcal/hr.m^2		
265	115.80	104.95	1751
266	116.20	101.90	1333
267	116.00	98.70	1093
268	114.00	94.10	955
269	112.20	91.00	896
270	108.00	85.30	837
271	104.45	79.85	772
272	97.30	72.70	772
	$q = 25.33 \times 10^3$ Kcal/hr.m^2		
273	118.40	104.40	1809
274	118.20	103.50	1723
275	118.80	101.25	1443
276	118.40	97.85	1233
277	117.25	93.00	1045
278	116.10	92.10	1055
279	113.70	86.50	931
280	110.10	80.45	854
281	104.00	72.00	790
282	98.40	65.30	764
	$q = 31.66 \times 10^3$ Kcal/hr.m^2		
283	120.30	105.00	2069
284	119.75	103.70	1973
285	120.50	101.25	1645
286	120.50	98.20	1420
287	119.35	93.00	1201
288	118.00	88.40	1069
289	116.75	84.25	974
290	115.90	80.40	892
291	112.05	75.30	865
292	109.20	71.50	842
293	110.65	73.75	860
294	104.45	64.40	784
	$q = 38.00 \times 10^3$ Kcal/hr.m^2		
295	121.40	104.60	2262
296	121.95	101.35	1845
297	122.15	97.85	1564
298	121.85	93.40	1336
299	121.50	89.15	1175
300	119.65	82.80	1031
301	117.25	76.65	936
302	116.95	74.70	899
303	115.50	72.65	887
304	112.80	69.50	877
305	108.25	64.00	859
	78.2 Wt. % WATER		
	$q = 12.66 \times 10^3$ Kcal/hr.m^2		
306	109.30	101.60	1644
307	109.20	100.30	1422
308	108.65	98.50	1247
309	107.00	95.40	1091
310	104.50	92.20	1029
311	99.30	85.75	934
312	94.10	80.00	898
313	83.50	69.05	876

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2 °C
	q = 19.00 x 10^3 Kcal/hr.m^2		
314	110.80	101.70	2088
315	110.70	99.55	1704
316	110.25	97.30	1467
317	109.50	94.15	1238
318	107.40	90.45	1121
319	102.95	85.00	1058
320	97.50	78.15	984
321	88.90	68.55	935
	q = 25.33 x 10^3 Kcal/hr.m^2		
322	112.35	101.35	2303
323	112.00	99.25	1987
324	111.70	97.10	1735
325	111.20	94.05	1477
326	109.95	90.15	1279
327	107.20	84.55	1113
328	103.25	78.50	1023
329	98.80	73.20	990
330	94.70	68.35	963
	q = 31.66 x 10^3 Kcal/hr.m^2		
331	113.50	101.60	2660
332	113.40	99.25	2237
333	112.75	97.10	2023
334	112.90	94.05	1679
335	112.45	90.90	1469
336	109.85	84.00	1225
337	107.30	78.50	1099
338	105.60	75.40	1048
339	102.40	71.50	1024
340	99.45	68.70	1030
341	97.10	65.20	994
	q = 38.00 x 10^3 Kcal/hr.m^2		
342	114.65	101.60	2912
343	114.55	99.25	2484
344	114.15	97.30	2255
345	114.45	94.50	1905
346	114.25	90.35	1590
347	112.25	84.00	1345
348	111.40	78.00	1138
349	107.60	72.45	1081
350	105.40	69.50	1058
351	103.05	66.00	1026
352	100.00	62.00	1000

Table E-4 Experimental Data of Heat Transfer to Water-Acetic acid Mixtures.

Tube-1, O.D.= 25.6 mm. , A = 1.248×10^{-2} m^2

Run No.	Temperature, °C t_W	t_L	h Kcal/hr. m^2 °C
	4.8 Wt. % WATER		
	q = 12.4×10^3 Kcal/hr. m^2		
1	117.15	110.5	1365
2	117.25	108.75	1460
3	117.25	106.75	1181
4	116.30	103.90	1000
5	113.40	97.00	756
6	112.15	95.25	734
7	114.40	91.15	533
	q = 19.3×10^3 Kcal/hr. m^2		
8	118.60	110.50	2383
9	118.65	109.00	2000
10	118.40	108.00	1856
11	118.50	105.80	1520
12	118.00	103.35	1317
13	114.30	96.25	1069
14	114.40	95.00	995
15	116.90	91.90	772
	q = 24.8×10^3 Kcal/hr. m^2		
16	119.65	110.25	2638
17	119.50	107.50	2667
18	119.55	106.25	1865
19	119.15	103.50	1535
20	116.35	96.50	1249
21	116.40	95.00	1159
22	117.55	93.70	1039
	q = 31.71×10^3 Kcal/hr. m^2		
23	120.50	110.50	3170
24	120.60	108.75	2675
25	120 15	107.40	2486
26	120.20	104.10	1969
27	119.35	97.90	1478
28	119.15	95.60	1346
29	118.20	95.25	1381
	q = 39.97×10^3 Kcal/hr. m^2		
30	121.30	110.50	3701
31	121.40	108.00	2983
32	121.20	107.60	2939
33	121.30	105.10	2467
34	120.90	98.30	1768
35	119.95	92.10	1435
	9.6 Wt. % WATER		
	q = 12.4×10^3 Kcal/hr. m^2		
36	113.90	107.30	1879
37	113.90	105.60	1494
38	112.80	93.00	899
39	109.25	92.55	743
	q = 19.3×10^3 Kcal/hr. m^2		
40	115.55	107.30	2339
41	115.50	105.30	1892
42	115.00	103.10	1544
43	115.00	100.10	1295
44	112.80	94.30	1043
	q = 24.8×10^3 Kcal/hr. m^2		
45	116.90	107.30	2583
46	116.95	105.00	2075
47	116.40	100.00	1512
48	114.65	95.80	1316
	q = 31.71×10^3 Kcal/hr. m^2		
49	118.00	107.30	2963
50	118.20	104.85	2375
51	118.20	102.65	2039
52	117.20	98.50	1696
53	116.75	94.05	1397

Run No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
	q = 39.97 x 10^3 Kcal/hr.m^2		
54	119.20	107.30	3359
55	119.20	105.00	2815
56	118.90	101.55	2304
57	118.40	94.5	1672
	14.4 Wt. % WATER		
	q = 12.4 x 10^3 Kcal/hr.m^2		
58	112.35	105.00	1687
59	112.05	100.50	1074
60	110.50	92.90	704
61	105.65	86.65	653
62	100.10	76.30	520
	q = 19.3 x 10^3 Kcal/hr.m^2		
63	113.50	105.00	2270
64	113.30	100.50	1508
65	113.00	93.85	1008
66	109.95	89.15	928
67	109.10	87.25	883
68	108.70	86.50	869
69	103.40	74.30	663
	q = 24.8 x 10^3 Kcal/hr.m^2		
70	114.60	105.00	2583
71	114.65	101.45	1879
72	114.50	95.40	1298
73	113.45	91.65	1138
74	110.20	82.75	903
75	104.50	72.10	765
	q = 31.71 x 10^3 Kcal/hr.m^2		
76	116.20	105.00	2831
77	116.10	100.80	2073
78	116.00	97.40	1705
79	114.50	95.50	1669
80	115.20	90.00	1258
81	113.80	80.10	919
82	105.55	68.80	864

Run N No.	Temperature, °C t_W	t_L	h Kcal/hr.m^2.°C
	q = 39.77 x 10^3 Kcal/hr.m^2		
83	117.15	105.00	3273
84	116.75	103.70	3047
85	117.25	99.90	2292
86	116.95	92.10	1600
87	115.80	85.30	1304
88	114.00	77.85	1100
89	110.00	70.00	994
90	107.20	63.30	906
	19.3 Wt. % WATER		
	q = 12.40 x 10^3 Kcal/hr.m^2		
91	110.85	104.10	1837
92	111.00	100.90	1228
93	110.80	97.80	954
94	110.05	94.05	775
95	106.65	87.95	663
96	102.60	81.65	593
97	97.80	75.10	546
	q = 19.30 x 10^3 Kcal/hr.m^2		
98	112.45	104.10	2311
99	112.35	101.05	1708
100	112.00	98.40	1419
101	110.30	94.25	1166
102	108.25	88.15	960
103	106.65	81.95	781
104	102.25	76.10	740
105	97.10	68.30	682
	q = 24.80 x 10^3 Kcal/hr.m^2		
106	113.80	104.10	2557
107	113.60	100.00	1923
108	113.10	97.00	1540
109	111.00	88.90	1122
110	109.30	84.30	980
111	107.20	77.65	839
112	102.00	70.15	730
113	98.40	65.00	743

Run No.	Temperature, °C		h
	t_W	t_L	Kcal/hr.m^2.°C
$q = 31.71 \times 10^3$ Kcal/hr.m^2			
114	115.05	104.10	2896
115	115.05	101.55	2349
116	114.85	97.10	1786
117	114.35	91.00	1358
118	112.15	85.65	1197
119	110.60	80.05	1038
120	108.50	73.80	914
121	104.45	67.25	853
122	101.15	61.9	810
$q = 39.97 \times 10^3$ Kcal/hr.m^2			
123	116.2	104.10	3303
124	116.30	101.65	2728
125	116.15	96.60	2044
126	115.40	88.40	1480
127	113.30	81.05	1239
128	112.45	78.10	1164
129	111.10	72.10	1025
130	109.00	66.55	941
131	105.90	61.96	910
29.1 Wt. % WATER			
$q = 12.4 \times 10^3$ Kcal/hr.m^2			
132	108.45	102.40	2050
133	108.45	100.75	1610
134	108.35	98.50	1259
$q = 19.3 \times 10^3$ Kcal/hr.m^2			
135	110.10	102.40	2506
136	110.00	100.80	2098
137	110.00	99.75	1883
138	109.75	97.00	1514
$q = 24.8 \times 10^3$ Kcal/hr.m^2			
139	111.10	102.40	2851
140	111.50	100.85	2329
141	111.40	98.80	1968
$q = 31.71 \times 10^3$ Kcal/hr.m^2			
142	112.85	102.40	3034
143	112.85	100.60	2588
144	112.85	98.00	2135
$q = 39.97 \times 10^3$ Kcal/hr.m^2			
145	114.05	102.40	3431
146	114.10	99.00	2647
147	114.05	96.25	2245
38.9 Wt. % WATER			
$q = 12.4 \times 10^3$ Kcal/hr.m^2			
148	107.55	101.60	2084
149	107.60	97.00	1170
150	106.90	92.55	864
151	105.80	88.05	719
152	100.60	80.15	616
153	95.00	71.00	517
$q = 19.3 \times 10^3$ Kcal/hr.m^2			
154	109.20	101.60	2539
155	109.20	97.55	1657
156	109.00	95.50	1430
157	108.80	92.00	1149
158	107.85	86.85	919
159	105.10	80.50	785
160	100.60	74.10	728
161	96.15	67.10	664
$q = 24.8 \times 10^3$ Kcal/hr. m^2			
162	110.70	101.60	2725
163	110.70	96.45	1740
164	110.65	91.35	1285
165	109.25	84.20	990
166	107.80	78.75	869
167	104.10	73.20	803
168	102.75	67.95	713

Run No.	Temperature, °C		h Kcal/hr.m^2 °C
	t_W	t_L	
	$q = 31.71 \times 10^3$ Kcal/hr.m^2		
169	111.75	101.60	3124
170	111.75	98.60	2411
171	111.75	91.65	1578
172	110.65	81.60	1091
173	110.25	78.35	994
174	109.00	74.65	923
175	106.00	68.25	840
	$q = 39.97 \times 10^3$ Kcal/hr.m^2		
176	112.75	101.60	3585
177	112.83	97.05	2533
178	113.15	93.85	2071
179	112.75	85.70	1478
180	112.40	80.10	1237
181	111.10	73.20	1055
182	109.00	66.20	933
	58.8 Wt. % WATER		
	$q = 12.4 \times 10^3$ Kcal/hr.m^2		
183	104.50	100.20	2884
184	103.05	92.10	1132
185	98.50	86.10	1000
186	94.30	80.00	869
187	90.80	75.20	795
	$q = 19.3 \times 10^3$ Kcal/hr.m^2		
188	106.20	100.20	3217
189	106.60	98.00	2244
190	105.80	93.40	1556
191	102.60	85.55	1132
192	98.45	79.20	1000
193	92.65	72.50	960
	$q = 24.8 \times 10^3$ Kcal/hr.m^2		
194	107.70	100.20	3307
195	107.70	98.00	2557
196	107.40	91.50	1560
197	104.20	84.50	1259
198	100.10	77.85	1115
199	94.85	70.30	1001

Run No.	Temperature, °C		h Kcal/hr.m^2 °C
	t_W	t_L	
	$q = 31.71 \times 10^3$ Kcal/hr.m^2		
200	109,00	100.20	3603
201	109.10	97.40	2710
202	109.00	93.70	2072
203	108.40	87.05	1485
204	106.00	80.85	1261
205	101.15	74.00	1170
106	97.30	67.00	1045
	$q = 39.97 \times 10^3$ Kcal/hr.m^2		
207	110.00	100.20	4078
208	110.00	98.00	3331
209	110.00	92.60	2297
210	109.40	84.40	1599
211	107.10	78.00	1373
212	98.40	62.90	1125
	79.3 Wt. % WATER		
	$q = 12.4 \times 10^3$ Kcal/hr.m^2		
213	103.80	99.55	2918
214	104.00	98.50	2254
215	103.60	95.20	1476
216	102.30	91.40	1138
217	97.80	85.25	990
218	91.60	77.20	860
	$q = 19.3 \times 10^3$ Kcal/hr.m^2		
219	104.95	99.55	3574
220	105.05	98.00	2737
221	104.80	94.20	1821
222	103.10	87.40	1229
223	100.40	82.80	1096
224	95.00	75.40	985
	$q = 24.8 \times 10^3$ Kcal/hr.m^2		
225	105.80	99.55	3968
226	105.90	98.00	3939
227	105.70	93.00	1953
228	104.60	85.20	1278
229	100.80	78.50	1112
230	95.50	70.50	992

Run No.	Temperature, °C		h Kcal/hr.m^2	Run No.	Temperature, °C		h Kcal/hr.m^2
	t_W	t_L			t_W	t_L	
	q = 31.71 x 10^3 Kcal/hr.m^2				q = 39.97 x 10^3 Kcal/hr.m^2		
231	107.20	99.55	4145	237	108.15	99.55	4648
232	107.30	97.15	3124	238	108.25	94.80	2172
233	107.30	95.40	2665	239	108.20	89.10	2093
234	107.00	90.90	1969	240	107.60	82.20	1574
235	105.80	83.10	1397	241	104.80	74.00	1298
236	102.15	74.80	1159	242	100.20	65.40	1145

Table E-5 Experimental Data of Heat Transfer to Acetone-Water Mixtures

Tube-1, O.D = 25.6 mm, A = 1.248×10^{-2} m^2

Run No.	Temperature, °C		$q \times 10^{-3}$ Kcal/hr.m^2	h Kcal/hr.m^{2}°C
	t_W	t_L		
	12.25 Wt. % ACETONE			
1	82.25	76.85	6.90	1278
2	83.49	76.86	12.40	1870
3	84.69	76.85	19.30	2462
4	85.52	76, 85	24.80	2860
5	86.09	76.85	31.71	3432
6	87.30	76.85	39.97	3825
	25.3 Wt. % ACETONE			
7	74.72	68.50	6.90	1109
8	76.65	68.50	12.40	1521
9	78.05	68.50	19.30	2021
10	78.65	68.50	24.8	2443
11	80.05	68.50	31.71	2745
12	81.65	68.50	39.97	3041
	39.3 Wt. % ACETONE			
13	69.79	63.74	6.90	1140
14	71.79	63.74	12.40	1540
15	73.19	63.74	19.30	2042
16	74.08	63.74	24.80	2400
17	75.14	63.74	31.71	2782
18	77.04	63.74	39.97	3005
	54.4 Wt. % ACETONE			
19	67.05	61.31	6.90	1202
20	68.67	61.30	12.40	1682
21	70.32	61.30	19.30	2140
22	71.15	61.32	24.80	2523
23	72.10	61.30	31.71	2936
24	74.00	61.30	39.97	3147

Run No.	Temperature, °C t_W	t_L	$q \times 10^{-3}$ Kcal/hr.m^2	h Kcal/hr.m^2.°C
	70.4 Wt. % ACETONE			
25	64.93	60.00	6.90	1400
26	66.40	60.01	12.40	1941
27	67.84	60.00	19.30	2462
28	68.80	60.00	24.80	2818
29	69.81	60.02	31.71	3229
30	71.10	60.00	39.97	3601
	87,8 Wt. % ACETONE			
31	62.28	58.72	6.90	1038
32	63.37	58.72	12.40	2667
33	64.67	58.72	19.30	3243
34	65.42	58.72	24.80	3701
35	66.34	58.72	31.71	4161
36	67.47	58.72	39.97	4568

APPENDIX F

SAMPLE CALCULATIONS

F-1 Pure Liquids

F-2 Binary Liquid Mixtures

F-3 Percent Deviations of the Proposed Correlations

F-4 Calculation of Natural Convective Heat Transfer Coefficient

F-1 Pure Liquids

Run No. 108 is selected to demonstrate the calculational procedure for pure liquids.

The following experimental data were taken for this run :

System : Water

Heat flux, $q = 25.33 \times 10^{3}$ Kcal/hr.m^{2}

Wall temperature = $105.9\ ^{o}C$

Liquid temperature = $99.0\ ^{o}C$

F-1.1 Calculation of Temperature Drop in the Wall of Test Surface

Using the equation of conductive heat transfer for cylindrical surface, the temperature drop for Run No. 108 is calculated as below :

$$\Delta t_m = \frac{q \times d_o}{2k} . \ln \frac{d_o}{d_h}$$

where

d_o = O.D. of test surface

d_h = I.D. of test surface + $\frac{1}{2}(d_o - d_i)$

+ diameter of the hole for thermocouple

$$\Delta t_m = \frac{25.33 \times 10^{3} \times 27 \times 10^{-3}}{2 \times 89} \ln \frac{27}{(27-7) + \frac{1}{2}(27-20+1.5)}$$

$$= \underline{0.129\ ^{o}C}$$

F-1.2 Calculation of Nu_B

The values of experimental Nu_B during saturated boiling were compared against the predicted values by a number of other correlations and by the proposed correlation for pure liquids.

(i) Experimental Nu_B

$$h = \frac{q}{t_w - t_L} = \frac{25.33 \times 10^3}{105.9 - 99.0} = 3670 \text{ Kcal/hr. m}^2 \text{. } ^\circ C$$

$$Nu_B = \frac{h}{K}\sqrt{\frac{\sigma}{\rho_L - \rho_v}} = \frac{3670}{0.5868}\sqrt{\frac{60.19 \times 10^{-4}}{959 - 0.585}} = \underline{15.68}$$

(ii) Predicted Nu_B using correlations of Table 2.3.

1. Rohsenow (22)

$$Nu_B = \frac{1}{0.006} (Re_B)^{0.69} (Pr)^{-0.7}$$

$$Re_B = \frac{25.33 \times 10^3}{1.015 \times 539}\sqrt{\frac{60.19 \times 10^{-4}}{959 - 0.585}} = 11.5 \times 10^{-2}$$

$$Pr = \frac{1.008 \times 1.015}{0.5868} = 1.76$$

$$Nu_B = \frac{1}{0.006} (11.5 \times 10^{-2})^{0.67} (1.76)^{-0.7}$$

$$= \frac{1}{0.006} \times 0.235 \times 0.67$$

$$= \underline{26.20}$$

2. McNelly (24)

$$\frac{hd}{k} = 0.225 \left(\frac{qd}{\mu \lambda}\right)^{0.69} \left(\frac{Pd}{\sigma}\right)^{0.31} \left(\frac{\rho_L - \rho_v}{\rho_v}\right)^{0.33} \left(\frac{c\mu}{k}\right)^{0.69}$$

$$\frac{q\,d}{\mu\lambda} = \frac{2.7 \times 10^{-2} \times 25.33 \times 10^{3}}{1.015 \times 539} = 1.25$$

$$\frac{Pd}{\sigma} = \frac{1.03 \times 10^{4} \times 2.7 \times 10^{-2}}{60.19 \times 10^{-4}} = 4.64 \times 10^{4}$$

$$\frac{\rho_L - \rho_v}{\rho_v} = \frac{959 - 0.585}{0.585} = 1650$$

$$\therefore\ h = \frac{0.5868}{2.7 \times 10^{-2}} \times 0.225\,(1.25)^{0.69}\,(4.64 \times 10^{4})^{0.31}\,(1650)^{0.33}\,(1.76)^{0.69}$$

$$= \frac{0.5868}{2.7 \times 10^{-2}} \times 0.225 \times 1.166 \times 28 \times 11.5 \times 1.478$$

$$= 2710\ \text{Kcal/hr.m}^{2}\ {}^{o}\text{C}$$

$$\therefore\ Nu_B = \frac{2710}{0.5868}\sqrt{\frac{60.19 \times 10^{-4}}{959.0 - 0.585}}$$

$$= \underline{11.55}$$

3. Forster and Greif (27)

$$q = 1.2 \times 10^{-3}\,\frac{\alpha\, c\, \rho_L\, t_s}{J \lambda \rho_v \sigma^{1/2}} \left(\frac{c\, t_s\, \alpha^{1/2}}{J(\lambda \rho_v)^2}\right)^{1/4} \left(\frac{\rho_L}{\rho_v}\right)^{5/8} \left(\frac{c\mu}{k}\right)^{1/3} \Delta P^{2}$$

$$\Delta P = \left(\frac{dP}{dt}\right)_s \Delta t + \left(\frac{d^2P}{dt^2}\right)_s \frac{\Delta t^2}{2} + \ldots \simeq 31.35 \times 10^{2}\ \text{kg/m}^{2}$$

$$\alpha = \frac{0.5868}{959 \times 1.008} = 6.07 \times 10^{-4}$$

$$\therefore\ q = 1.2 \times 10^{-3}\,\frac{6.07 \times 10^{-4} \times 1.008 \times 959 \times 99}{427 \times 539 \times 0.585 \times (60.19 \times 10^{-4})^{\frac{1}{2}}} \left[\frac{1.008 \times 99\,(6.07 \times 10^{-4})^{\frac{1}{2}}}{427\,(539 \times 0.585)^{2}}\right]^{\frac{1}{4}}$$

$$\times \left(\frac{959}{1.015}\right)^{5/8} (1.76)^{1/3}\,(31.35 \times 10^{2})^{2}$$

$$= 16.2 \times 10^{3}\ \text{Kcal/hr.m}^{2}$$

$$\therefore\ h = \frac{q}{\Delta t} = \frac{16.2 \times 10^{3}}{105.9 - 99.0} = 2350\ \text{Kcal/hr.m.}^{2}\ {}^{o}\text{C}$$

$$\therefore\ Nu_B = \frac{2350}{0.5868}\sqrt{\frac{60.19 \times 10^{-4}}{959.0 - 0.585}}^{\frac{1}{2}} = \underline{10.05}$$

4. Kichigin and Tobilevich (30)

$$Nu_B = 1.04 \times 10^{-4}\ (Pe_B)^{0.7}\ (Kp)^{0.7}\ (Ar)^{0.125}$$

$$Pe_B = \frac{25.33 \times 10^{3}}{0.585 \times 539 \times 6.07 \times 10^{-4}}\sqrt{\frac{60.19 \times 10^{-4}}{959 - 0.585}} = 334.025$$

$$Kp = \frac{1.03 \times 10^{4}}{(60.19 \times 10^{-4} \times 958.42)^{\frac{1}{2}}} = 4.3 \times 10^{3}$$

$$Ar = \frac{9.81}{(0.298 \times 10^{-6})^{2}}\left(\frac{60.19 \times 10^{-4}}{959.0 - 0.585}\right)^{3/2}\left(1 - \frac{0.585}{959}\right)$$

$$= 1.725 \times 10^{6}$$

$$\therefore\ Nu_B = 1.04 \times 10^{-4}\ (334.025)^{0.7}\ (4.3 \times 10^{3})^{0.7}\ (1.725 \times 10^{6})^{0.125}$$

$$= 1.04 \times 10^{-4} \times 58 \times 348 \times 6.1$$

$$= \underline{12.80}$$

5. Kutateladze (30)

$$Nu_B = 7.0 \times 10^{-4}\ (Pe_B)^{0.7}\ (Pr)^{-0.35}\ (Kp)^{0.7}$$

$$= 7.0 \times 10^{-4}\ (334.025)^{0.7}\ (1.76)^{-0.35}\ (4.3 \times 10^{3})^{0.7}$$

$$= 7.0 \times 10^{-4} \times 58 \times 0.82 \times \text{[illegible]}$$

$$= \underline{11.55}$$

6. Borishanskii and Minchenko (30)

$$Nu_B = 8.7 \times 10^{-4} (Pe_B)^{0.7} (Kp)^{0.7}$$

$$= 8.7 \times 10^{-4} (334.025)^{0.7} (4.3 \times 10^3)^{0.7}$$

$$= \underline{17.55}$$

7. Kruzhilin and Averin (30)

$$Nu_B = 0.082 (Pe_B)^{0.7} (Pr)^{-0.5} (Kt)^{0.377}$$

$$K_t = \frac{427 (0.585 \times 539)^2}{1.008 \times 99 \times 959 \{60.19 \times 958.415 \times 10^{-4}\}^{1/2}} = 178$$

$$Nu_B = 0.082 (334.025)^{0.7} (1.76)^{-0.5} (178)^{0.377}$$

$$= \underline{26.10}$$

8. Labuntsov (29, 30)

$$Nu_B = 0.125 (Pe_B)^{0.65} (Pr)^{-0.32} (K_t)^{0.35}$$

$$= 0.125 (334.025)^{0.65} (1.76)^{-0.32} (178)^{0.35}$$

$$= \underline{29.00}$$

(iii) Predicted Nu_B by the proposed correlation

$$Nu_B = 0.084 (Pe_B)^{0.6} (K_{sub})^{0.5} (K_t)^{0.37}$$

$$= 0.084 (334.025)^{0.6} (1)^{-0.5} (178)^{0.37}$$

$$= \underline{18.1}$$

(iv) Percent Error in the values of Nu_B calculated as above

$$\text{Percent error} = \frac{(Nu_B)_{\text{calctd.}} - (Nu_B)_{\text{exptl.}}}{(Nu_B)_{\text{calctd.}}}$$

The calculated values of percent error have been shown in the following Table F.1 .

Table F-1 Percent Error in Predicted Nu_B

Correlation	% Error	Correlation	% Error
Rohsenow (22)	+40.02	Kutateladze (30)	-37.5
McNelly (24)	-37.4	Borishanskii and Minchenko (30)	+10.65
Forster and Greif (27)	-53.5	Kruzhilin and Averin (30)	+40
Kichigin and Tobilevich (30)	-22.6	Labuntsov (29, 30)	+43
		Proposed	+13.4

F-2 Binary Liquid Mixtures

To illustrate the procedure followed in processing the experimental data of mixtures, Run No. 119 of water-acetic acid system is selected.

The following data were taken for this run :

System : Water-Acetic acid mixture containing 19.3 Wt. % Water.

(44.3 Mole % Water)

$t_s = 104.1\ ^{o}C$

$t_W = 110.60\ ^{o}C$

$t_L = 80.05\ ^{o}C$

$q = 31.71 \times 10^{3}\ Kcal/hr.m^{2}$

F-2.1 Calculation of physical properties of the mixture

(i) $$\rho_L = \frac{100}{\frac{19.3}{955.44} + \frac{80.7}{955.3}} = 955.35\ kg/m^{3}$$

(ii) $$\rho_v = \frac{100 \times 1 \times 10^{3}}{(\frac{19.3}{18}\ \ \frac{80.7}{60}) \times 82.06 \times 377.1} = 1.34\ kg/m^{3}$$

(iii) Critical temperature is calculated by Kay's method.

$$T_c = 0.443 \times 647 + 0.557 \times 594 = 617\ ^{o}K$$

(iv) Surface tension is calculated using the equation of Meissner and Michaels (71)

$$\sigma = (31.42 \times 10^{-4})_{35^{o}C} \left(\frac{617 - 377}{617 - 308}\right)^{1.2} = 23.2 \times 10^{-4}\ kg/m$$

(v) $C = 0.193 \times 1.009 + 0.807 \times 0.5633$

$= 0.647\ Kcal/kr.\ ^{o}C$

(vi) $\lambda = 0.193 \times 539 + 0.807 \times 93.26$

$= 179.3\ Kcal/kg.$

(vii) Thermal conductivity is calculated as follows :

$$k = 0.588 \times 0.193 + 0.1343 \times 0.807 - 0.72 \times 0.4537 \times 0.193 \times 0.807$$

$= 0.171\ Kcal/hr.m.\ ^{o}C$

F-2.2 Calculation of dimensionless parameters.

(i) $$Pe_B = \frac{31.71 \times 10^3 \times \left(\frac{23.2 \times 10^{-4}}{955.35 - 1.34}\right)^{1/2} \times 955.35 \times 0.647}{1.34 \times 179.3 \times 0.171}$$

$$= 740$$

(ii) $$K_{sub} = 1 + \frac{955.35}{1.34} \times \frac{24.05}{104.1}$$

$$= 7.16$$

(iii) $$K_t = \frac{427\,(1.34 \times 179.3)^2}{0.647 \times 104.1 \times 955.35 \left[23.2 \times 10^{-4}(955.35 - 1.34)\right]^{\frac{1}{2}}}$$

$$= 260$$

(iv) $$K_c = 1 + \frac{(0.58 - 0.443)^2}{0.58\,(1 - 0.58)}$$

$$= 1.077$$

F-2.3 Calculation of Nu_B

(i) Experimental Nu_B

$$Nu_B = \frac{q}{(t_W - t_L)} \quad \frac{1}{k} \sqrt{\frac{\sigma}{\rho_L - \rho_v}}$$

$$= \frac{31.71 \times 10^3}{(110.6 - 80.05)} \times \frac{1}{0.171} \sqrt{\frac{23.2 \times 10^{-4}}{(955.35 - 1.34)}}$$

$$= \underline{9.35}$$

(ii) Predicted Nu_B using proposed correlation

$$Nu_B = 0.0576\,(Pe_B)^{0.6}\,(K_{sub})^{-0.5}\,(K_t)^{0.37}\,(K_c)^{-0.034}$$

$$= 0.0576\,(740)^{0.6}\,(7.16)^{-0.5}\,(260)^{0.37}\,(1.077)^{-0.034}$$

$$= \underline{8.9}$$

Percent error in Nu_B

$$= \frac{8.9 - 9.35}{8.9} = - 5.05 \%$$

F-3 Percent Deviations of the Proposed Correlations

F-3.1 Pure liquids

Percent standard deviation

$$= \frac{\text{Standard deviation}}{\left(\dfrac{\sum Nu_B}{\text{Number od data points}}\right)} \times 100$$

$$= \frac{2.97}{\left(\dfrac{1924}{133}\right)} \times 100$$

$$= \underline{20.54} \%$$

Percent Average deviation

$$= \frac{\text{Average deviation}}{\left(\dfrac{\sum Nu_B}{\text{Number of data points}}\right)} \times 100$$

$$= \frac{2.91}{\left(\dfrac{1924}{133}\right)}$$

$$= \underline{20.16 \%}$$

F-3.2 Binary liquid mixtures

Percent standard deviation

$$= \frac{3.61}{\dfrac{7900}{697}} \times 100$$

$$= \underline{31.88 \%}$$

Percent Average deviation

$$= \frac{3.60}{\dfrac{7900}{697}} \times 100$$

$$= \underline{31.84} \%$$

F-4 Calculation of Experimental and Predicted Natural Convective Heat Transfer Coefficient

To illustrate the calculation for natural convective heat transfer, Run No. 36 for water is used. The experimental data for this run are reproduced below :

$$q = 23.43 \times 10^{3} \text{ Kcal/hr.m}^{2}$$

$$t_W = 98.7 \ ^{o}C$$

$$t_L = 77.45 \ ^{o}C$$

(i) Experimental heat transfer coefficient

$$h_c = \frac{q}{t_W - t_L}$$

$$= \frac{23.43 \times 10^{3}}{98.7 - 77.45}$$

$$= 1100 \text{ Kcal/hr.m.}^{2} \ ^{o}C$$

(ii) Predicted heat transfer coefficient

$$Nu_c = C \, (Gr \times Pr)^{n}$$

All the physical properties in the above correlation are taken at the average temperature $\left(t_{av} = \frac{t_W + t_L}{2} \right)$

$$h_c = \frac{58.4 \times 10^{-2}}{25.6 \times 10^{-3}} \times 0.135 \left(\frac{9.81 \times 16.8 \times 10^{-6} \times 6.8 \times 21.25}{(3.34)^2} \times 2.0 \right)^{\frac{1}{3}}$$

$$= \underline{1080} \text{ Kcal/hr.m.}^2 \ ^{\circ}\text{C}$$

(iii) Percent error = $\dfrac{\text{Calculated } Nu_c - \text{Experimental } Nu_c}{\text{Calculated } Nu_c}$

$$= \frac{1080 - 1100}{1080} \times 100 = \underline{-1.85} \ \%$$

APPENDIX G

LISTING OF COMPUTER PROGRAMS AND RESULTS OF SOME EXPERIMENTAL RUNS

```
C  C  S.S.ALAM   CALCULATION OF DIMENSIONLESS PARAMETERS
C     IJ=1 IF ANOTHER DATA SET IS TO BE EXECUTED
C     IJ=2 IF THIS DATA SET IS THE LAST SET
C     AK= THERMAL CONDUCTIVITY AT TS  KCAL/HR/METER/DEG.CENTIGRADE
C     SIG=SURFACE TENSION AT TS  KGF/METER
C     RHOL=LIQUID DENSITY AT TS  KGF/CUBIC METER
C     RHOV=VAPOR DENSITY AT TS   KGF/CUBIC METER
C     TS=SATURATION TEMPERATURE   DEGREE CENTIGRADE
C     DELH=DELTA H FOR BOILING AT TS  KCAL/KGM
C     CP=SPECIFIC HEAT AT TS  KCAL/KG/DEGREE CENTIGRADE
C     B=EXPONENT OF (RHOL/RHOV)
C
C
   32 READ 1,IJ
    1 FORMAT(30X,I10)
      READ5,AK,SIG.RHOL,RHOV
      READ 5,TS,DELH,CP
    5 FORMAT(4F15.6)
      READ 30,B
   30 FORMAT(F20.6)
      AAA=SQRTF(SIG/(RHOL-RHOV))
      ABB=RHOV*DELH*AK/(RHOL*CP)
      BBB=(RHOL/RHOV)**B
      ABC=SQRTF(SIG*(RHOL-RHOV))
      ACC=CP*TS*RHOL*ABC
      TK=427.0*(RHOV*DELH)*(RHOV*DELH)/ACC
      PUNCH 1100,TK
 1100 FORMAT(6X,4H KT=,4X,F14.8)
C
      DIMENSION  TW(200),TL(200),Q(200),H(200)
C
C     ATW=WALL TEMPERATURE   DEGREE CENTIGRADE
C     ATL=LIQUID TEMPERATURE  DEGREE CENTIGRADE
C     AQ=HEAT FLUX   KCAL /HR/METER SQUARE
C
C
C     CALCULATION  OF  DIMENSIONLESS  PARAMETERS
C
      I=0
      PUNCH 21
   21 FORMAT(2X,10HNUS. NUMB.,4X,10HPEC. NUMB.,2X,14HSUBCOOL. TERM.)
   31 READ 2,ATW,ATL,AQ
    2 FORMAT(3F20.6)
      IF(ATW-500.0)34,23,34
   34 HC=AQ/(ATW-ATL)
      ANU=HC*AAA/AK
      PEC=AQ*AAA/ABB
      ANSUB=(TS-ATL)*BBB/TS+1.0
```

```
      PUNCH 22,ANU,PEC,ANSUB
   22 FORMAT(3F14.8)
      I=I+1
      TW(I)=ATW
      TL(I)=ATL
      Q(I)=AQ
      H(I)=HC
      LL=I
      GO TO 31
   23 PUNCH 25
   25 FORMAT(7X,11HWALL  TEMP.,6X,12HLIQU.  TEMP.,8X,10HHEAT  FLUX,
     18X,10HH  BOILING)
      PUNCH 26,(TW(L),TL(L),Q(L),H(L),L=1,LL)
   26 FORMAT(4F18.8)
C     XAW IS WEIGHT PERCENT A IN  LIQUID
C     YAW IS WEIGHT PERCENT A IN  VAPOR
C     AMA IS MOLECULAR WEIGHT OF  A
C     AMB IS MOLECULAR WEIGHT OF  B
C     XAW+XBW=100.0    ,   YAW+YBW=100.0
C     XAM IS MOLE FRACTION A IN  LIQUID
C     YAM IS MOLE FRACTION A IN VAPOR
C
      READ 110,XAW,YAW,AMA,AMB
  110 FORMAT(4F10.5)
      AM=YAW/AMA
      BM=(100.0-YAW)/AMB
      YAM=AM/(AM+BM)
      AM=XAW/AMA
      BM=(100.0-XAW)/AMB
      XAM=AM/(AM+BM)
      CK=(YAM-XAM)*(YAM-XAM)/YAM
      CK=CK/(1.0-XAM)
      CK=CK+1.0
      PUNCH 111,XAM,YAM,CK
  111 FORMAT(5H XAM=F5.3,2X,5H YAM=F5.3,2X,4H KC=F14.8)
      GO TO (32,33),IJ
   33 STOP
      END
```

CHECK PROGRAM

```
                            * D A T A *
                                       1
       0.5868         0.00609      959.0            0.580
      99.0          539.600          1.0077
            0.5
           99.40              73.00            38000.
          500.00              73.00            38000.
    .50       .60     10.      20.
                                       2
       0.5868         0.00609      959.0            0.580
      99.0          539.600          1.0077
            0.5
           99.40              73.00            38000.
          500.00              73.00            38000.
    .50       .60     10.      20.

                            * R E S U L T S *

C  C  S.S.ALAM    CALCULATION OF DIMENSIONLESS PARAMETERS
       KT=       180.94895000
  NUS. NUMB.     PEC. NUMB.  SUBCOOL. TERM.
    6.18329900  504.05061000   11.67906800
       WALL  TEMP.          LIQU.  TEMP.          HEAT  FLUX            H  BOILING
       99.40000000           73.00000000    38000.00000000      1439.39390000
 XAM= .010   YAM= .012   KC=      1.00033130
       KT=       180.94895000
  NUS. NUMB.     PEC. NUMB.  SUBCOOL. TERM.
    6.18329900  504.05061000   11.67906800
       WALL  TEMP.          LIQU.  TEMP.          HEAT  FLUX            H  BOILING
       99.40000000           73.00000000    38000.00000000      1439.39390000
 XAM= .010   YAM= .012   KC=      1.00033130
0     STOP END AT S. 0033 + 00 L.  Z
```

```
C  C  S.S.ALAM         CURVE   FITTING  PROGRAM
C
C     NP IS NO OF DATA POINTS    IO IS NO OF NON RANDOM VARIABLES
C     AY  ARE RANDOM VARIABLES         AX  ARE NONRENDOM VARIABLES
C     NP UPTO  50  AND  IO  UPTO 3 PERMITTED
C
      DIMENSION AY(50),AX(50,4),XMAT(50,4),YLOG(50),XAVG(4),XTANS(4,50)
      DIMENSION A(4,4),G(4),C(4,4),B(4),YPRID(50),VARB(4)
      READ 1111,NT
 1111 FORMAT(I2)
      DO 1112 NNT=1,NT
      READ 1,NP,IQ
    1 FORMAT(2I10)
      DO 45  I=1,NP
      READ 2,AY(I),(AX(I,K),K=1,IQ)
    2 FORMAT(4F14.8)
   45 CONTINUE
      AA=NP
C
C     TAKING LOG OF AY AND AX AND SUMMING
C
      DO 3  J=1,IQ
    3 XAVG(J)=0.0
      DO4I=1,NP
      YLOG(I)=LOGF(AY(I))
      DO 4  J=1,IQ
      AX(I,J)=LOGF(AX(I,J))
    4 XAVG(J)=XAVG(J)+AX(I,J)
C
C     DETERMINATION OF AVERAGE VALUE OF X(IQ)
C
      DO5J=1,IQ
    5 XAVG(J)=XAVG(J)/AA
C
C     FORMATION OF X MATRIX
C
      NQ=IQ+1
      DO12I=1,NP
      DO12J=1,NQ
      IF(J-1)10,10,893
   10 XMAT(I,J)=1.0
      GO TO 12
  893 XMAT(I,J)=AX(I,J-1)-XAVG(J-1)
   12 CONTINUE
C
C     TRANSPOSE OF XMATRIX
C
      DO35I=1,NP
      DO35J=1,NQ
   35 XTANS(J,I)=XMAT(I,J)
```

```
C
C     MULTIPLICATION OF XTRANSPOSE MATRIX WITH X MATRIX
C
      DO 20I=1,NQ
      DO 20K=1,NQ
      A(I,K)=0.0
      DO20J=1,NP
   20 A(I,K)=A(I,K)+XTANS(I,J)*XMAT(J,K)
C
C     MULTIPLICATION OF X TRANSPOSED MATRIX WITH YMATRIX
C
      DO25I=1,NQ
      G(I)=0.0
      DO25J=1,NP
   25 G(I)=G(I)+XTANS(I,J)*YLOG(J)
C
C     INVERSION OF AMATRIX
C
      GO TO (7,8,9),IQ
    7 AA=A(1,1)*A(2,2)
      C(1,1)=A(2,2)/AA
      C(2,2)=A(1,1)/AA
      C(1,2)=0.0
      C(2,1)=0.0
      GO TO 6
    8 AA=A(2,2)*A(3,3)-A(2,3)*A(3,2)
      BB=A(1,1)*A(3,3)
      CC=A(1,1)*A(2,2)
      DD=A(1,1)*A(2,3)
      EE=A(1,1)*AA
      C(1,1)=AA/EE
      C(1,2)=0.0
      C(1,3)=0.0
      C(2,1)=0.0
      C(2,2)=BB/EE
      C(2,3)=-DD/EE
      C(3,1)=0.0
      C(3,2)=C(2,3)
      C(3,3)=CC/EE
      GO TO 6
    9 AA=A(3,3)*A(4,4)-A(3,4)*A(4,3)
      BB=A(2,2)*A(4,4)-A(2,4)*A(2,4)
      CC=A(2,2)*A(3,3)-A(2,3)*A(3,2)
      DD=A(2,3)*A(4,4)-A(2,4)*A(3,4)
      EE=A(2,2)*A(3,4)-A(2,4)*A(2,3)
      FF=A(2,3)*A(3,4)-A(2,4)*A(3,3)
      GG=A(1,1)*(A(2,2)*AA-A(2,3)*DD+A(2,4)*FF)
      C(1,1)=1.0/A(1,1)
      C(1,2)=0.0
      C(1,3)=0.0
      C(1,4)=0.0
      C(2,1)=0.0
      C(2,2)=A(1,1)*AA/GG
```

```
      C(2,3)=-A(1,1)*DD/GG
      C(2,4)=A(1,1)*FF/GG
      C(3,1)=0.0
      C(3,2)=C(2,3)
      C(3,3)=A(1,1)*BB/GG
      C(3,4)=-A(1,1)*EE/GG
      C(4,1)=0.0
      C(4,2)=C(2,4)
      C(4,3)=C(3,4)
      C(4,4)=A(1,1)*CC/GG
      GO TO 6
C
C     MULTIPLICATION OF C MATRIX WITH G MATRIX TO GET B MATRIX
C
    6 DO 22I=1,NQ
      B(I)=0.0
      DO22J=1,NQ
   22 B(I)=B(I)+C(I,J)*G(J)
C
C     CALCULATION OF  YPRIDECTED FROM XMATRIX AND BMATRIX
C
      DO 24 I=1,NP
      YPRID(I)=0.0
      DO24J=1,NQ
   24 YPRID(I)=YPRID(I)+XMAT(I,J)*B(J)
C
C     CALCULATION OF SUM OF SQUARES OF ERRORS
C
       SUM=0.0
      DO26I=1,NP
   26 SUM=SUM+(YPRID(I)-YLOG(I))**2
      AB=IQ
      AA=NP
      AC=AA-(AB+1.0)
      IF(AC)27,27,28
   27 PUNCH 29
   29 FORMAT(21H DATA POINTS ARE LESS)
      STOP
   28 AC=SQRTF(SUM/AC)
C
C     CALCULATION OF  STANDARD DEVIATION IN  B  VALUES
C
      DO 30 I=1,NQ
   30 VARB(I)=AC*SQRTF(C(I,I))
      B1=B(1)
      DO 31 I=2,NQ
   31 B1=B1-B(I)*XAVG(I-1)
      B(1)=EXPF(B1)
      ERSQ=0.0
      DO23I=1,NP
      YPRID(I)=EXPF(YPRID(I))
      AX(I,1)=YPRID(I)-AY(I)
      AX(I,2)=(AX(I,1)/AY(I))*100.0
```

```
   23 ERSQ=ERSQ+AX(I,1)*AX(I,1)
      AC=AA-(AB+1.0)
      ERSQ=SQRTF(ERSQ/AC)
C
C
      PUNCH 32
      PUNCH 8989
 8989 FORMAT(//)
   32 FORMAT(3X,13H EXPERIMENTAL,9X,11H CALCULATED,8X,14H PERCENT ERROR)
      PUNCH 33,(AY(I),YPRID(I),AX(I,2),I=1,NP)
   33 FORMAT(3F20.8)
      PUNCH 34
   34 FORMAT(////4X,4HB(1),8X,4HB(2),8X4HB(3),8X,4HB(4),8X,4HB(5))
C
C     SDB(1) IS NOT CALCULATED DUE TO TRANSFORMATION OF MODEL
C
      PUNCH 8989
      PUNCH 36,(B(I),I=1,NQ)
   36 FORMAT(6E12.4)
      PUNCH 8989
      PUNCH 37
   37 FORMAT(2X,8H  SDB(1),4X,8H  SDB(2),4X,8H  SDB(3),4X,8H  SDB(4),4X,
     18H  SDB(5))
      PUNCH 8989
      PUNCH 38,(VARB(I),I=2,NQ)
   38 FORMAT(12X,5E12.4)
      PUNCH 8989
      PUNCH 68,ERSQ
   68 FORMAT(10X,36H STANDARD DEVIATION IN Y VALUES IS =E20.8)
      PUNCH 8989
      PUNCH 7878,B(1)
 7878 FORMAT(F14.8)
      PUNCH 8989
 1112 CONTINUE
      STOP
      END
```

CHECK PROGRAM

* DATA *

```
 1
          5            2
   18.              1.            3.
   36.              2.            3.
    4.              2.            1.
    8.              1.            2.
    8.              4.            1.
```

```
                              * R E S U L T S *

C  C  S.S)ALAM        CURVE   FITTING  PROGRAM
   EXPERIMENTAL            CALCULATED          PERCENT ERROR


            18.00000000          17.99999500          -.00002778
            36.00000000          36.00000500           .00001389
             4.00000000           3.99999690          -.00007750
             8.00000000           7.99999940          -.00000750
             8.00000000           7.99999700          -.00003750


   B(1)         B(2)         B(3)         B(4)         B(5)

 0.2000E+01  0.1000E+01  0.2000E+01

   SDB(1)       SDB(2)       SDB(3)       SDB(4)       SDB(5)

             0.7618E-06  0.7988E-06

            STANDARD DEVIATION IN Y VALUES IS =       0.58723930E-05

   1.99999520

0     STOP END AT S. 1112 + 01 L.  Z
```

```
C  C  S. S. ALAM CONSTANT CORRECTION PROGRAM
C        B2N AND B3N ARE SELECTED POWERS FOR PECLET NO. AND KSUB
C        B20 B30 ARE POWER CALCULATED BY CURVE FITTING
C        B10 IS  CONSTANT BY CURVE FITTING
C        PEM IS MEAN PECLET NO.  AND AKSM IS MEAN KSUB
C        B1N IS CORRECTED CONSTANT
         READ 1, B2N, B3N
       1 FORMAT(2F10.5)
       6 READ 2, B10, B20,B30
       2 FORMAT(3E12.4)
         IF(B10-5000.0)3,4,3
       4 STOP
       3 READ 5, PEM, AKSM
       5 FORMAT(2F14.8)
         B2C=(PEM**B20)/(PEM**B2N)
         B3C=(AKSM**B30)/(AKSM**B3N)
         B1N=B10*B2C*B3C
         PUNCH 5, B1N
         GO TO 6
         END
```

CHECK PROGRAM

DATA

```
  0.6         -0.5
 0.5871         0.6639       -0.7175
 363.9             2.7
 0.2669         0.7037       -0.5191
 256.8             2.9
 0.3321E+01   0.4480       -0.5
 340.6             1.0
 0.5000E+04   0.7226       -0.4980
```

RESULTS

```
C  C  S. S. ALAM CONSTANT CORRECTION PROGRAM
       .68950473
       .46493450
      1.36888710
0        STOP END AT S. 0004 + 00 L.  Z
```

```
C  C  S. S. ALAM  CORRELATION VERIFICATION PROGRAM
C     NUS=BA*(PEC**BB)*(KSUB**BC)*(KT**BD)*(KCON**BE)
C     KC AND KT  CHANGE WITH SET , NUS,PEC AND KSUB CHANGE WITHIN SET
      READ 1,BA,BB,BC,BD,BE
    1 FORMAT(5F15.9)
      READ 2,NT,SUMS
    2 FORMAT(I10,F20.9)
C     NT IS NO OF POINTS ALREADY EXECUTED
C     SUMS IS SUM OF SQUARE OF ERROR OF ALREADY EXECUTED POINTS
    9 READ 7,A,AKT,AKCON
    7 FORMAT(3F14.8)
      IF(A-500.0)13,14,13
   13 AKTP=AKT**BD
      AKCP=AKCON**BE
      PUNCH 5
    5 FORMAT(//)
      PUNCH 6
    6 FORMAT(60H         NUS  EXPER.        NUS    CALC.       PERCENT  ERRO
     1R    )
   11 READ 7,ANUS,APEC,AKSUB
      IF(ANUS-99999.0)8,9,8
    8 APECP=APEC**BB
      AKSP=AKSUB**BC
      ANUSC=BA*APECP*AKSP*AKTP*AKCP
      AA=ANUSC-ANUS
      ERR=AA*100.0/ANUSC
      PUNCH 10,ANUS,ANUSC,ERR
   10 FORMAT(3F20.9)
      SUMS=SUMS+AA*AA
      NT=NT+1
      GO TO 11
   14 AA=NT
      STD=SQRTF(SUMS/(AA-5.0))
      DM=SQRTF(SUMS/AA)
      PUNCH 5
      PUNCH 2,NT,SUMS
      PUNCH 5
      PUNCH 12,STD,DM
   12 FORMAT(21H STANDARD DEVIATION =F12.8,20H AVERAGE DEVIATION =F12.8)
      STOP
      END
```

```
                           C H E C K   P R O G R A M

                                 *D A T A*

  0.0576          0.6          -0.5           0.37          -0.034
  2.0             0.5           0.5           1.0            2.0
      0           0.0
  1.0          1.0          0.8
  2.5          4.0          1.0
  7.7          9.0          4.0
  7.6          9.0          4.0
99999.0        9.0          4.0
  1.0          2.0          1.0
  8.0          4.0          1.0
 25.0          9.0          4.0
 24.0          9.0          4.0
99999.0        9.0          4.0
 500.0         9.0          4.0


                              *R E S U L T S*

C  C  S. S. ALAM  CORRELATION VERIFICATION PROGRAM


    NUS  EXPER.          NUS    CALC.          PERCENT  ERROR
      2.500000000          2.559999300              2.343723200
      7.700000000          7.679996300              -.260464960
      7.600000000          7.679996300              1.041618900


    NUS  EXPER.          NUS    CALC.          PERCENT  ERROR
      8.000000000          8.000008800               .000110000
     25.000000000         24.000021000             -4.166575500
     24.000000000         24.000021000               .000087500


      6            1.010357400

 STANDARD DEVIATION =  1.00516540 AVERAGE DEVIATION =   .41035704
0    STOP END AT S. 0012 + 01 L.  Z
```

TABLE G-1 DIMENSIONLESS GROUPS OF SOME EXPERIMENTAL RUNS FOR PURE LIQUIDS

WATER

KT= 177.53290000

NUS. NUMB.	PEC. NUMB.	SUBCOOL. TERM.			RUN.NO.
8.37310250	91.52497800	1.00000000	...	...	001
6.57223550	91.52497800	1.61610010	...	...	002
5.81191800	91.52497800	2.60186030	...	...	003
11.09739400	164.47966000	1.00000000	...	...	004
8.32304610	164.47966000	1.73932010	...	...	005
4.95511550	164.47966000	4.01889060	...	...	008
14.41883100	256.00465000	1.02053660	...	...	021
7.53711600	256.00465000	3.25903370	...	...	023
5.08639720	256.00465000	5.72343430	...	...	025
16.77716400	328.95934000	1.04107330	...	...	038
7.39826320	328.95934000	4.42962400	...	...	040
4.96666590	328.95934000	8.37266490	...	...	042
19.88594500	420.61696000	1.00000000	...	...	051
11.07469300	420.61696000	3.25903370	...	...	053
7.16940670	420.61696000	6.13416770	...	...	055
5.35240550	420.61696000	9.87184190	...	...	057
21.09044300	475.39931000	1.00000000	...	...	060
10.47348600	475.39931000	4.01889060	...	...	062
6.00234850	475.39931000	8.82447170	...	...	064
5.34584160	475.39931000	10.85760200	...	...	065
22.59233600	530.18164000	1.00000000	...	...	069
11.44678300	530.18164000	4.01889060	...	...	071
6.54101900	530.18164000	8.82447170	...	...	073
22.77306500	548.48662000	1.00000000	...	...	074
14.15377800	548.48662000	2.95098370	...	...	075
10.73292500	548.48662000	4.59391730	...	...	076
8.47875490	548.48662000	6.42168110		...	077
6.85829750	548.48662000	8.55749490	...	...	078

ACETIC ACID

KT= 273.09011000

NUS. NUMB.	PEC. NUMB.	SUBCOOL. TERM.			RUN-NO.
30.62422200	363.99774000	1.00000000	...	...	164
19.44855700	363.99774000	1.75724000	...	...	166
14.65587700	363.99774000	2.58157730	...	...	168

```
10.41534400   363.99774000     4.26859320        ...        ...       170
39.66065500   598.05019000     1.00958530        ...        ...       183
25.44268400   598.05019000     1.94894640        ...        ...       185
16.94048000   598.05019000     3.42508530        ...        ...       187
12.48576100   598.05019000     5.06417460        ...        ...       189
44.96606800   753.83369000     1.00000000        ...        ...       193
26.64133700   753.83369000     2.23650590        ...        ...       196
16.56644500   753.83369000     4.45071420        ...        ...       198
14.88368900   753.83369000     5.47634330        ...        ...       199


   A C E T O N E

     KT=         1126.06940000
NUS. NUMB.       PEC. NUMB.  SUBCOOL. TERM.                          RUN.NO.
 27.90968100   121.77450000     1.00000000        ...        ...       202
 38.01336700   218.84115000     1.00000000        ...        ...       203
 45.69729300   340.61567000     1.00000000        ...        ...       204
 51.13302700   437.68231000     1.00000000        ...        ...       205



 56.39663700   559.63332000     1.00000000        ...        ...       206
 61.50869900   705.40976000     1.00000000        ...        ...       207
```

TABLE G-2 VERIFICATION OF PROPOSED CORRELATION USING RUNS OF TABLE G-1

WATER

NUS EXPER.	NUS CALC.	PERCENT ERROR
8.373102500	8.578989400	2.399896800
6.572235500	6.748420200	2.610754700
5.811918000	5.318562800	-9.276099900
11.097394000	12.194938000	8.999996500
8.323046100	9.246767300	9.989666300
4.955115500	6.083122900	18.543228000
14.418831000	15.741525000	8.402578500
7.537116000	8.808797700	14.436495000
5.086397200	6.647108100	23.479547000
16.777164000	18.115785000	7.389251900
7.398263200	8.782423000	15.760568000
4.966665900	6.388016000	22.250258000
19.885945000	21.421230000	7.167118700
11.074693000	11.865883000	6.667771700
7.169406700	8.649014900	17.107245000
5.352405500	6.817817300	21.493855000
21.090443000	23.054058000	8.517437500
10.473486000	11.499907000	8.925472100
6.002348500	7.760739500	22.657518000
5.345841600	6.996494800	23.592573000
22.592336000	24.613143000	8.210276100
11.446783000	12.277615000	6.767047100
6.541019000	8.285577600	21.055364000
22.773065000	25.119553000	9.341280800
14.153778000	14.622734000	3.207033600
10.732925000	11.719806000	8.420625700
8.478754900	9.912599600	14.464870000
6.858297500	8.586945100	20.131112000

ACETIC ACID

NUS EXPER.	NUS CALC.	PERCENT ERROR
30.624222000	23.034118000	-32.951572000
19.448557000	17.376252000	-11.926075000
14.655877000	14.336037000	-2.231021000
10.415344000	11.148830000	6.579040100
39.660655000	30.880439000	-28.432937000
25.442684000	22.225676000	-14.474286000
16.940480000	16.765605000	-1.043058000
12.485761000	13.787983000	9.444615600

```
   44.966068000           35.651483000          -26.126781000
   26.641337000           23.839251000          -11.754085000
   16.566445000           16.899072000            1.968315100
   14.883689000           15.234646000            2.303676700


 A C E T O N E

  NUS   EXPER.       NUS    CALC.        PERCENT  ERROR
   27.909681000          20.169359000         -38.376638000
   38.013367000          28.670529000         -32.586904000
   45.697293000          37.386695000         -22.228758000
   51.133027000          43.456385000         -17.665164000
   56.396637000          50.361697000         -11.983194000
   61.508699000          57.865960000          -6.295132700
```

TABLE G-3 DIMENSIONLESS GROUPS OF SOME EXPERIMENTAL RUNS FOR BINARY MIXTURES

27.50 WT. PERCENT WATER - GLYCERINE

XAM= .660 YAM=1.000 KC= 1.33971830
KT= 255.75571000

NUS. NUMB.	PEC. NUMB.	SUBCOOL. TERM.			RUN.NO.
10.34606500	215.61798000	.98748150	...	...	066
9.45776680	215.61798000	1.17525900	...	...	067
7.73817280	215.61798000	1.80118440	...	...	068
6.59379540	215.61798000	2.61488730	...	...	069
5.64047560	215.61798000	3.52873820	...	...	070
5.33515080	215.61798000	4.19221900	...	...	071
5.06118360	215.61798000	4.84318140	...	...	072
4.96720940	215.61798000	5.23125510	...	...	073
13.07179500	323.59729000	1.00000000	...	...	077
11.95930200	323.59729000	1.25037010	...	...	078
9.62478080	323.59729000	1.98896190	...	...	079
7.65786370	323.59729000	3.24081260	...	...	080
6.87148180	323.59729000	3.94184900	...	...	081
6.12295430	323.59729000	5.00592200	...	...	082
5.57626200	323.59729000	6.14510610	...	...	083
5.21416720	323.59729000	7.49710490	...	...	084
15.84921800	431.40627000	1.00000000	...	...	087
14.17078300	431.40627000	1.35051810	...	...	088
11.56405800	431.40627000	1.97644340	...	...	089
9.09406550	431.40627000	3.36599770	...	...	090
8.41967380	431.40627000	3.95436750	...	...	091
7.43403760	431.40627000	4.95584800	...	...	092
6.63142470	431.40627000	6.09503210	...	...	093
6.21352400	431.40627000	7.20917920	...	...	094
5.74655670	431.40627000	8.61125190	...	...	095
17.73891600	539.21527000	1.00000000	...	...	099
16.14853100	539.21527000	1.30044410	...	...	100
14.10564400	539.21527000	1.80118440	...	...	101
10.79049200	539.21527000	3.22829410	...	...	102
10.00656800	539.21527000	3.86673800	...	...	103
8.80277030	539.21527000	4.83066290	...	...	104
7.77919230	539.21527000	5.98236550	...	...	105
7.17162920	539.21527000	7.15910510	...	...	106
6.42396960	539.21527000	8.76147390	...	...	107
6.07402570	539.21527000	9.57517690	...	...	108
5.87587700	539.21527000	10.52658300	...	...	109
19.05380300	647.19458000	1.00000000	...	...	112
17.73145800	647.19458000	1.30044410	...	...	113
16.38738200	647.19458000	1.55081420	...	...	114

```
 12.77470900  647.19458000    2.91533140     ...      ...      115
 12.32647300  647.19458000    3.30340510     ...      ...      116
 10.35151300  647.19458000    4.59281130     ...      ...      117
  9.03677170  647.19458000    5.70695840     ...      ...      118
  7.65786370  647.19458000    7.50962330     ...      ...      119
  7.02609020  647.19458000    8.88665910     ...      ...      120
  6.17000240  647.19458000   10.61421200     ...      ...      121
  6.21090830  647.19458000   10.87710100     ...      ...      122
  5.97965120  647.19458000   11.81598900     ...      ...      123


86.00 WT. PERCENT   WATER - GLYCERINE

 XAM= .969    YAM=1.000   KC=     1.03083470
       KT=        204.08842000
 NUS. NUMB.       PEC. NUMB.  SUBCOOL. TERM.                     RUN.NO.
  8.45048290  170.27341000    1.07722590     ...      ...      204
  6.98303350  170.27341000    1.57919490     ...      ...      205
  6.40750860  170.27341000    1.86879230     ...      ...      206
  5.32496130  170.27341000    2.93064970     ...      ...      207
  5.02658020  170.27341000    3.85736160     ...      ...      208
  4.94138380  170.27341000    4.51378250     ...      ...      209
  4.75986340  170.27341000    5.17020340     ...      ...      210
 11.43902600  255.54461000    1.09653240     ...      ...      215
  7.95532290  255.54461000    1.84948580     ...      ...      216
  6.86341580  255.54461000    2.48660030     ...      ...      217
  6.16257390  255.54461000    3.29747320     ...      ...      218
  5.81452150  255.54461000    3.99250710     ...      ...      219
  5.50368240  255.54461000    4.86129950     ...      ...      220
  5.35220500  255.54461000    5.63355940     ...      ...      221
 14.67455600  340.68132000    1.00000000     ...      ...      226
 12.28028600  340.68132000    1.38612990     ...      ...      227
  9.11427490  340.68132000    2.08116380     ...      ...      228
  8.15823190  340.68132000    2.89203670     ...      ...      229
  6.78271620  340.68132000    4.28210450     ...      ...      230
  5.86244810  340.68132000    5.73009180     ...      ...      231
  5.51596780  340.68132000    6.52165820     ...      ...      232
  5.12803120  340.68132000    7.96964550     ...      ...      233
 17.15492700  425.81802000    1.00000000     ...      ...      237
 14.58168800  425.81802000    1.34751690     ...      ...      238
 13.19609800  425.81802000    1.59850140     ...      ...      239
 11.08873600  425.81802000    2.04255080     ...      ...      240
  9.65674740  425.81802000    2.67966520     ...      ...      241
  8.55230960  425.81802000    3.76082910     ...      ...      242
  7.38313320  425.81802000    4.76476700     ...      ...      243
  6.45207430  425.81802000    6.05830230     ...      ...      244
  5.91549210  425.81802000    7.29391810     ...      ...      245
  5.55492870  425.81802000    8.93497040     ...      ...      246
  5.07189120  425.81802000   10.30573100     ...      ...      247
 19.23264900  511.08923000    1.00000000     ...      ...      249
 17.95047200  511.08923000    1.09653240     ...      ...      250
 15.98329700  511.08923000    1.38612990     ...      ...      251
 12.72851600  511.08923000    1.90740530     ...      ...      252
```

```
 11.74611400   511.08923000     2.46729380     ...     ...     253
 10.11659500   511.08923000     3.22024720     ...     ...     254
  8.53741990   511.08923000     4.45586300     ...     ...     255
  7.57649800   511.08923000     5.47910740     ...     ...     256
  6.60441890   511.08923000     6.63749720     ...     ...     257
  6.08755160   511.08923000     8.68398600     ...     ...     258
  5.51234940   511.08923000    10.61463500     ...     ...     259


1.00 WT. PERCENT   WATER - ETHYLENE GLYCOL

XAM= .034    YAM= .005    KC=     1.15330570
      KT=        223.19283000
 NUS. NUMB.      PEC. NUMB.  SUBCOOL. TERM.                    RUN.NO.
 12.04776100   217.18504000     1.00000000     ...     ...     001
 10.92445500   217.18504000     1.13715290     ...     ...     002
  7.78836300   217.18504000     1.75563510     ...     ...     003
  6.54126940   217.18504000     2.26543000     ...     ...     004
  5.05320810   217.18504000     3.24490910     ...     ...     005
  4.97075450   217.18504000     3.47781030     ...     ...     006
 14.88541800   325.94911000      .98706110     ...     ...     009
 10.86342400   325.94911000     1.64436000     ...     ...     010
  9.66293740   325.94911000     1.99241800     ...     ...     011
  8.24836390   325.94911000     2.49444950     ...     ...     012
  6.57429160   325.94911000     3.47004690     ...     ...     013
 17.01193000   434.54163000     1.01164500     ...     ...     017
 14.89731800   434.54163000     1.27818750     ...     ...     018
 13.37489600   434.54163000     1.56931410     ...     ...     019
 10.47273400   434.54163000     2.34306370     ...     ...     020
  9.07013530   434.54163000     2.89814500     ...     ...     021
  7.41500170   434.54163000     3.83621940     ...     ...     022
  6.46649260   434.54163000     4.56338880     ...     ...     023
  6.03819970   434.54163000     5.23233300     ...     ...     024
 15.67912200   542.61950000     1.58484080     ...     ...     029
 13.24655800   542.61950000     2.05452500     ...     ...     030
 10.56258000   542.61950000     2.89814500     ...     ...     031
  8.45677050   542.61950000     3.85304010     ...     ...     032
  7.19968350   542.61950000     4.74582810     ...     ...     033
  6.42673760   542.61950000     5.54804350     ...     ...     034
 21.62408800   651.89823000     1.00000000     ...     ...     038
 20.55468800   651.89823000     1.09962990     ...     ...     039
 18.21494000   651.89823000     1.35840910     ...     ...     040
 15.61153700   651.89823000     1.79574580     ...     ...     041
 13.68847300   651.89823000     2.28225060     ...     ...     042
 12.20116300   651.89823000     2.82827460     ...     ...     043
  9.58193120   651.89823000     3.86597900     ...     ...     044
  8.21659830   651.89823000     4.76523660     ...     ...     045
  7.16606610   651.89823000     5.63344060     ...     ...     046
  6.56485130   651.89823000     6.40848390     ...     ...     047
  6.34363730   651.89823000     6.95192000     ...     ...     048
  5.96526580   651.89823000     7.76707480     ...     ...     049
```

```
29.80 WT. PERCENT   WATER - ETHYLENE GLYCOL

 XAM= .594    YAM= .032    KC=    25.31688000
        KT=         261.13123000
  NUS. NUMB.        PEC. NUMB.  SUBCOOL. TERM.                        RUN.NO.
    8.38160860     225.11540000     1.00000000     ...        ...       173
    7.60553440     225.11540000     1.32269540     ...        ...       174
    6.82224000     225.11540000     1.77446890     ...        ...       175
    6.05750510     225.11540000     2.61347700     ...        ...       176
    5.38974880     225.11540000     4.17532280     ...        ...       177
   10.27287700     337.85092000     1.00000000     ...        ...       179
    9.11793890     337.85092000     1.56794390     ...        ...       180
    7.74337560     337.85092000     2.34241280     ...        ...       181
    6.81828210     337.85092000     3.28468350     ...        ...       182
    6.31529390     337.85092000     4.52383380     ...        ...       183
    5.58308590     337.85092000     5.85333890     ...        ...       184
    5.43538530     337.85092000     6.61490020     ...        ...       185
    5.33194360     337.85092000     6.87305640     ...        ...       186
   11.67218900     450.40861000     1.03872340     ...        ...       187
   10.40154500     450.40861000     1.59375950     ...        ...       188
    9.06977980     450.40861000     2.30368940     ...        ...       189
    8.02463000     450.40861000     3.33631470     ...        ...       190
    7.23346940     450.40861000     4.56255730     ...        ...       191
    6.43982830     450.40861000     6.33092820     ...        ...       192
   12.96807400     562.96632000     1.00000000     ...        ...       193
   11.61845500     562.96632000     1.59375950     ...        ...       194
   10.81127900     562.96632000     2.04553300     ...        ...       195
    8.60193930     562.96632000     3.98170560     ...        ...       196
    8.02399670     562.96632000     4.83362140     ...        ...       197
    7.32575990     562.96632000     6.25348130     ...        ...       198
    6.96792110     562.96632000     6.89887210     ...        ...       199
   14.30099000     675.70184000     1.00000000     ...        ...       200
   13.17035600     675.70184000     1.50340480     ...        ...       201
   12.13332000     675.70184000     2.01971740     ...        ...       202
   10.79461700     675.70184000     3.41376160     ...        ...       203
    8.95890510     675.70184000     4.78199010     ...        ...       204
    8.47830390     675.70184000     5.63390610     ...        ...       205
    7.90221400     675.70184000     6.47291420     ...        ...       206


57.40 WT. PERCENT   WATER - ETHYLENE GLYCOL

 XAM= .823    YAM= .033    KC=   106.38296000
        KT=         227.57872000
  NUS. NUMB.        PEC. NUMB.  SUBCOOL. TERM.                        RUN.NO.
    8.39776500     204.76363000     1.16362690     ...        ...       257
    7.60924260     204.76363000     1.63814490     ...        ...       258
    6.38097940     204.76363000     2.47264210     ...        ...       259
    5.74740710     204.76363000     3.71620670     ...        ...       260
    5.51281900     204.76363000     5.18884890     ...        ...       261
   11.20937000     307.30719000     1.01636260     ...        ...       265
    8.53485390     307.30719000     1.99812400     ...        ...       266
```

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   7.03015370  307.30719000   3.06169900    ...    ...   267
   6.11164170  307.30719000   4.56706660    ...    ...   268
   5.73687130  307.30719000   5.58155350    ...    ...   269
   5.35778270  307.30719000   7.44690030    ...    ...   270
  11.58149200  409.68901000   1.19635220    ...    ...   273
  11.02999200  409.68901000   1.49088070    ...    ...   274
   9.23879680  409.68901000   2.22720180    ...    ...   275
   7.89006750  409.68901000   3.33986480    ...    ...   276
   6.68622180  409.68901000   4.92704590    ...    ...   277
   6.75586990  409.68901000   5.22157430    ...    ...   278
   5.96106210  409.68901000   7.05419580    ...    ...   279
   5.46849540  409.68901000   9.03408140    ...    ...   280
  13.24575800  512.07083000   1.00000000    ...    ...   283
  12.62679700  512.07083000   1.42542990    ...    ...   284
  10.52779700  512.07083000   2.22720180    ...    ...   285
   9.08789690  512.07083000   3.22532600    ...    ...   286
   7.69108560  512.07083000   4.92704590    ...    ...   287
   6.84662460  512.07083000   6.43241350    ...    ...   288
   6.23569560  512.07083000   7.79051680    ...    ...   289
  14.47877000  614.61439000   1.13090150    ...    ...   295
  11.80792800  614.61439000   2.19447630    ...    ...   296
  10.01001400  614.61439000   3.33986480    ...    ...   297
   8.54985370  614.61439000   4.79614430    ...    ...   298
   7.51911370  614.61439000   6.18697310    ...    ...   299
   6.60090410  614.61439000   8.26503490    ...    ...   300
   5.99121510  614.61439000  10.27764600    ...    ...   301
   5.75723890  614.61439000  10.91579000    ...    ...   302
   5.67662380  614.61439000  11.58666000    ...    ...   303
   5.61762920  614.61439000  12.61751000    ...    ...   304
   5.49702450  614.61439000  14.41740600    ...    ...   305


38.90 WT. PERCENT   WATER - ACETIC ACID

 XAM= .680    YAM= .780    KC=      1.05915420
         KT=            262.92500000
  NUS. NUMB.         PEC. NUMB.   SUBCOOL. TERM.
                                                            RUN.NO.
  15.62121300  240.65370000   1.00000000    ...    ...   148
   8.76851130  240.65370000   2.39059440    ...    ...   149
   6.47708830  240.65370000   3.73584350    ...    ...   150
   5.38818660  240.65370000   5.09620760    ...    ...   151
  19.03503800  374.56585000   1.00000000    ...    ...   154
  12.41770700  374.56585000   2.22432770    ...    ...   155
  10.71602100  374.56585000   2.84404920    ...    ...   156
   8.61108880  374.56585000   3.90211020    ...    ...   157
   6.88887120  374.56585000   5.45897140    ...    ...   158
   5.88074340  374.56585000   7.37859640    ...    ...   159
  20.42774100  481.30741000   1.00000000    ...    ...   162
  13.04508300  481.30741000   2.55686120    ...    ...   163
   9.63173230  481.30741000   4.09860720    ...    ...   164
   7.42085580  481.30741000   6.26007480    ...    ...   165
   6.51111880  481.30741000   7.90762690    ...    ...   166
   6.01593650  481.30741000   9.58540940    ...    ...   167
```

```
  23.41748500   615.41363000      1.00000000      ...      ...      169
  18.07509300   615.41363000      1.90690940      ...      ...      170
  11.82524700   615.41363000      4.00791630      ...      ...      171
   8.18201240   615.41363000      7.04606290      ...      ...      172
   7.45101800   615.41363000      8.02854820      ...      ...      173
   6.91957700   615.41363000      9.14706980      ...      ...      174
   6.29635690   615.41363000     11.08181000      ...      ...      175
  26.87010300   775.72005000      1.00000000      ...      ...      176
  18.98616300   775.72005000      2.37547930      ...      ...      177
  15.52340100   775.72005000      3.34284940      ...      ...      178
  11.07584600   775.72005000      5.80662000      ...      ...      180
   9.27559280   775.72005000      7.49951770      ...      ...      180
   7.90505660   775.72005000      9.58540940      ...      ...      181


12.25 WT. PERCENT   ACETONE - WATER

      KT=         366.65756000
 XAM= .041    YAM= .027    KC=      1.00748530
  NUS. NUMB.      PEC. NUMB.  SUBCOOL. TERM.                          RUN.NO.
   5.37797650     76.39045500     1.00000000      ...      ...      001
   7.87175790    137.28139000      .99519000      ...      ...      002
  10.36107500    213.67185000     1.00000000      ...      ...      003
  12.03915900    274.56279000     1.00000000      ...      ...      004
  14.44401200    351.06396000     1.00000000      ...      ...      005
  16.09835300    442.51109000     1.00000000      ...      ...      006


70.40 WT. PERCENT   ACETONE - WATER

 XAM= .424    YAM= .031    KC=      6.05652540
      KT=         933.47204000
  NUS. NUMB.      PEC. NUMB.  SUBCOOL. TERM.                          RUN.NO.
  12.53733000    105.02983000     1.00000000      ...      ...      025
  17.38295800    188.74927000      .99581700      ...      ...      026
  22.05180400    293.77911000     1.00000000      ...      ...      027
  25.24479300    377.49855000     1.00000000      ...      ...      028
  28.92595100    482.68060000      .99163400      ...      ...      029
  32.25626400    608.41198000     1.00000000      ...      ...      030
```

TABLE G-4 VERIFICATION OF PROPOSED CORRELATION USING RUNS OF TABLE G-3

27.50 WT. PERCENT WATER - GLYCERINE

NUS EXPER.	NUS CALC.	PERCENT ERROR
10.346065000	11.218785000	7.779095500
9.457766800	10.283561000	8.030243600
7.738172800	8.306752600	6.844790300
6.593795400	6.894201300	4.357370500
5.640475600	5.934725200	4.958099800
5.335150800	5.444881100	2.015292800
5.061183600	5.065765600	.090450296
4.967209400	4.874246700	-1.907221800
13.071795000	14.223358000	8.096280700
11.959302000	12.719875000	5.979406200
9.624780800	10.085301000	4.566259300
7.657863700	7.900875900	3.075762700
6.871481800	7.163944100	4.082420100
6.122954300	6.357117900	3.683486800
5.576262000	5.737695400	2.813558200
5.214167200	5.194640300	-.375904750
15.849218000	16.901725000	6.227216400
14.170783000	14.543900000	2.565453500
11.564058000	12.022336000	3.811888100
9.094065500	9.212429800	1.284832500
8.419673800	8.499484100	.939001690
7.434037600	7.592280400	2.084259100
6.631424700	6.846098100	3.135704400
6.213524000	6.294891300	1.292592600
5.746556700	5.759676000	.227778430
17.738916000	19.322196000	8.194099600
16.148531000	16.943792000	4.693524300
14.105644000	14.397180000	2.024952100
10.790492000	10.753999000	-.339343530
10.006568000	9.826166800	-1.835934600
8.802770300	8.791302700	-.130442550
7.779192300	7.899871600	1.527610900
7.171629200	7.221496000	.690532820
6.423969600	6.527817200	1.590847200
6.074025700	6.244290500	2.726727700

5.875877000	5.955427100	1.335758100
19.053803000	21.558582000	11.618477000
17.731458000	18.904897000	6.207063700
16.387382000	17.311728000	5.339420700
12.774709000	12.626306000	-1.175347700
12.326473000	11.861491000	-3.920097300

```
     10.351513000            10.059606000             -2.901773600
      9.036771700             9.024390900              -.137192630
      7.657863700             7.867037700              2.658866100
      7.026090200             7.231876900              2.845550300
      6.170002400             6.617232900              6.758572700
      6.210908300             6.536777400              4.985164400
      5.979651200             6.271698700              4.656593200


86.00 WT. PERCENT   WATER - GLYCERINE

   NUS   EXPER.          NUS     CALC.         PERCENT   ERROR
      8.450482900             8.652499800              2.334780700
      6.983033500             7.146232600              2.283708200
      6.407508600             6.569228800              2.461783600
      5.324961300             5.245816000             -1.508731900
      5.026580200             4.572458200             -9.931681800
      4.941383800             4.226926400            -16.902527000
      4.759863400             3.949491800            -20.518376000
     11.439026000            10.941480000             -4.547337200
      7.955322900             8.424832400              5.572923900
      6.863415800             7.265806800              5.538146100
      6.162573900             6.309517600              2.328921300
      5.814521500             5.734082300             -1.402826000
      5.503682400             5.196497100             -5.911391700
      5.352205000             4.827201100            -10.875948000
     14.674556000            13.614942000             -7.782728700
     12.280286000            11.564155000             -6.192679000
      9.114274900             9.437624400              3.426174700
      8.158231900             8.005971200             -1.901839200
      6.782716200             6.579414700             -3.089963300
      5.862448100             5.687679600             -3.072755700
      5.515967800             5.331345500             -3.462958800
      5.128031200             4.822769000             -6.329604400
     17.154927000            15.564716000            -10.216768000
     14.581688000            13.408312000             -8.751109000
     13.196098000            12.310758000             -7.191596100
     11.088736000            10.890673000             -1.818647900
      9.656747400             9.508260300             -1.561664200
      8.552309600             8.026004900             -6.557492800
      7.383133200             7.130509100             -3.542862000
      6.452074300             6.323620500             -2.031333100
      5.915492100             5.763162400             -2.643161600
      5.554928700             5.207086300             -6.680173500
      5.071891200             4.848438800             -4.608749500
     19.232649000            17.366196000            -10.747621000
     17.950472000            16.584183000             -8.238506500
     15.983297000            14.750366000             -8.358646800
     12.728516000            12.574283000             -1.226574900
     11.746114000            11.055906000             -6.242889500
     10.116595000             9.677433300             -4.538000700
      8.537419900             8.226950900             -3.773803900
```

```
       7.576498000          7.419077700          -2.121831100
       6.604418900          6.740662600           2.021221100
       6.087551600          5.893120000          -3.299298100
       5.512349400          5.330308200          -3.415209600

1.00 WT. PERCENT   WATER - ETHYLENE GLYCOL

    NUS  EXPER.          NUS    CALC.          PERCENT  ERROR
      12.047761000         10.701040000         -12.584954000
      10.924455000         10.034982000          -8.863722900
       7.788363000          8.076234900           3.564431900
       6.541269400          7.109691600           7.995033100
       5.053208100          5.940525000          14.936674000
       4.970754500          5.738165900          13.373809000
      14.885418000         13.741870000          -8.321633000
      10.863424000         10.646809000          -2.034553200
       9.662937400          9.672252900            .096311584
       8.248363900          8.644315300           4.580483000
       6.574291600          7.329093000          10.298701000
      17.011930000         16.129941000          -5.468023700
      14.897318000         14.349919000          -3.814648700
      13.374896000         12.950661000          -3.275778700
      10.472734000         10.598752000           1.188989000
       9.070135300          9.529866800           4.824112500
       7.415001700          8.283141400          10.480802000
       6.466492600          7.594569400          14.853729000
       6.038199700          7.092497900          14.864977000
      15.679122000         14.724225000          -6.485210500
      13.246558000         12.932111000          -2.431521000
      10.562580000         10.888429000           2.992617200
       8.456770500          9.443292300          10.446799000
       7.199683500          8.508819300          15.385634000
       6.426737600          7.869648600          18.335138000
      21.624088000         20.693594000          -4.496531600
      20.554688000         19.733890000          -4.159331900
      18.214940000         17.754999000          -2.590487300
      15.611537000         15.442354000          -1.095577700
      13.688473000         13.697908000            .068879131
      12.201163000         12.304819000            .842401660
       9.581931200         10.524613000           8.956927900
       8.216598300          9.479683100          13.324124000
       7.166066100          8.718648000          17.807599000
       6.564851300          8.174444900          19.690555000
       6.343637300          7.848443700          19.173309000
       5.965265800          7.425185800          19.661730000
```

```
29.80 WT. PERCENT   WATER - ETHYLENE GLYCOL

    NUS   EXPER.            NUS     CALC.          PERCENT   ERROR
      8.381608600          10.432473000            19.658474000
      7.605534400           9.071046900            16.155935000
      6.822240000           7.831647900            12.888831000
      6.057505100           6.453244100             6.132404000
      5.389748800           5.105547900            -5.566511200
     10.272877000          13.310035000            22.818557000
      9.117938900          10.629530000            14.220685000
      7.743375600           8.696561700            10.960493000
      6.818282100           7.343997100             7.158431400
      6.315293900           6.257862800             -.917743030
      5.583085900           5.501453700            -1.483829600
      5.435385300           5.175086300            -5.029848400
      5.331943600           5.076966600            -5.022231100
     11.672189000          15.518805000            24.786805000
     10.401545000          12.528434000            16.976495000
      9.069779800          10.420682000            12.963671000
      8.024630000           8.659136800             7.327598700
      7.233469400           7.404642100             2.311694400
      6.439828300           6.286000900            -2.447142500
     12.968074000          18.081462000            28.279726000
     11.618455000          14.322612000            18.880334000
     10.811279000          12.642421000            14.484108000
      8.601939300           9.061477300             5.071336400
      8.023996700           8.224270100             2.435151000
      7.325759900           7.230571700            -1.316468500
      6.967921100           6.884058500            -1.218214500
     14.300990000          20.174244000            29.112634000
     13.170356000          16.453543000            19.954285000
     12.133320000          14.195541000            14.527244000
     10.794617000          10.918945000             1.138644800
      8.958905100           9.225567100             2.890467200
      8.478303900           8.499484100              .249193940
      7.902214000           7.929528000              .344459340


57.40 WT. PERCENT   WATER - ETHYLENE GLYCOL

    NUS   EXPER.            NUS     CALC.          PERCENT   ERROR
      8.397765000           8.269749300            -1.547999700
      7.609242600           6.969846200            -9.173751900
      6.380979400           5.673077400           -12.478271000
      5.747407100           4.627530900           -24.200296000
      5.512819000           3.916190900           -40.769925000
     11.209370000          11.289293000              .707953980
      8.534853900           8.051556300            -6.002536400
      7.030153700           6.504439800            -8.082385500
      6.111641700           5.325648800           -14.758631000
      5.736871300           4.817410300           -19.086209000
      5.357782700           4.170646800           -28.464071000
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   11.581492000         12.364897000          6.335717900
   11.029992000         11.076403000           .419007860
    9.238796800          9.062339200         -1.947152800
    7.890067500          7.400408200         -6.616652500


    6.686221800          6.092940600         -9.737189900
    6.755869900          5.918607200        -14.146279000
    5.961062100          5.092093800        -17.065048000
    5.468495400          4.499644000        -21.531734000
   13.245758000         15.461278000         14.329475000
   12.626797000         12.950084000          2.496408500
   10.527797000         10.360140000         -1.618288900
    9.087896900          8.609118100         -5.561299000
    7.691085600          6.965499500        -10.416856000
    6.846624600          6.096189500        -12.309904000
    6.235695600          5.539396000        -12.569955000
   14.478770000         16.221716000         10.744522000
   11.807928000         11.645114000         -1.398131400
   10.010014000          9.439407600         -6.044945000
    8.549853700          7.877042100         -8.541424400
    7.519113700          6.935376900         -8.416799900
    6.600904100          6.000493800        -10.006014000
    5.991215100          5.380993200        -11.340320000
    5.757238900          5.221336400        -10.263703000
    5.676623800          5.067923500        -12.010842000
    5.617629200          4.856488200        -15.672662000
    5.497024500          4.543240200        -20.993481000

38.90 WT. PERCENT   WATER - ACETIC ACID

  NUS   EXPER.        NUS     CALC.        PERCENT   ERROR
   15.621213000         12.126822000        -28.815389000
    8.768511300          7.843215300        -11.797406000
    6.477088300          6.274118600         -3.235031200
    5.388186600          5.371847000          -.304170980
   19.035038000         15.813516000        -20.371952000
   12.417707000         10.603007000        -17.114956000
   10.716021000          9.376915700        -14.280879000
    8.611088800          8.005320200         -7.567075200
    6.888871200          6.763199900         -1.782915700
    5.880743400          5.821591200         -1.016083000
   20.427741000         18.380822000        -11.136166000
   13.045083000         11.495065000        -13.484203000
    9.631732300          9.079184400         -6.085875900
    7.420855800          7.346411300         -1.013345100
    6.511118800          6.536451200           .387555860
    6.015936500          5.936898900         -1.331294300
   23.417485000         21.301581000         -9.933084300
   18.075093000         15.425768000        -17.174671000
   11.825247000         10.640267000        -11.136750000
    8.182012400          8.024880900         -1.958053900
    7.451018000          7.517846400           .888930100
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    6.919577000          7.043214400          1.755411500
    6.296356900          6.398918700          1.602798900
   26.870103000         24.475661000         -9.782951300
   18.986163000         15.880306000        -19.557916000
   15.523401000         13.386777000        -15.960705000
   11.075846000         10.157171000         -9.044595100
    9.275592800          8.937537600         -3.782419800
    7.905056600          7.905496000           .005558159

12.25 WT. PERCENT   ACETONE - WATER

     NUS  EXPER.         NUS    CALC.         PERCENT  ERROR



    5.377976500          6.901001100         22.069618000
    7.871757900          9.833379800         19.948603000
   10.361075000         12.791962000         19.003238000
   12.039159000         14.868723000         19.030309000
   14.444012000         17.231398000         16.176203000
   16.098353000         19.798995000         18.691059000

70.40 WT. PERCENT   ACETONE - WATER

     NUS  EXPER.         NUS    CALC.         PERCENT  ERROR
   17.382958000         15.819974000         -9.879813900
   12.537330000         11.105850000        -12.889423000
   22.051804000         20.586229000         -7.119200800
   25.244798000         23.928390000         -5.501448200
   28.925951000         27.847386000         -3.873128300
   32.256264000         31.862727000         -1.235101400
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