NUCLEATE POOL

A
submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
CHEMICAL ENGINEERING
(Equipment & Plant Design)

by
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CERTIFICATE

Certified that the thesis entitled 'NUCLEATE POOL BOILING OF LIQUIDS' which is being submitted by Sri Satish Chandra Gupta in partial fulfilment of the requirements for the award of the degree of MASTER OF ENGINEERING IN CHEMICAL ENGINEERING (Equipment and Plant Design) of 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 he has worked for a period of about seven months for preparing this thesis at this University.

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ABSTRACT

This thesis presents an experimental investigation on pool boiling of water and ethyl acetate at atmospheric and subatmospheric pressures. The test section was a horizontal stainless steel tube 25.5 mm O.D. and 173 mm long. The tube was internally heated by means of an electric heater made of nichrome wire wound on a porcelain rod. Calibrated copper constantan thermocouples were used for measuring wall and liquid temperatures. The energy input to the test section was measured by a wattmeter. The liquid temperature was varied to cover the regions of natural convection through subcooled to saturated boiling. The heatflux ranged from 12.44×10^3 to 43.54×10^3 Kcal/hr.m^2. The pressures used were 725, 625 and 470 mm of Hg.

The experimental data for distilled water during both natural convection and saturated boiling at 1 atmosphere pressure were found to compare well with the results of earlier workers. The values of heat transfer coefficient for both the systems, water and ethyl acetate, were found to increase with the increase in pressure during boiling. The increase in degree of subcooling was found to decrease the value of heat transfer coefficient. The value of heat transfer coefficient increases with the increase in heat flux.

All the experimental data points for water and ethyl acetate were correlated by the following equation with a maximum error of ± 20 percent .

$$Nu_B = 2.17x10^{-4}(Pe_B)^{0.65}\ (K_p)^{0.65}\ (Pr)^{-0.45}(K'_{sub})^{-0.5}$$

The physical properties used in various dimensionless groups were taken at the saturation temperature of the liquid corresponding to the system pressure.

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NOMENCLATURES

A	Surface area	m^2
C	Specific heat	Kcal/kg.^oC
d	Diameter of test section	m
d_b	Bubble diamter, $\sqrt{\frac{\sigma}{\rho_L-\rho_V}}$	m
f	Frequency of bubble formation	1/hr
g	Acceleration due to gravity	m/sec^2
h	Heat transfer coefficient	Kcal/hr.m^2.^oC
J	Mechanical equivalent of heat	Kg.m/Kcal
k	Thermal conductivity	Kcal/hr.m.^oC
M	Molecular weight	-
P	Pressure	Kg/m^2
q	Heat flux	Kcal/hr.m^2
R	Curvature radius of bubble	m
t	Temperature	^oC
T	Absolute temperature,(t+273)	^oK
Δt	Temperature difference, (t_W-t_L)	^oC
Δt_{sub}	Degree of subcooling, (t_S-t_L)	^oC

GREEK LETTERS

α	Thermal diffusivity, $k/\rho C$	m^2/hr
β	Coefficient of volumetric expansion	1/^oC
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

SUBSCRIPTS

atm.	Atmosphere
B	Boiling
c	Critical
Expt.	Experimental
L	Liquid
Pred.	Predicted
S	Saturation
SW	Saturation temperature of water
V	Vapor
W	Wall

DIMENSIONLESS GROUPS

Ar	Archimedes number	$= \frac{g}{\nu^2}\left(\frac{\sigma}{\rho_L-\rho_V}\right)^{3/2}\left(1-\frac{\rho_V}{\rho_L}\right)$
Bu	Buoyancy number	$= \left(\frac{\rho_L-\rho_V}{\rho_L}\right)$
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_P	Criterion for pressure in boiling	$= \frac{P}{\sqrt{\sigma(\rho_L-\rho_V)}}$
K_{sub}	Criterion for sub-cooling term	$= 1+\sqrt{\frac{\rho_L}{\rho_V}}\;\frac{\Delta t_{sub}}{t_s}$

K'_{sub}	Modified criterion for subcooling term	$= 1+\sqrt{\frac{\rho_L}{\rho_V}}\left(\frac{P}{P_{atm.}}\right)^2\frac{\Delta t_{sub}}{t_s}$
K_t	Criterion for bubble break off frequency	$= \frac{J(\rho_V\lambda)^2}{Ct_s\,\rho_L\sqrt{\sigma(\rho_L-\rho_V)}} = \frac{1}{K_u}$
K_q	Criterion for number of active starting points	$= \frac{J\,q\,\rho_V\lambda}{t_s k(\rho_L-\rho_V)}$
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	$= \frac{q}{\lambda\mu}\sqrt{\frac{\sigma}{\rho_L-\rho_V}}$

CHAPTER 1

INTRODUCTION

Boiling is a familiar but an extremely complicated phenomenon. With the development of the nuclear reactors, rocket nozzles and space crafts great interest has developed in the boiling process as a method of increasing heat transfer rates at modest temperature difference. Critical heat flux density in nucleate boiling is of great importance for determining the highest safe thermal limit of nuclear reactors. Liquid agitation, pressure, liquid properties and degree of subcooling are some of the factors to affect the peak heat flux. Modern engineering requires a knowledge of the heat transfer rates to boiling liquids over a wide range of pressures upto the critical point. Yet, even for water, the lack of systematic experimental data is keenly felt when designing heat exchangers and other heat transfer equipments.

Amongst many others the boiling of industrial solvents is an important area of boiling heat transfer. In some of the process industries organic liquids boil at pressures usually lower than 1 atmosphere. Therefore it is considered important to obtain experimental data on the boiling of organic liquids at subatmospheric pressures.

The present investigation, therefore, was undertaken with the following objectives:

1. To collect experimental data on saturated and subcooled boiling of water and ethyl acetate at atmospheric and subatmospheric pressures.
2. To develop, as a result of data analysis, a generalized correlation to predict heat transfer coefficient for both subcooled and saturated boiling of water and ethyl acetate.
3. To check the validity of the correlations available in the literature to the liquids investigated.

CHAPTER 2

LITERATURE REVIEW

There does not seem to be a correlation which alone can correlate the experimental data for nucleate pool boiling. The reason is due to the difference in surface characteristics of heat transfer surfaces besides many other factors.

A number of workers have obtained the correlations of the following general form:

$$h_B = c\,(t_W - t_S)^n \tag{2.1}$$

The value of constant c in Eq.(2.1) depends on the thermodynamic and transport properties of the liquid and its vapor. The value of n generally varies from 1 to 3. The values of c and n are also affected by the microroughness and wettability of the heat transfer surface. It may be mentioned that the value of n has been found to vary from 1 to 25 if the surface is polished [1,2].

Rohsenow [3] undertook a serious study of heat transfer in nucleate pool boiling. The results obtained by him were correlated by the following equation:

$$Nu_B = \frac{1}{C_{sf}}\,(Re_B)^{0.67}\,(Pr)^{-0.7} \tag{2.2}$$

The value of C_{sf} depends upon solid liquid combination and is given in Table 2.1.

Table 2.1 Values of C_{sf} in Eq. 2.2 [4]

Liquid-Surface combination	C_{sf}	Liquid-surface combination	C_{sf}
Water - nickel	0.006	Benzene-chromium	0.010
Water - platinum	0.013	n pentane-chromium	0.015
Water - Copper	0.013	Ethanol-chromium	0.0027
Water - brass	0.006	Isopropanol-copper	0.0025
Water - stainless steel	0.014	35 percent K_2CO_3-copper	0.0054
CCl_4 - copper	0.013	n butanol-copper	0.0030

In his study Rohsenow [3] was of the opinion that the movement of bubbles at the instant of breaking away from the surface is of prime importance and the agitation caused by bubble release breaks the stagnant liquid film and thus provides an excellent convective heat transfer in boiling.

Sciance et al [5] modified Eq.(2.2) for correlating most of the saturated hydrocarbons namely methane, propane and n-butane. Ethane data could not be fitted in the modified correlation which is given below:

$$\frac{q\sqrt{\frac{\sigma}{(\rho_L-\rho_V)}}}{\lambda\mu} = c\left[\frac{C\wedge t}{\lambda}\left(\frac{T_R}{Pr}\right)^{1.18}\right]^n \qquad (2.3)$$

where T_R is reduced temperature.

The values of constant c and exponent n are given in table 2.2

Table 2.2 Values of c and n in Eq.(2.3)

Liquid	$c \times 10^{-5}$	n
Methane	3.25	2.89
Propane	5.77	2.60
n-Butane	2.33	2.84

Forster and Zuber [6] studied the mechanism of boiling heat transfer. They held the opinion that the bubble boundary layer moves even when the bubble may remain attached to the heat transfer surface. The bubble boundary movement has been reported to have a velocity of about 10 ft/sec. It is important to note that the mechanism proposed by Forster and Zuber is very much different than the mechanism of Rohsenow. Based on this mechanism, the following correlation has been recommended by the authors [6]

$$Nu_B = 0.0015 \quad (Re_B)^{0.62} \, (Pr)^{0.333} \qquad (2.4)$$

Forster and Grief [7] also studied the mechanism of boiling heat transfer. They conclude that the high heat transfer rate in nucleate boiling can be explained by the mechanism of liquid vapor exchange. They recommended a correlation for computing the pool boiling heat flux, q for water at pressures ranging from 14.7 to 700 psia in the following form:

$$q = 4.3\times10^{-5} \frac{k_L t_S (\Delta P)^2}{(\lambda \rho_V)^{3/2} \sigma^{1/2}} \left[(C t_s \alpha_L)^{1/4} \left(\frac{\rho_L}{\mu_L}\right)^{5/8} (Pr)^{1/3} \right] \qquad (2.5)$$

However Eq.(2.5) is not as widely verified as the correlation recommended by Rohsenow.

Gilmour [8] recommended the following equation for the boiling of saturated liquids

$$\frac{h}{CG} = 0.001 \left(\frac{DG}{\mu}\right)^{-0.3} \left(\frac{C\mu}{k}\right)^{-0.6} \left(\frac{P^2}{\rho_L \sigma}\right)^{0.425} \ldots (2.6)$$

$$\text{where } G = \frac{q}{\lambda \rho_V} \rho_L$$

It may be pointed out that the experimental data of many other workers have been correlated satisfactorily by the Eq.(2.6).

Huber and Hoehme [9] measured the heat transfer coefficient for pool boiling of saturated benzene on a 3/8 in O.D. tube. The pressure range was from 13.5 to 488.5 psia. They found that the heat transfer data were in best agreement with the predicted values from the equations of Rohsenow [3], Gilmour [8] and Levy [10].

Minchenko and Firsova [11] studied the pool boiling for water over a wide range of pressure from 0.05 to 2.02 Kg/cm^2. Three test sections of 11, 12 and 13 mm

O.D. and 400, 427 and 435 mm length respectively were used. They found that the value of heat transfer coefficient decreases with an increase in pressure. Data were correlated in the following form:

$$Nu_B = 0.55\ (K_p\ Re_B)^{0.7} \qquad (2.7)$$

Kruzhilin [12] suggested the following dimensionless equation:

$$Nu_B = 0.082\,(Pr^{-})^{0.45}\,(K_q\ )^{0.70}(K_u)^{1/3} \qquad (2.8)$$

The Eq.(2.8) can be reduced to a simple and convenient form for the saturated boiling of water at pressures ranging from 0.2 to 100 atmospheres.

$$h = 3q^{0.7}\ p^{0.15} \qquad (2.9)$$

Veneraki [13] conducted experiments for obtaining heat transfer data for pool boiling of water. The pressure was varied from 1 to 0.1 atm. and the heat flux from $4x10^3$ to $55x10^3$ Kcal/hr.m^2. Heat transfer surface was a brass pipe. He also studied the effect of orientation of pipe on the value of heat transfer coefficient. The following equation correlated the heat transfer data.

$$h = c\ q^n p^m \qquad (2.10)$$

The value of m in Eq. (2.10) depends on the liquid and on the orientation of the heating surface. For vertical pipe m was 0.37 and for horizontal 0.17. At 1 atmosphere pressure, heat transfer coefficient for a vertical pipe was higher than for a horizontal pipe by 20 percent at high heat flux. At low heat flux this value was 40 percent. Corresponding to 0.1 atm. pressure, the value of heat transfer coefficient for vertical pipe was 25-30 percent higher than for horizontal pipe.

Cryder and Gilliland [14] studied nucleate boiling of water and five organic liquids on the outside of a 1.04 in O.D. brass tube at 1 atmosphere pressure. The following equation correlates their experimental data.

$$h = (\text{constant}) \frac{(\Delta t)^{2.39} k_L^{2.97} C_L^{0.43} \rho_L^{3.1} d^{2.1}}{\sigma^{1.65} \mu_L^{3.45}} \qquad (2.11)$$

Jakob and Linke [15] studied nucleate boiling at low bubble populations for water and carbon tetrachloride. They used flat vertical and horizontal chromium surfaces. Their experimental data were found to be correlated by the following equation:

$$h = (\text{constant})\, k_L^{0.5} \left(\frac{\rho_L}{\sigma}\right)^{2.5} \left(\frac{\Delta t}{\rho_V \lambda C_1}\right)^4 \qquad (2.12)$$

where $C_1 = f.d_b$

Cryder and Finalborgo [16] obtained experimental data for the boiling of liquids outside single tubes with variable pressure at low fluxes. The equation for calculating heat transfer coefficient recommended by them was in the following form:

$$\log \frac{h_{atm.}}{h} = 0.15\ (t_{s_{atm.}} - t_s) \qquad (2.13)$$

Jakob [17] recommended the following equations for calculating the heat transfer coefficient at pressures other than atmospheric.

For subatmospheric pressures,

$$h = h_{atm.} \left(\frac{P}{P_{atm.}}\right)^{1/4} \qquad (2.14)$$

For super atmospheric pressures upto 226 psia.,

$$h = h_{atm.} \left(\frac{P}{P_{atm.}}\right)^{1/6} \qquad (2.15)$$

Bonilla and Perry [18] recommended the following correlation for water and numerous organic liquids on horizontal plates.

$$h = (\text{constant}) \frac{(\Delta t)^{2.7} k_L^{1.85} C_L^{1.85} \sigma^{0.85} \mu_{Latm.}^{3.7} \gamma_{Latm.}^{2.7}}{\mu_L^{1.85} \rho_L^{0.85} \sigma_{atm.}^{2.7} \rho_{Vatm.}^{2.7} \lambda_{atm.}^{2.7} C_1^{2.7}} \qquad (2.16)$$

where $C_1 = f.d_b$

Chi-Fang Lin et al [19] conducted boiling heat transfer studies for both pure liquids and the binary liquid mixtures. Heat flux ranged from 4000 to 40,000 Kcal/hr.m^2 and pressure from 200 to 760 mm of Hg. The correlation recommended for the boiling of pure liquids is given in the following general form:

$$h = cp^{n}q^{m} \tag{2.17}$$

The values of constant c and exponents n and m in Eq.(2.17) are given in Table 2.3.

Table 2.3 Values of c, n, and m in Eq.(2.17)

Liquid	c	n	m
Water	4.0	0.2	0.69
Benzene	4.5	0.2	0.6
Toluene	3.1	0.7	0.6

Borishanskii et al [20] have investigated the effect of pressure on boiling heat transfer. They used stainless-steel tubes of different diameters; 6.94 mm, 4.99 mm and 6 mm. Pressures were changed over a wide range from 1.03 to 100 Kg/cm^2. Experimental results showed that the relation relating the effect of pressure on boiling heat transfer rate is complicated.

Fujishiro et al [21] studied the pool boiling at subatmospheric pressure and its relation to nucleate boiling. The boiling curve with pressure as a parameter was discontinuous at the starting point of boiling with 160 mm Hg. absolute as a boundary. Below 50 mm Hg.

absolute incipient boiling was immediately followed by film boiling. The superheat necessary for incipient boiling increased with decrease in pressure.

Kozitskii [22] obtained data for the boiling of n-butane on horizontal tubes. The stainless steel tubes of different roughnesses were used. The tubes were of $6.0\mathrm{x}10^{-3}$m in O.D. and 0.18m in length. The heat transfer coefficient was described by the following equation:

$$h=4.2\ T_s^{0.80}\ \frac{P_c^{0.3}}{T_c^{0.85} M^{0.15}}\ F\left(\frac{P}{P_c}\right) q^{0.7} \qquad (2.18)$$

$F\left(\frac{P}{P_c}\right)$ is a function which characterizes the effect of pressure on heat transfer coefficient. They recommend that the value of the function depends on the value of the ratio of $\left(\frac{P}{P_c}\right)$ as given below:

For $0.02 \leq \frac{P}{P_c} \leq 0.127,\ F\left(\frac{P}{P_c}\right) = 2.14\left(\frac{P}{P_c}\right)^{0.3}$

and $0.127 \leq \frac{P}{P_c} \leq 0.80\ ;\ F\left(\frac{P}{P_c}\right) = 2.6\left(\frac{P}{P_c}\right)^{0.4}$

Recently much significance has attached to surface boiling because the bubbles form and collapse on and near the heating surface. This causes additional turbulence to the normal and the heat transfer coefficient between surface and liquid increases. Subcooled boiling is used profitably in the cooling of rocket motors, nuclear boiler tubes etc.

Ellion [1] seems to have conducted an excellent work about the growth and collapse of bubbles at a heating surface in a degassed subcooled liquid.

Tolubinskii and Kostanchuk [23] carried out the investigation of heat transfer during the subcooled boiling of water over a pressure range of 1 to 10 bars. The heat flux was changed from 0.14 to 1.2 MW/m^2. The liquid was subcooled upto 20°C. The experimental data were correlated by the following equation:

$$Nu_B = 75\ K^{0.7}\ Pr^{-0.2} \tag{2.19}$$

$$\text{where } K = \frac{q}{\lambda \rho_v d_b f}$$

Alam [24] studied the surface boiling of three pure liquids; water, acetic acid and acetone and four binary mixtures at 1 atmosphere pressure. The test sections were made of brass. The heat flux range was 6.9×10^3 to 39.97×10^3 Kcal/hr.m^2. He correlated the experimental data by the following equation with a standard deviation of 20.54 per cent and an average deviation of 20.16 per cent.

$$Nu_B = 0.084\ (Pe_B)^{0.6} (K_{sub})^{-0.5}\ (K_t)^{0.37} \tag{2.20}$$

Besides the above correlations there exists other correlations for computing heat transfer coefficient. These correlations are given in Table 2.4. These equations have been used for comparing the experimental data of the present study.

Table 2.4 Correlations for Pool Boiling of Liquids

	AUTHORS		CORRELATIONS
a	Rohsenow	[3]	$Nu_B = \frac{1}{C_{sf}} (Re_B)^{0.67} (Pr)^{-0.7}$
b	McNelly	[25]	$Nu_B = 0.225 (\frac{qd}{\mu \lambda})^{0.69} (\frac{pd}{\sigma})^{0.31} (Bu)^{0.33} (Pr)^{0.69}$
c	Kichigin and Tobilevich	[26]	$Nu_B = 1.04 x 10^{-4} (Pe_B)^{0.7} (K_P)^{0.7} (Ar)^{0.125}$
d	Kutateladze	[26]	$Nu_B = 7.0 x 10^{-4} (Pe_B)^{0.7} (Pr)^{-0.35} (K_P)^{0.7}$
e	Borishanskii and Minchenko	[26]	$Nu_B = 8.7 x 10^{-4} (Pe_B)^{0.7} (K_P)^{0.7}$
f	Kruzhilin and Averin	[27]	$Nu_B = 0.082 (Pe_B)^{0.7} (Pr)^{-0.5} (K_t)^{0.377}$
g	Labuntsov	[28]	$Nu_B = 0.125 (Pe_B)^{0.65} (Pr)^{-0.32} (K_t)^{0.35}$
h	Rice and Calus	[29]	$Nu_B = E (Pe_B)^{0.7} (K_P)^{0.7} (\frac{T_{SW}}{T_S})^4$
i	Alam	[24]	$Nu_B = 0.084 (Pe_B)^{0.6} (K_{sub})^{-0.5} (K_t)^{0.37}$

CHAPTER 3

EXPERIMENTAL INVESTIGATION

3.1 EXPERIMENTAL SET UP

The experimental set up for obtaining experimental data on pool boiling of liquids has been shown in Fig.3.1. It consisted of a cylindrical vessel (5) which was made of stainless steel. The vessel was 381 mm long, 232 mm internal diameter and 1.5 mm thick. A liquid level indicator (10) was fitted to know the level of liquid in the vessel. Two diametrically opposite sight glasses (6) were provided to the vessel for visual observation of the bubbles' formation and their collapse on and near the heat transfer surface. An anxiliary heater (9) of 2 K.W. capacity was provided at the bottom of the vessel. This helped indeaerating the test liquid. The vessel body was thoroughly lagged with rockwool to reduce the heat losses.

A water-cooled condenser (3) was fitted beneath the top cover of the vessel and to condense the vapors which were generated during boiling. An external condenser (1) was put in series with the above condenser. It condensed the remaining vapors which could not be condensed by internal condenser. Cold water was used as the cooling medium.

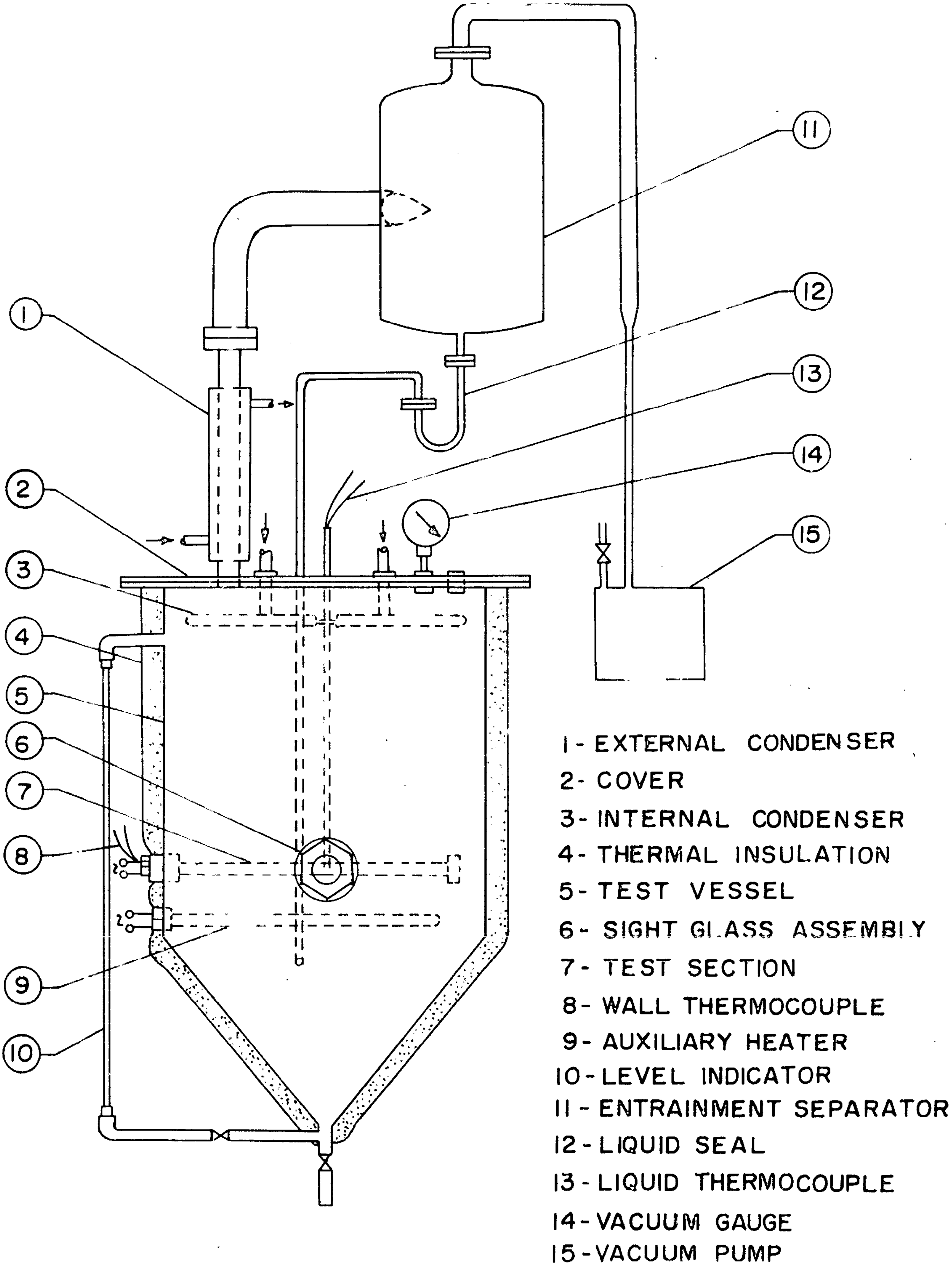

FIG. 3·1 SCHEMATIC DIAGRAM OF EXPERIMENTAL SET-UP.

An entrainment separator (11) was used, at the top of the vessel, for separating the noncondensable gas from the liquid. The separator had a tangential entry for separating the noncondensable gas from the entrained liquid. The separated liquid was returned back to the pool of the test liquid via liquid seal (12). A care was taken that the returned liquid did not disturb the vicinity of heat transfer surface. The test section was kept submerged in a liquid height of 100 mm. This was accomplished with an aim that the condensate drips, after joining the pool, did not disturb the liquid near the heating surface. Vacuum was created by a vacuum pump. It was measured by a vacuum gauge.

The test section has been shown in Fig.3.2. It was made of 304 stainless steel. It had 25.5 mm O.D., 18 mm I.D. and 173 mm length. A blind flange (8) was welded to the right and of the test section and the left end with a flange (3). The test section was kept in horizontal position by attaching the left end of it to the vessel wall (1). This arrangement is shown clearly in Fig.3.2. The right end of the test section remained floating in the pool of the liquid. A test heater was inserted in the test section. It was made of nichrome wire (26 gauge) uniformly wound on a poralain rod of 12 mm diameter. Mica sheet was used for electrical insulation between test surface and heater. The power to the heater was alternate current. It was regulated by an

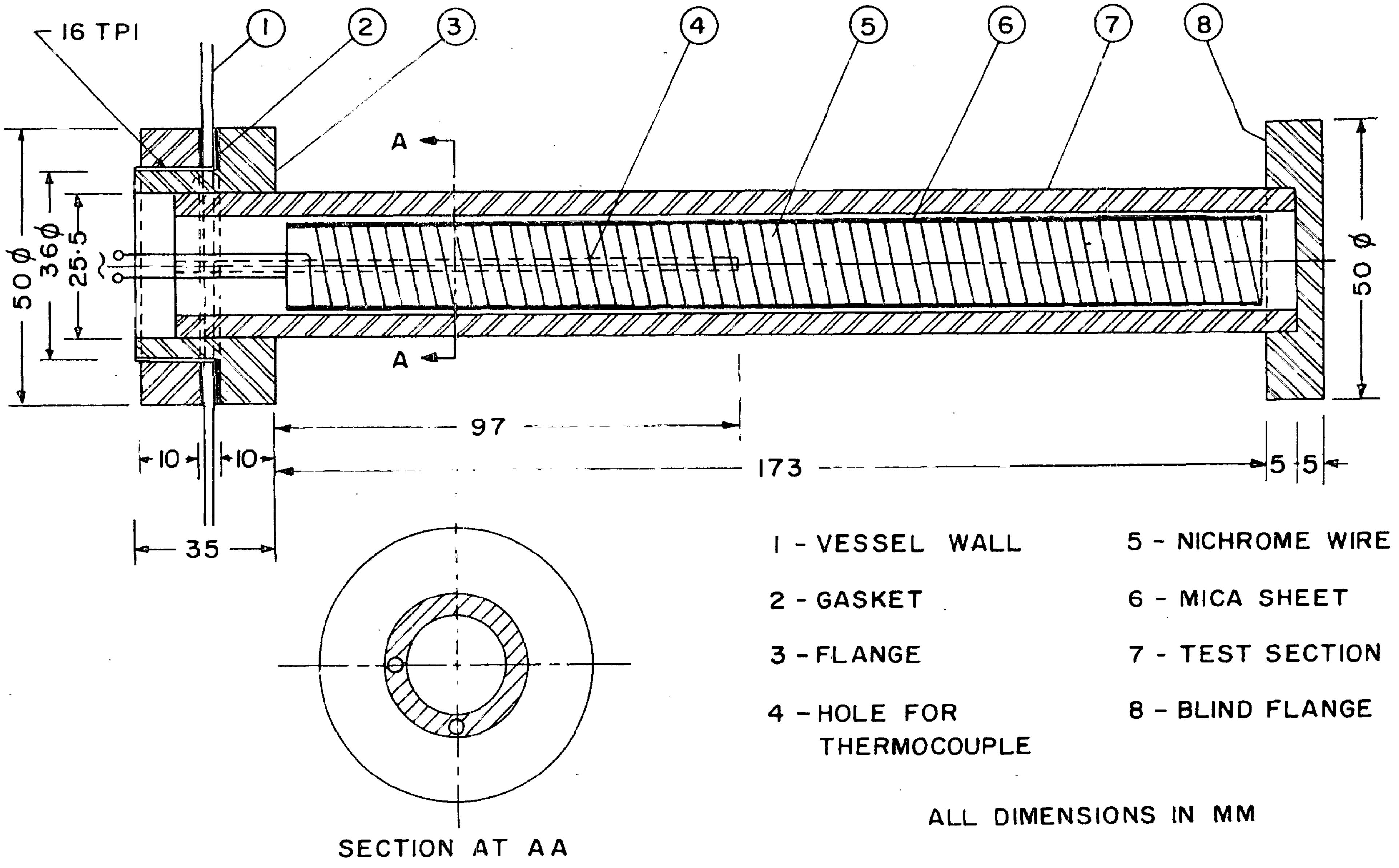

FIG. 3·2 TEST SECTION.

autotransformer and was measured by a calibrated wattmeter.

The test surface temperature was measured by means of calibrated copper-constantan thermocouples. It was measured at two positions, 90° apart as shown in Fig.3.2. To accommodate the thermocouples 2 holes of 2 mm bore were made in the wall thickness of the test surface upto a distance of 97 mm from the left end of the test section. The surface temperature was taken as arithmatic average of the thermocouple readings. The liquid temperature was also measured by a copper-constantan thermocouple. The position of the thermocouple was 30mm off the test section in a horizontal plane passing through the axis of the test surface. This distance was selected to be well beyond the boundary layer having temperature gradient based on the observation of Alam [24]. All the thermocouples were connected through cold junction to a potentiometer. The cold junctions were kept in a melting ice bath to obtain a reference temperature of 0°C. The e.m.f. of the thermocouples was measured by a potentiometer and a sensitive spot galvanometer. The measurements were made upto 0.01 mv with an accuracy of 0.01 per cent.

3.2 EXPERIMENTAL PROCEDURE

The thermocouples were calibrated against a standard mercury in glass thermometer of 0.1°C least count. The average reading of the thermocouple was 0.6°C less than the actual reading of the thermometer.

The test surface was stabilized till the experimental data were reproduced. It took a period of about 72 hours of aging and 12 hours of boiling. Before conducting the series of the experimental runs, the test liquid was boiled for a period of about an hour by auxiliary heater. This was done to remove the dissolved air from the liquid. The liquid temperatures were brought back to the desired value. The test surface was energized and the heat flux was adjusted. It took about 20 minutes for attaining steady state. The thermocouple and wattmeter readings were noted. It may be mentioned that no reading was taken just after switching off the auxiliary heater. It took about 10 minutes before the turbulence caused by the auxiliary heater subsided. The heat flux to the heat transfer surface was varied progressively by an autotransformer. The experimental data covered natural convection through surface boiling to saturated boiling. The data were taken for distilled water and ethyl acetate.

The experimental parameters were varied over a respective ranges as enlisted in Table 3.1.

Table 3.1 Expdrimental Parameters

Parameters	Water	Ethyl Acetate
Heat flux, $\frac{Kcal}{hr. m^2}$	12.44×10^3 to 43.54×10^3	12.44×10^3 to 43.54×10^3
Pressure, mm Hg	470,625 and 725	470,625 and 725
Liquid temperature, °C	60 to 98.7	49 to 71.85

CHAPTER 4

RESULTS AND DISCUSSION

Experimental data were obtained for the nucleate pool boiling of distilled water and ethyl acetate at pressures; 470 mm, 625 mm and 725 mm of Hg. The results of the present investigation have been represented in Figures 4.1 to 4.19. The study covers regions of natural convection through surface boiling to saturated boiling.

4.1 HEAT TRANSFER DATA FOR DISTILLED WATER AT ATMOSPHERIC PRESSURE

4.1.1 Natural Convection

The experimental data for natural convection have been compared with the predicted values of heat transfer coefficient in Fig.4.1. The plot shows an indiscernable scatter between experimental and predicted values. The maximum scatter is ± 10 per cent. The predicted values of heat transfer coefficient are calculated using the following equation [12]

$$Nu = c\ (Gr \times Pr)^n \qquad (4.1)$$

The values of c and n depend on the value of the product of Gr and Pr.

4.1.2 Pool Boiling

Fig. 4.2 shows a plot between heat transfer coefficient and heat flux for saturated boiling of water.

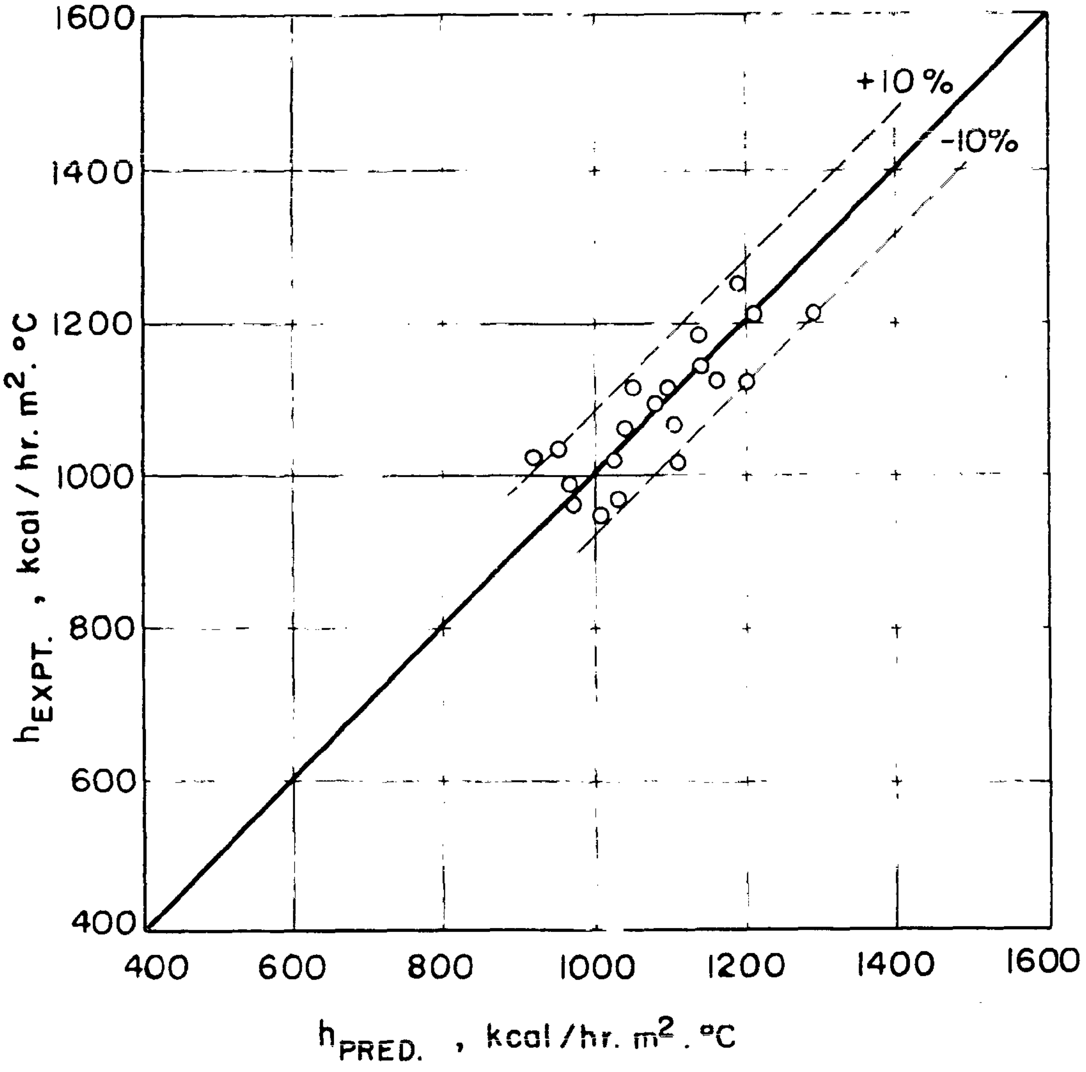

FIG. 4·1 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF h DURING NATURAL CONVECTION FOR WATER.

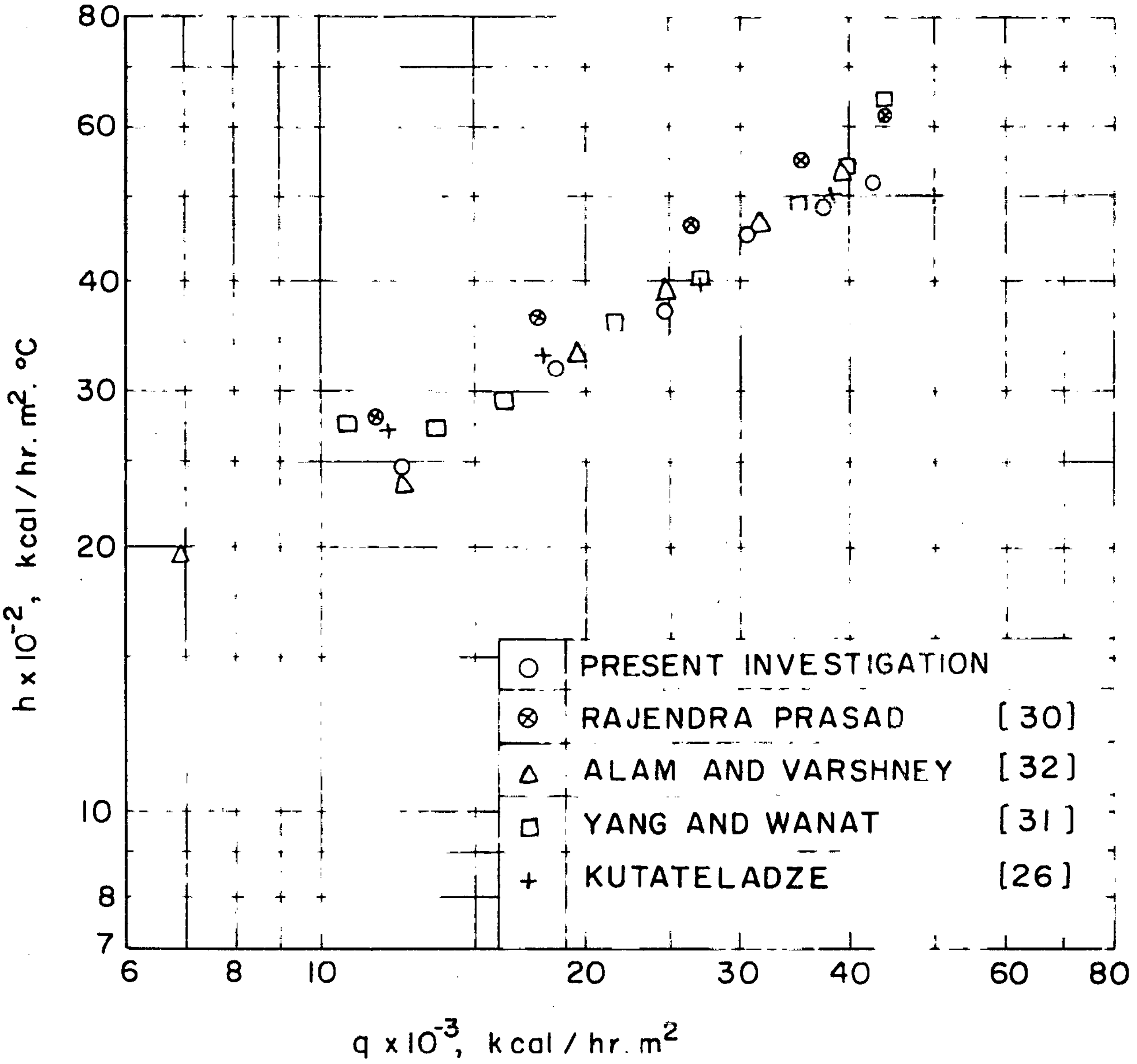

FIG. 4·2 h AS A FUNCTION OF q FOR WATER USING DATA OF THIS INVESTIGATION AND OF OTHERS.

The experimental data of other workers [32,26,30,31] for saturated boiling of water at 1 atmosphere pressure have also been plotted in Fig.4.2. From this plot it is clearly seen that there exists deviation amongst the data points of various workers. The deviation might be due to the difference in surface liquid combination and experimental error. The plot also shows that the data points of individual worker, if considered separately, can be represented well by a power law as given below:

$$h = cq^{0.7} \tag{4.2}$$

where c has different values for individual studies. This difference is due to different surface liquid combinations used by various workers.

4.2 EFFECT OF PRESSURE ON BOILING HEAT TRANSFER

Figs.4.3 and 4.4 have been drawn to show the variation of heat transfer coefficient with heat flux at pressures 725 mm, 625mm and 470 mm of Hg for water and ethyl acetate respectively. Both the figures are found to have the following common features:

a. The variation of heat transfer coefficient with heat flux can be represented by a power law, $h \propto q^n$. The value of n is 0.7 for water and 0.6 for ethyl acetate.

b. A decrease in pressure does not alter the above power law, but the lines start shifting to the

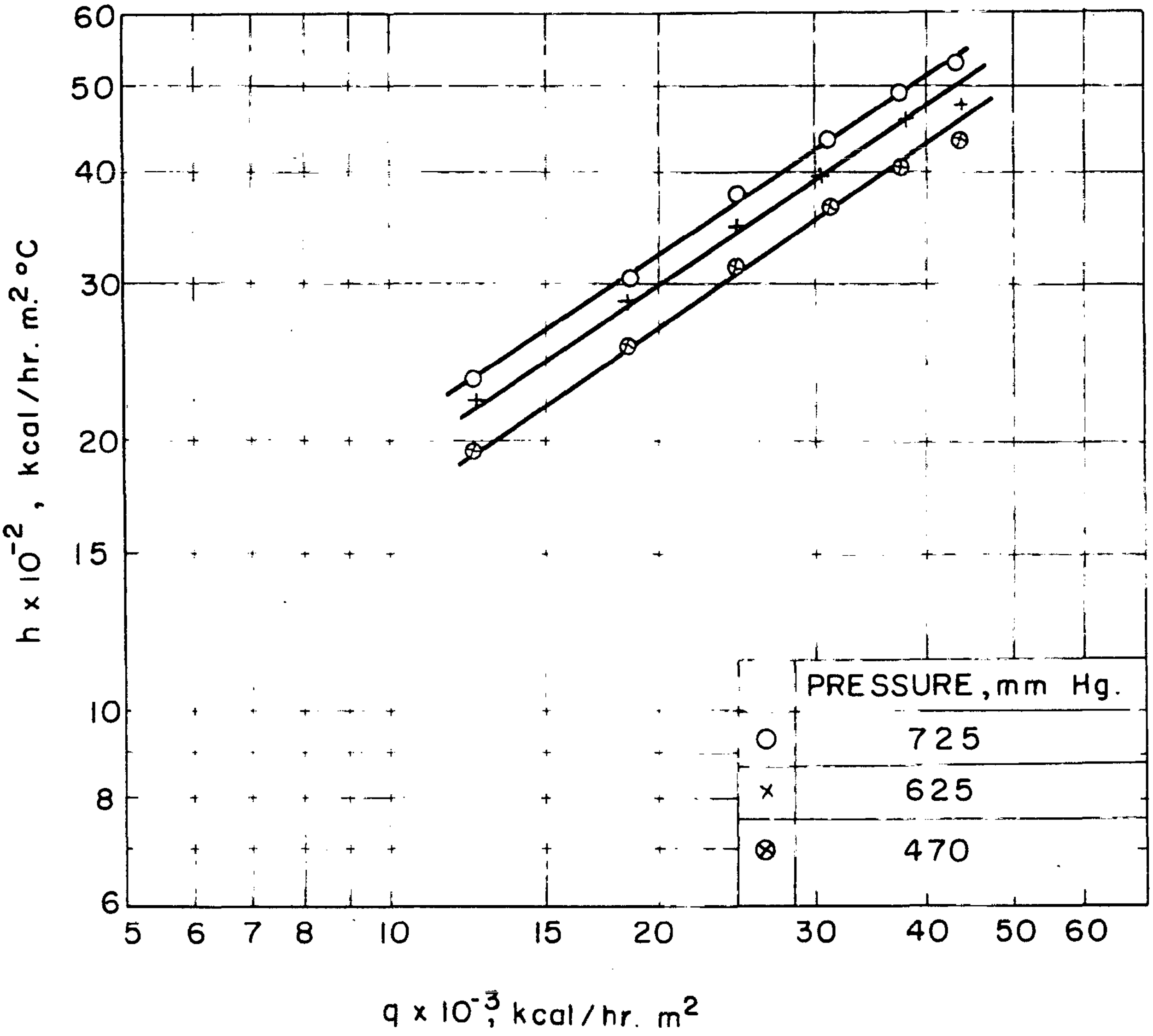

FIG. 4·3 VARIATION OF HEAT TRANSFER COEFFICIENT WITH HEAT FLUX FOR SATURATED BOILING OF WATER.

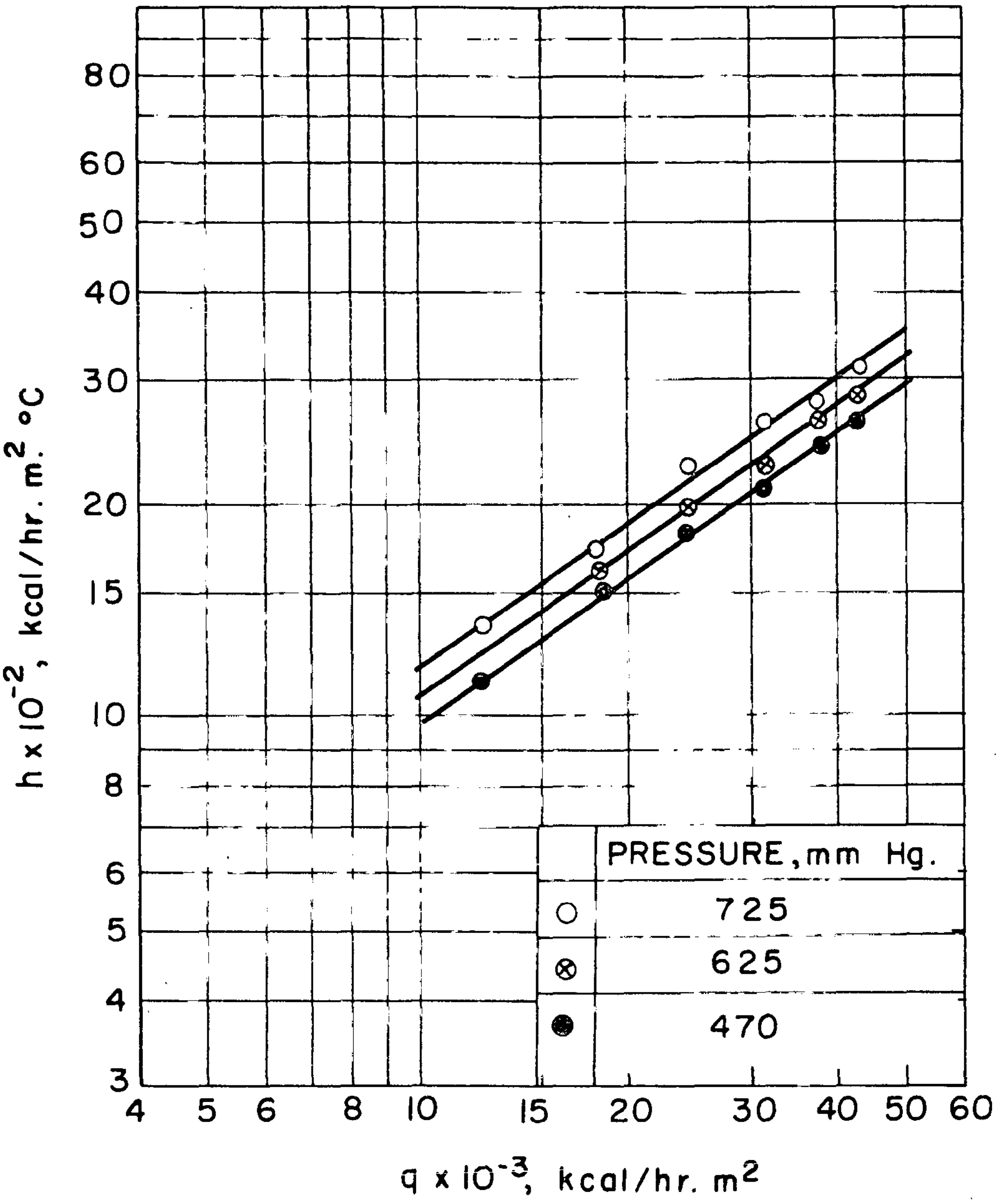

FIG. 4·4 VARIATION OF HEAT TRANSFER COEFFICIENT WITH HEAT FLUX FOR ETHYL ACETATE right, i.e. for a given value of heat flux heat transfer coefficient becomes smaller with the decrease in pressure.

The above two points can be reasoned out by considering the mechanism of boiling heat transfer. The increase in the value of heat transfer coefficient with the increase in heat flux can be attributed to the fact that number of favorite sites for bubble nucleation becomes greater due to increase in heat flux. This, inturn, leads to increased turbulence, and so does the heat transfer coefficient. The increase in heat transfer coefficient with the increase in pressure can be easily explained. An increase in pressure lowers the value of the surface tension of a liquid. Due to lowering of surface tension the minimum radius of curvature for nucleation of bubbles becomes smaller. Therefore at higher pressures a larger number of sites for bubble formation become active than at lower pressure.

The results of Figs. 4.3 and 4.4 suggest that heat transfer coefficient for saturated boiling can be plotted as a function of product of heat flux and pressure. The exponents of q and p were obtained by drawing suitable graphs for both the liquids. Figs. 4.5 and 4.6 represent such a plot. All the data points are found to be represented well by the following equation:

$$h = c\, q^n p^m \tag{4.3}$$

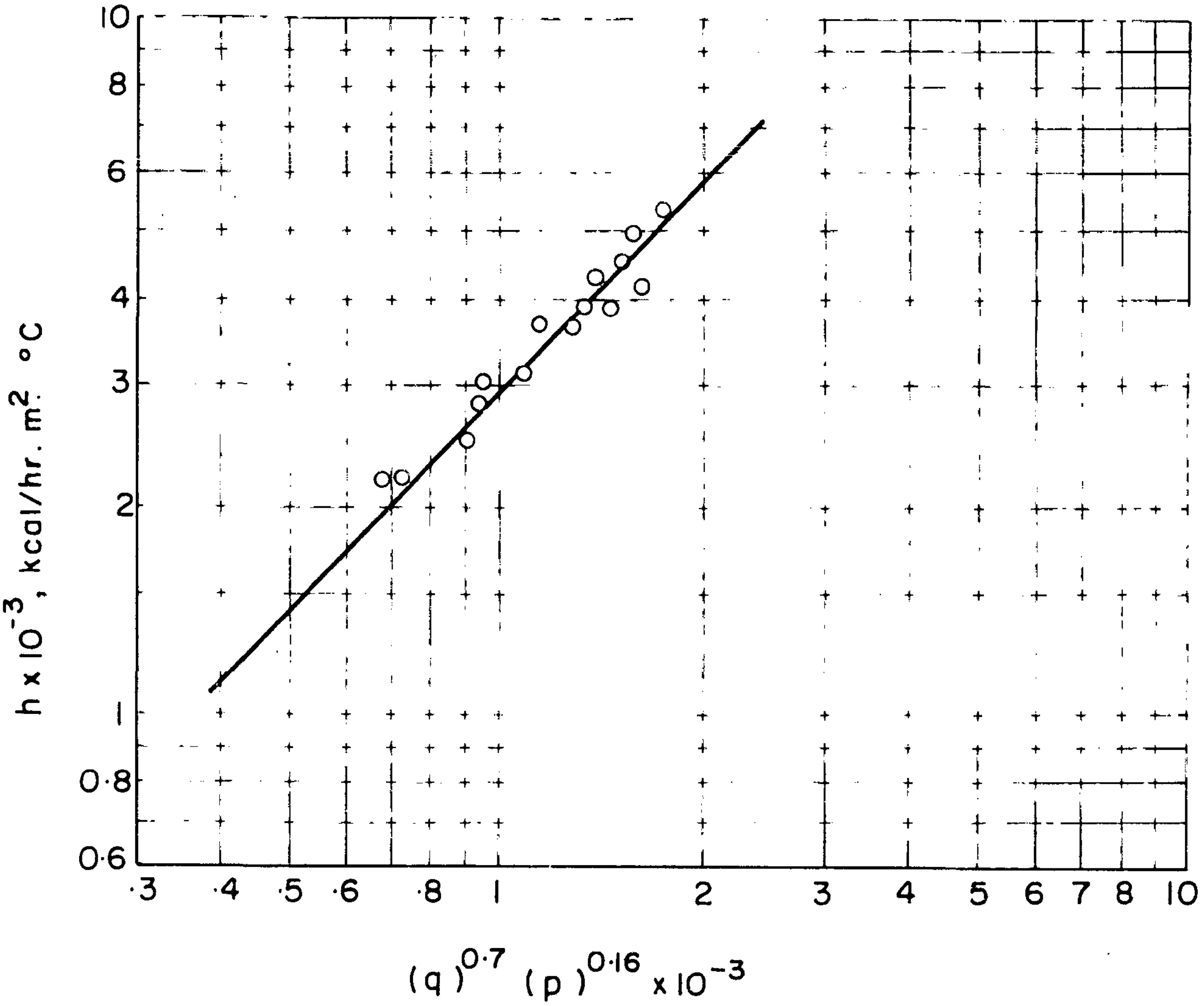

FIG. 4·5 h AS A FUNCTION OF $(q)^{0.7}(p)^{0.16}$ FOR SATURATED BOILING OF WATER.

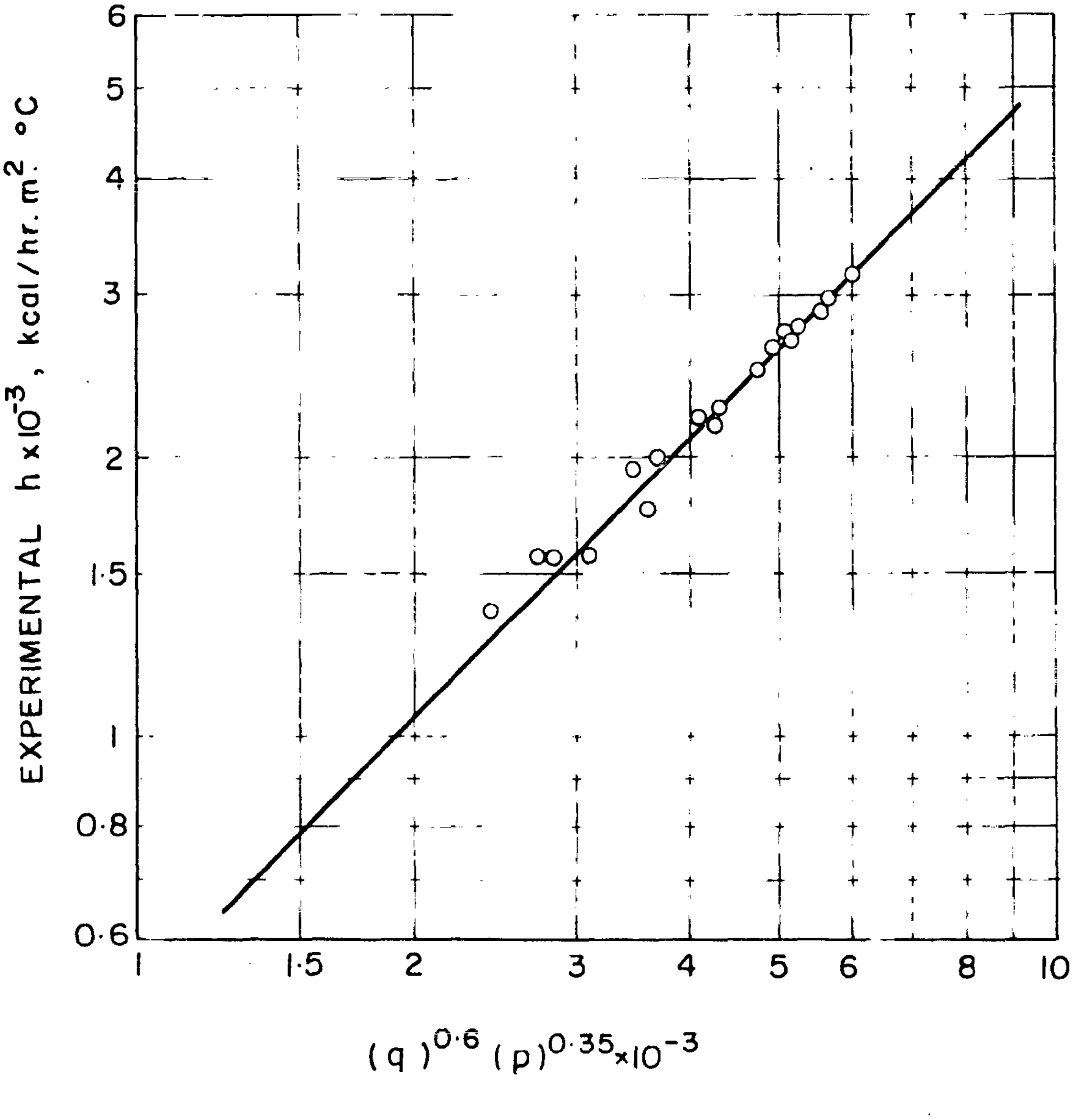

FIG. 4·6 h AS A FUNCTION OF $q^{0.6}p^{0.35}$ FOR SATURATED BOILING OF ETHYL ACETATE.

The values of constant c and exponents n and m in Eq.(4.3) are given in Table 4.1

Table 4.1 Values of c, n and m in Eq.(4.3)

System	c	n	m
Water	2.92	0.7	0.16
Ethyl acetate	5.25	0.6	0.35

Pressure p in Eq.(4.3) is in Kg/cm^2. The above equation is simple and convenient for computing heat transfer coefficient for saturated boiling of water and ethyl-acetate.

4.3 EFFECT OF DEGREE OF SUBCOOLING ON BOILING HEAT TRANSFER

Figs. 4.7 and 4.8 are the typical plots to show the effect of degree of subcooling on heat transfer coefficient for water at 625 mm of Hg and for ethyl acetate at 470 mm of Hg respectively. The degree of subcooling and heat transfer coefficient are expressed in their respective dimensionless forms, K'_{sub} and Nu_B, which have been defined in the nomenclature. From these figures the following points can be noted:

a. Nu_B decreases linearly with the increase in K'_{sub} which can be represented by the following relationship:

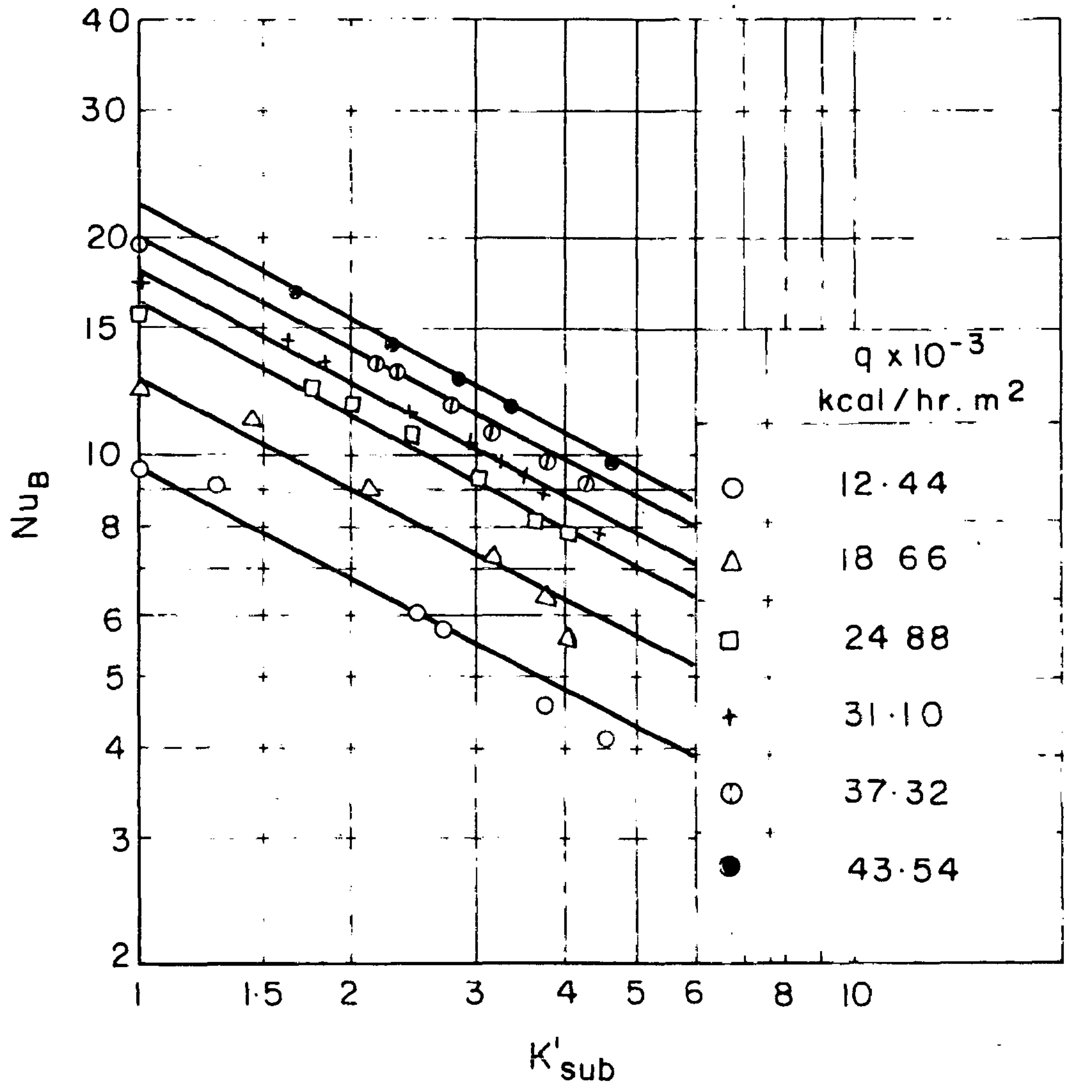

FIG. 4·7 VARIATION OF Nu_B WITH K'_{sub} FOR WATER AT 625 mm Hg.

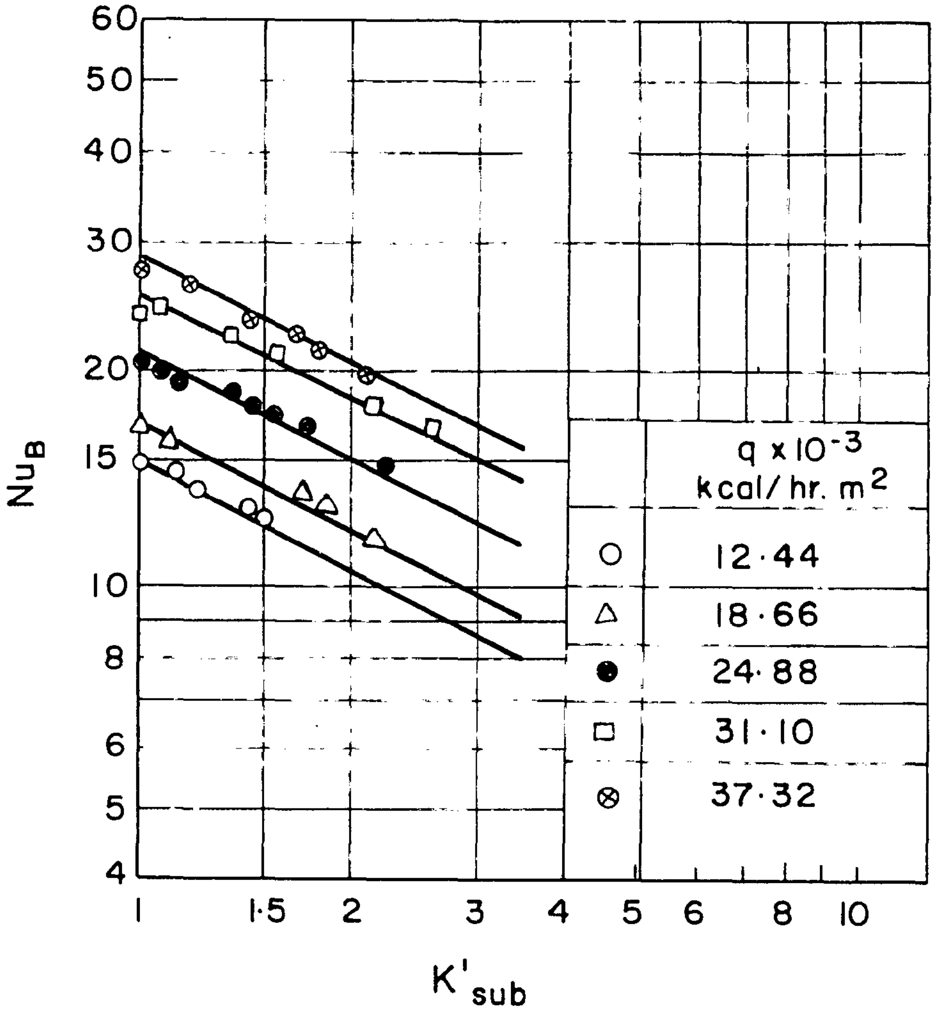

FIG. 4·8 VARIATION OF Nu_B WITH K'_{sub} FOR ETHYL ACETATE AT 470 mm Hg.

$$Nu_B = C_1 (K'_{sub})^{-0.5} \qquad (4.4)$$

The values of constant C_1 depends on the heat flux and the liquid. The negative value of exponent is reasonable because high degree of subcooling, or K'_{sub}, suppresses the size of the turbulence due to bubble formation. Therefore heat transfer coefficient or Nu_B decreases. It may be mentioned that the possibility of using the criterion for degree of subcooling as suggested by Alam and Varshney [32] was examined for the present investigation. It was found that the experimental data of this study at 1 atmosphere pressure can be well fitted with the criterion [32]. The data for subatmospheric pressures do not yield an expected trend therefore it was argued to modify the form of K_{sub} in the following form:

$$K'_{sub} = 1 + \sqrt{\frac{\rho_L}{\rho_V}} \left(\frac{P}{P_{atm.}}\right)^2 \frac{\Delta t_{sub}}{t_s}$$

At 1 atmosphere pressure K'_{sub} assumes the form of K_{sub}.

The effect of degree of subcooling on Nu_B is in accordance with the results of Jiji and Clark [33]

b. An increase in the value of heat flux shifts the curves to the right. This behaviour is for the reasons stated in section 4.2.

4.4 EFFECT OF PECLET NUMBER ON BOILING HEAT TRANSFER

Figs.4.9 and 4.10 show the variation of Nu_B with Pe_B for saturated boiling of water and ethyl acetate respectively. In these figures pressure has been taken as parameter. All the curves appear to belong to a family of parallel lines. Further it is clearly seen that the variation of Nu_B with Pe_B can be well fitted into the following equation:

$$Nu_B = C_2(Pe_B)^{0.65} \qquad (4.5)$$

The value of C_2 depends on the pressure and the liquid.

4.5 GENERAL CORRELATION

The effect of pressure is in confirmity with the mechanism of heat transfer which has been explained in detail in section 4.2.

From the theory of similarity for boiling heat transfer it is well known that pressure can be represented in the dimensionless form as below:

$$K_P = \frac{P}{\sqrt{\sigma(\rho_L - \rho_V)}}$$

The data points of Figs.4.9 and 4.10 have been plotted in Fig.4.11. $Nu_B/(Pe_B)^{0.65}$ is ordinate and K_P is abscissa. From the figure it is found that the experimental data of respective liquids can be represented by

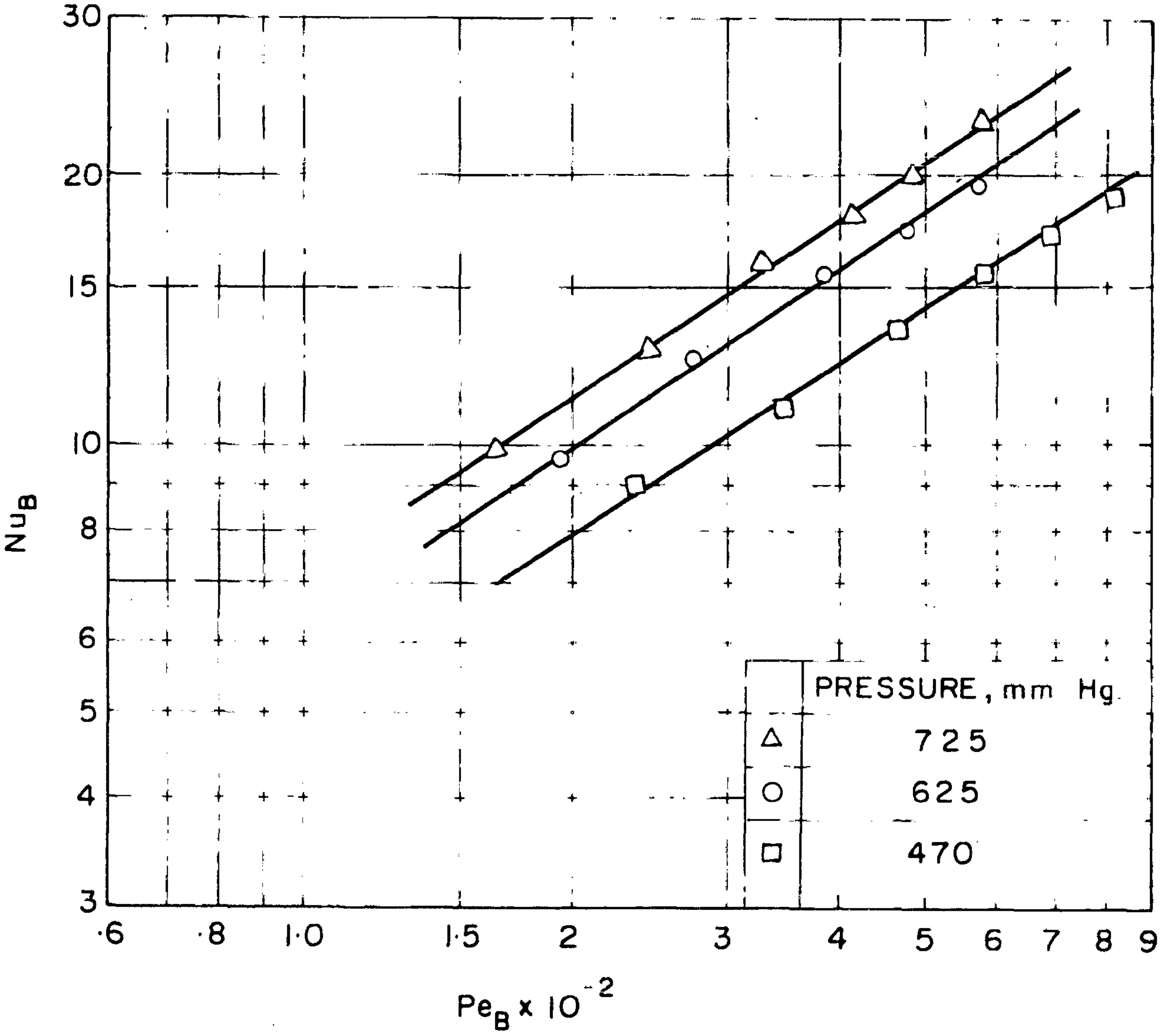

FIG. 4·9 VARIATION OF Nu_B WITH Pe_B FOR SATURATED BOILING OF WATER.

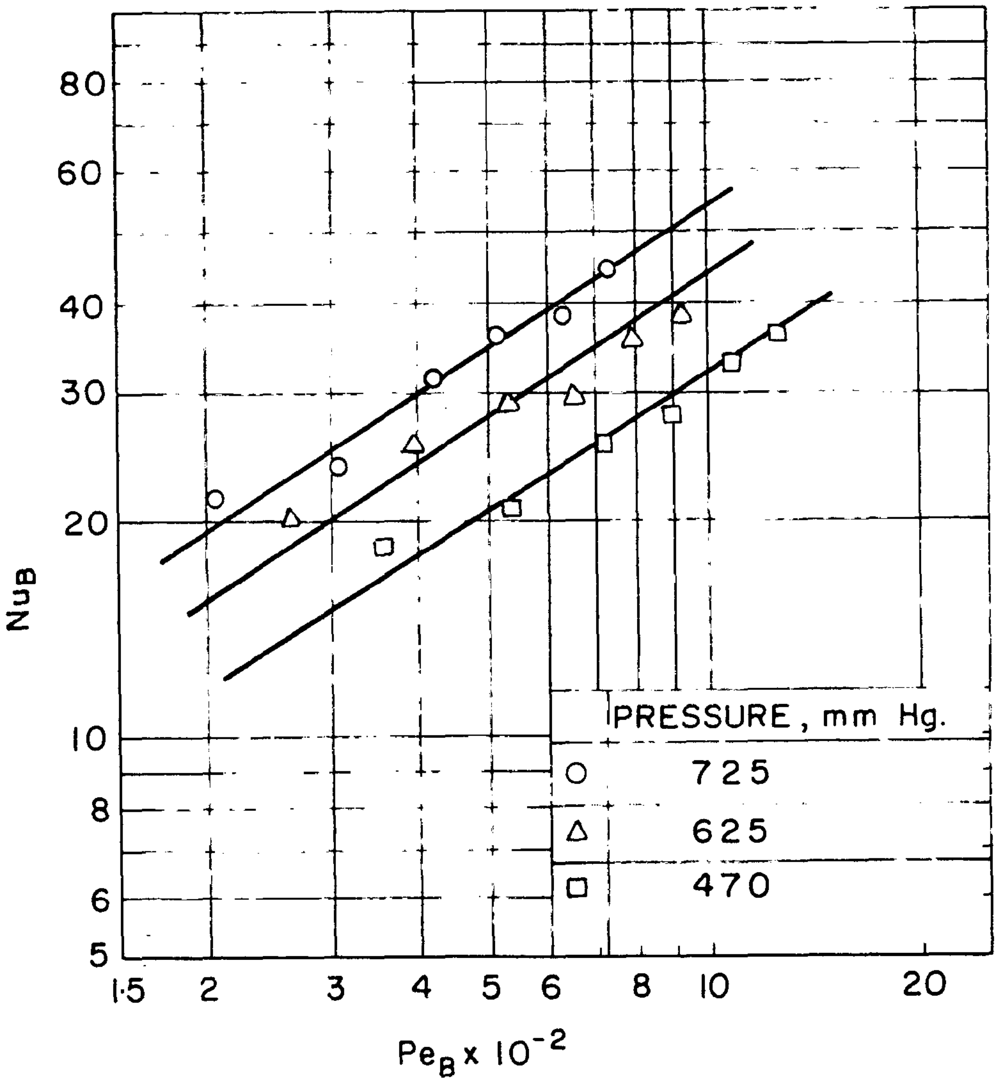

FIG. 4·10 VARIATION OF Nu_B WITH Pe_B FOR SATURATED BOILING OF ETHYL ACETATE.

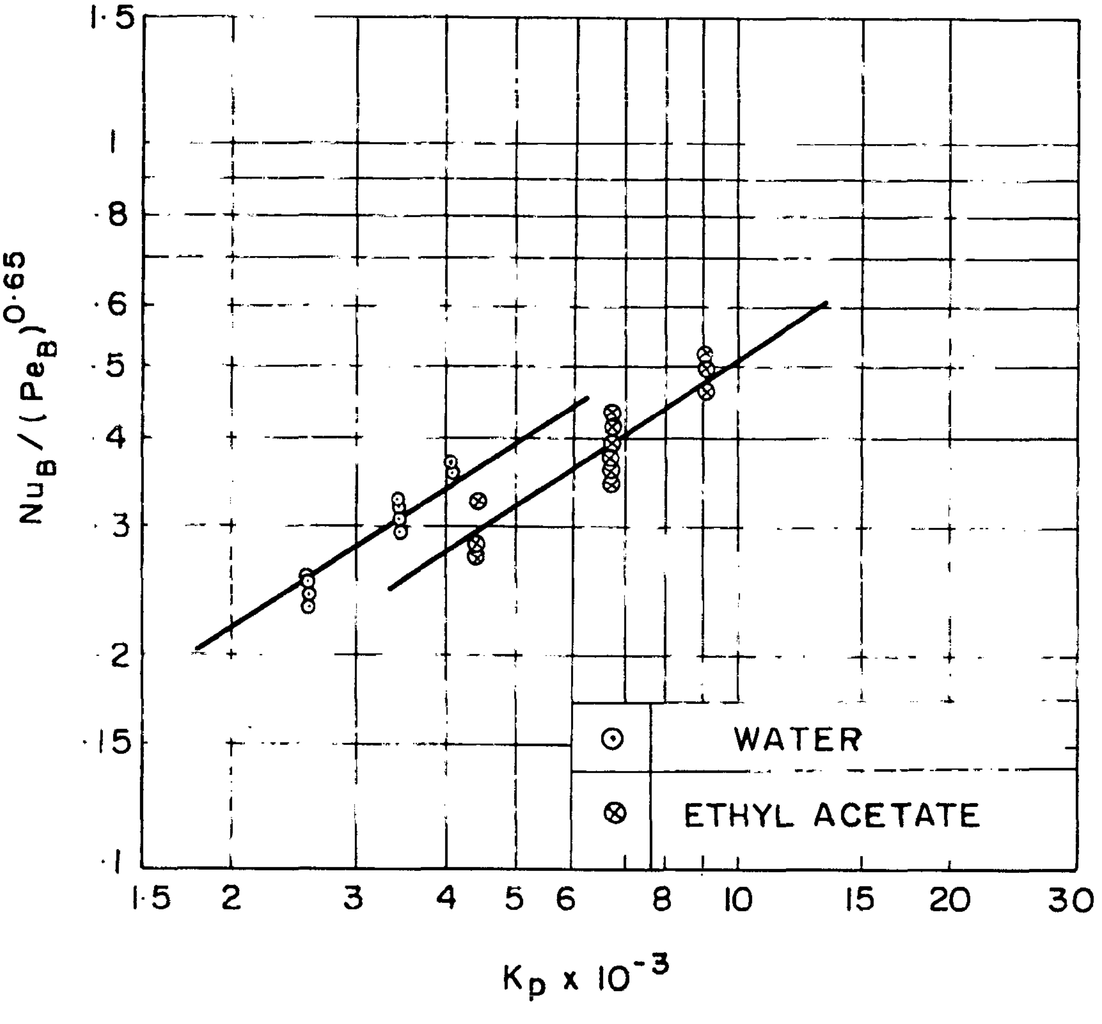

FIG. 4·11 $Nu_B/(Pe_B)^{0.65}$ AS A FUNCTION OF K_p FOR SATURATED BOILING.

two parallel lines. The equation of such line is given below:

$$Nu_B = C_3(Pe_B)^{0.65} (K_P)^{0.65} \qquad (4.6)$$

The value of C_3 in Eq.(4.6) depend on the liquid.

Since C_3 is believed to depends on the liquid only, therefore it was argued to choose the suitable physical properties of the liquids in the dimensionless form. **Prandtl** number, which contains only physical properties of liquid, was chosen for this purpose. Prandtl number was found to unify the values of constant C_3 in Eq.(4.6) This has been shown in Fig.4.12.

The results of Figs.4.7 and 4.8 and 4.12 leads to the following general correlation which can correlate most of the experimental data for both subcooled and saturated boiling as shown in Fig.4.13.

$$Nu_B = 2.17 x 10^{-4}(Pe_B)^{0.65} (K_P)^{0.65}(Pr)^{-0.45}(K'_{sub})^{0.50} \qquad (4.7)$$

Almost all the data points are found to lie within ± 20 percent of the line represented by Eq.(4.7).

All the physical properties used in the Eq.(4.7) are determined at the saturation temperature. Surface tension has been calculated using the method recommended by Meissner and Michaels [34].

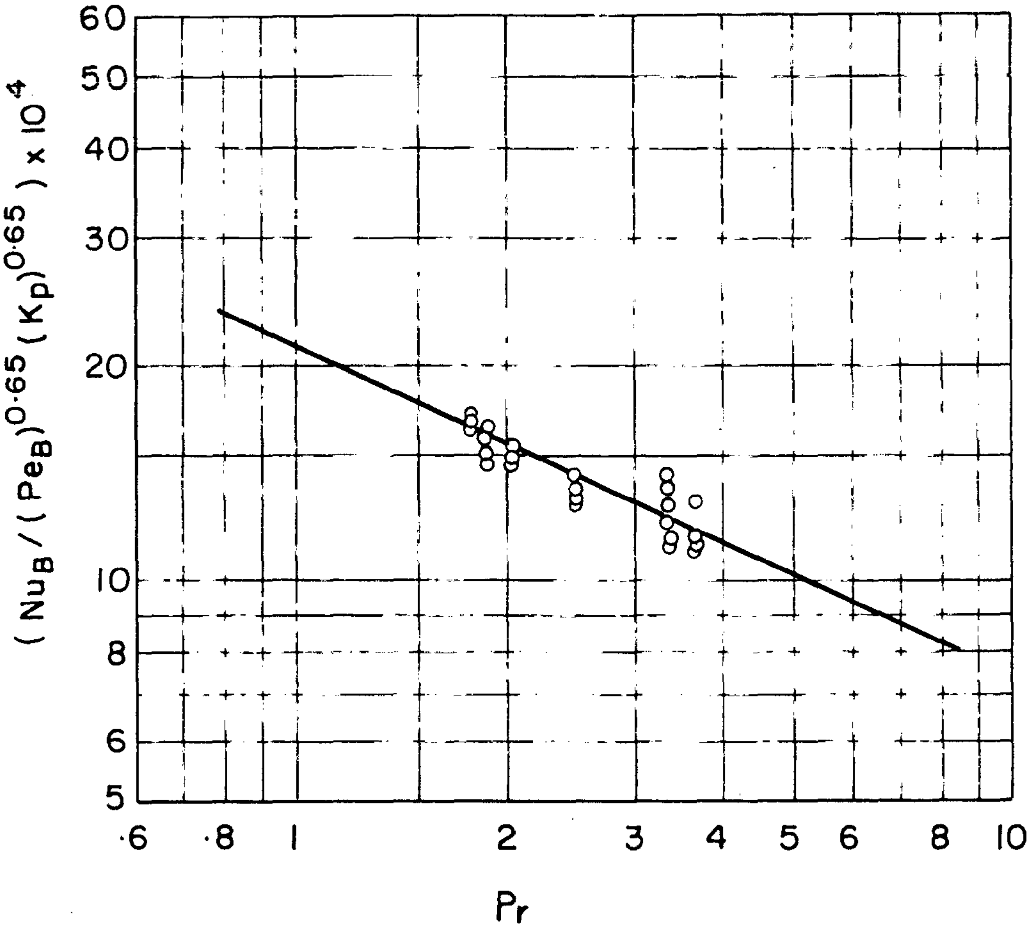

FIG. 4·12 $Nu_B/(Pe_B)^{0\cdot65}(K_p)^{0\cdot65}$ AS A FUNCTION OF P_r.

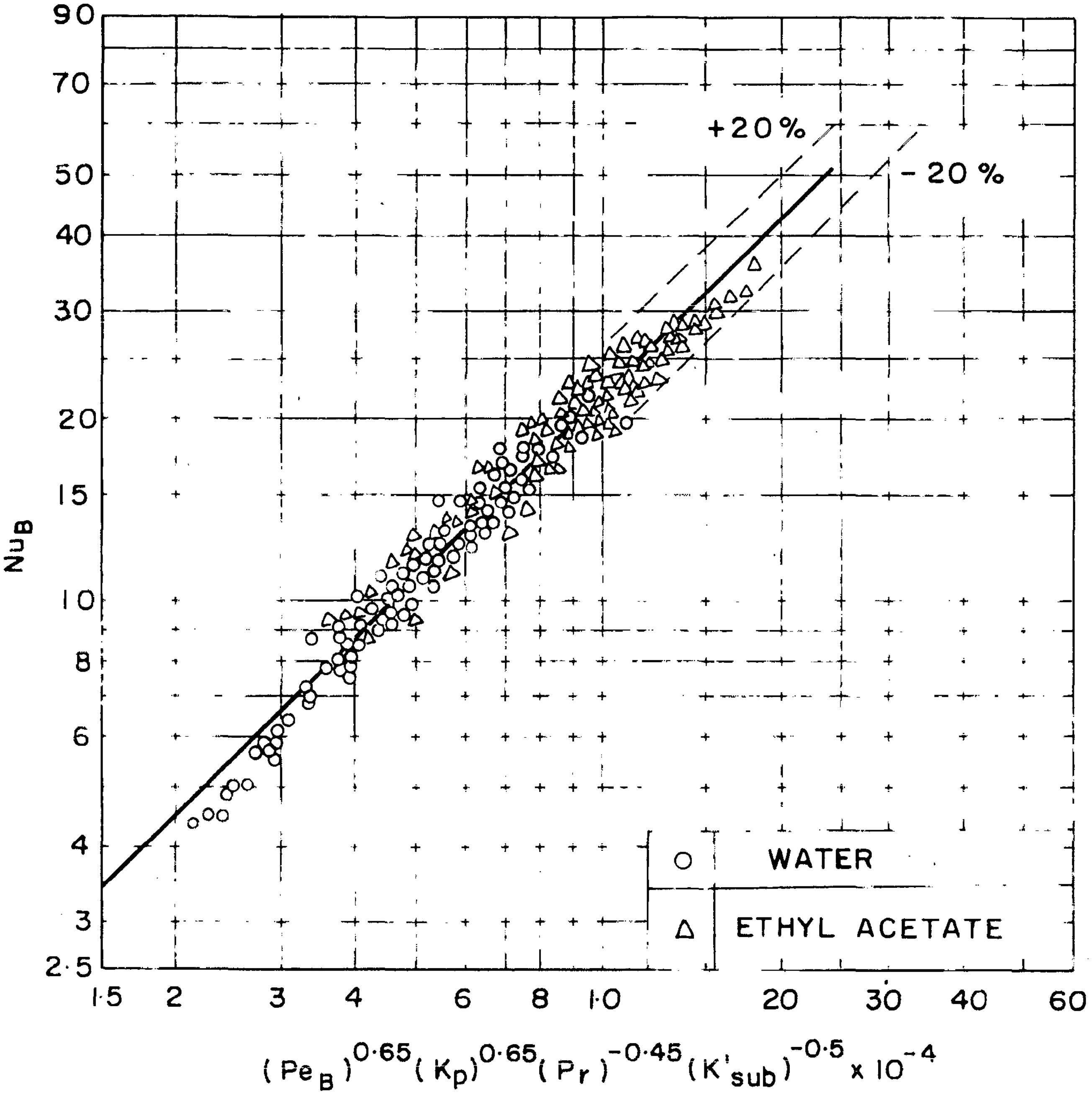

FIG. 4.13 Nu_B AS A FUNCTION OF

$(Pe_B)^{0.65} (K_p)^{0.65} (Pr)^{-0.45} (K'_{sub})^{-0.5}$

4.6 EXPERIMENTAL DATA OF PRESENT INVESTIGATION CHECKED AGAINST THE CORRELATIONS OF EARLIER WORKERS

Some of the correlations [3,24,25,26,27,28,29] were used for calculating Nu_B theoretically for comparing the experimental values of Nu_B. These correlations are applicable for saturated boiling only.

Figs.4.14 to 4.16 show the comparison between experimental and theoretically calculated Nu_B for saturated boiling of water. From these figures the following can be concluded:

a. The values of predicted Nu_B using various correlations do not coincide amongst themselves. They form seperate groups. This seems to be reasonably justified since these authors have used different surface liquid combinations in deriving their correlations. It can be mentioned that suitable values of surface-liquid factor should be multiplied to individual correlation and then the predicted values of Nu_B are likely to coincide between themselves.

b. Correlations due to Kichigin and Tobilevich[26], and Borishanskii and Minchenko [26] appear to correlate the experimental data of the present investigations.

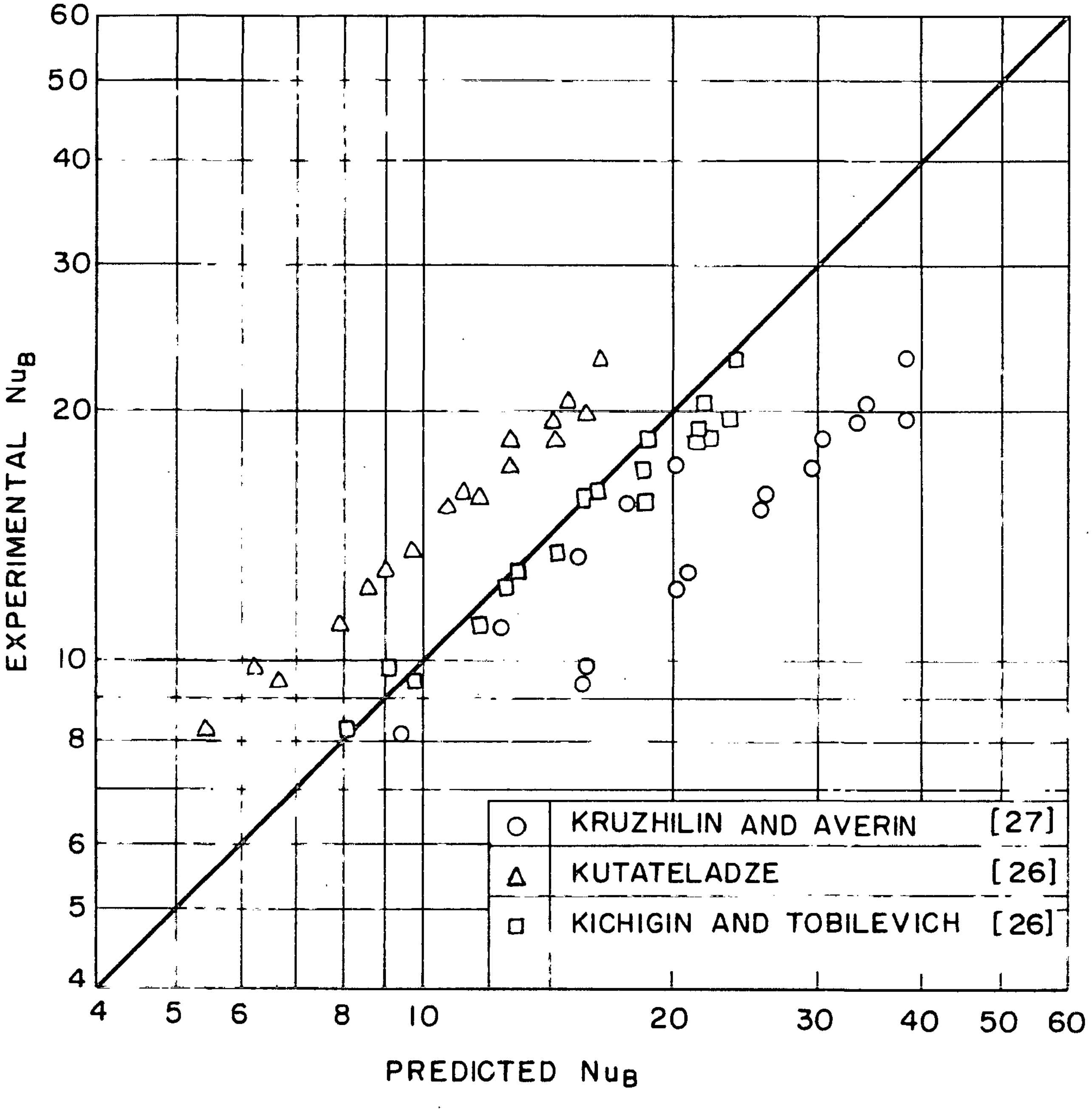

FIG. 4·14 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF Nu_B USING EARLIER CORRELATIONS FOR SATURATED BOILING OF WATER.

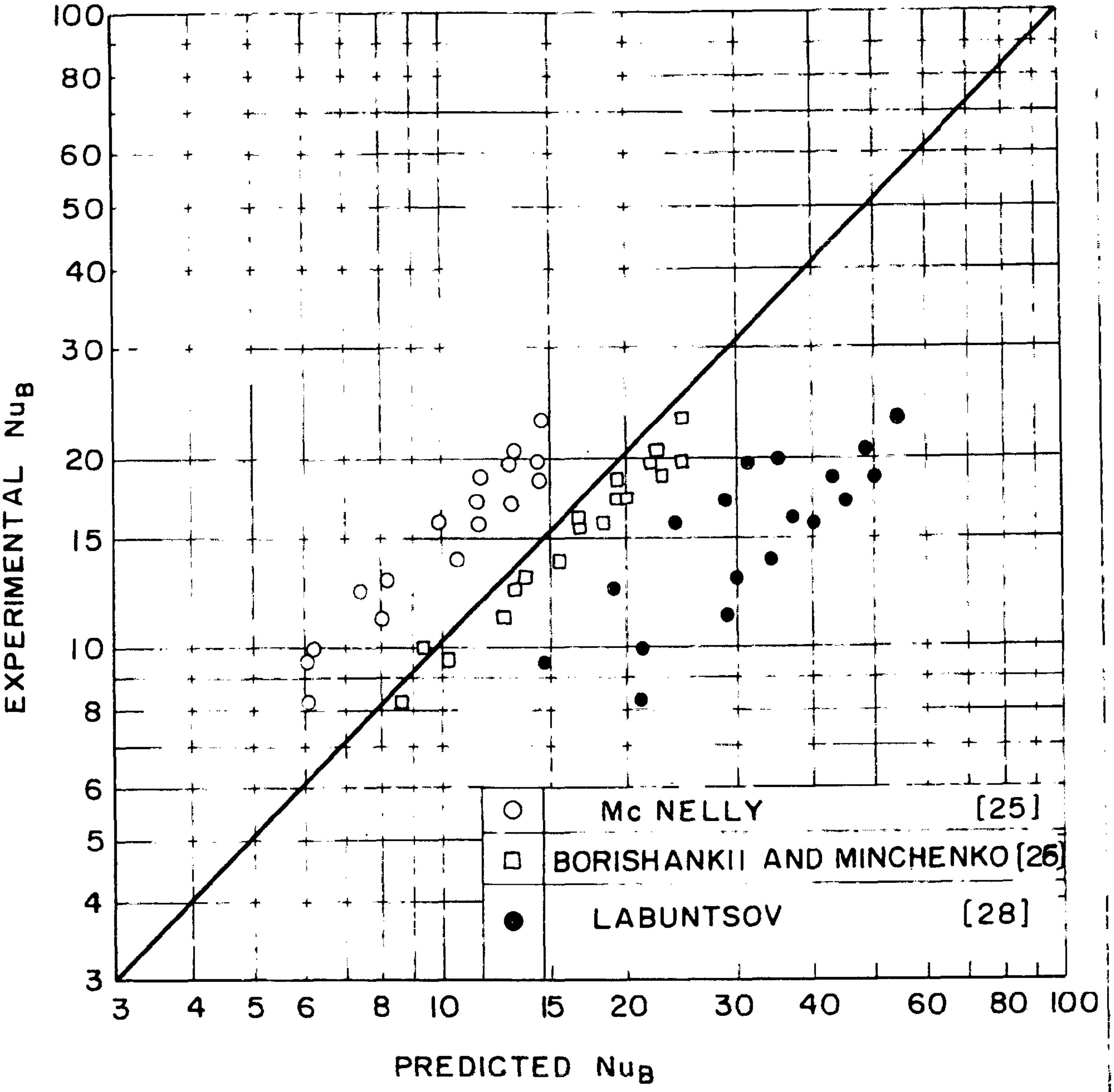

FIG. 4·15 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF Nu_B USING EARLIER CORRELATIONS FOR SATURATED BOILING OF WATER.

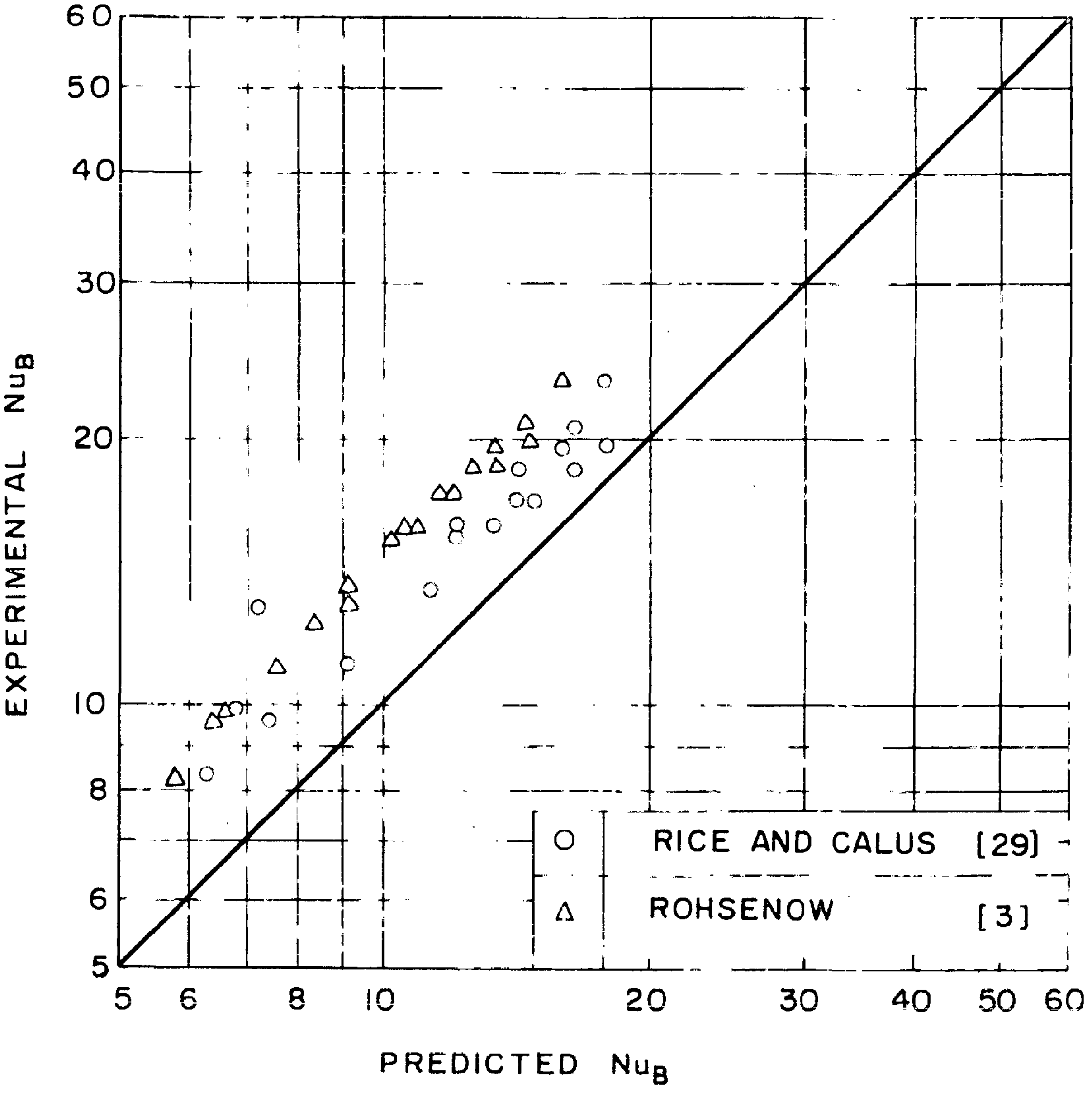

FIG. 4.16 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF Nu_B USING EARLIER CORRELATIONS FOR SATURATED BOILING OF WATER.

Fig.4.17 and 4.18 have been drawn to show a comparison between experimental and predicted values of Nu_B for ethyl acetate. These figures are also found to have separate groupings as in the case of water.

It was not possible to check the validity of the correlations due to Rohsenow [3] and Rice and Calus [29] for the data of ethyl acetate. These correlations require surface liquid combination factor which is not available in the literature.

The correlations recommended by Kutateladze [26] and Kichigin and Tobilevich [26] are found to best represent the experimental data for ethyl acetate.

The correlation proposed by Alam [24] is applicable for both subcooled and saturated boiling. Thus the experimental data of this investigation for subcooled and saturated boiling have been compared with the predicted values using the correlation of Alam [24] in Fig.4.19. Almost all data points can be represented by a line parallel to the line of equivalence. The reason for the deviation is obvious since the present author used heat transfer surface of stainless steel while the heat transfer surface in the investigation conducted by Alam was made of brass.

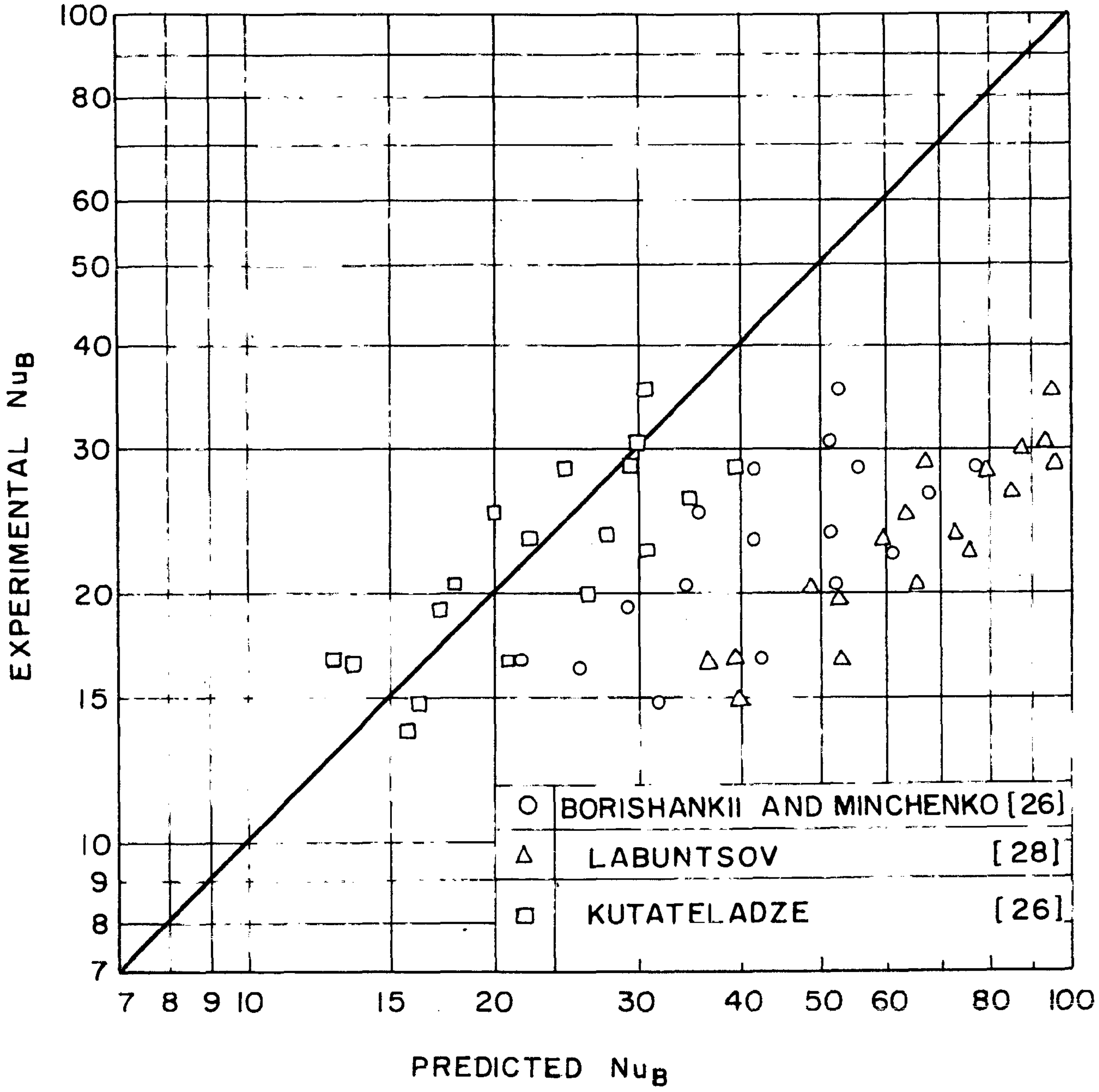

FIG. 4·17 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF Nu_B USING EARLIER CORRELATIONS FOR SATURATED BOILING OF ETHYL ACETATE.

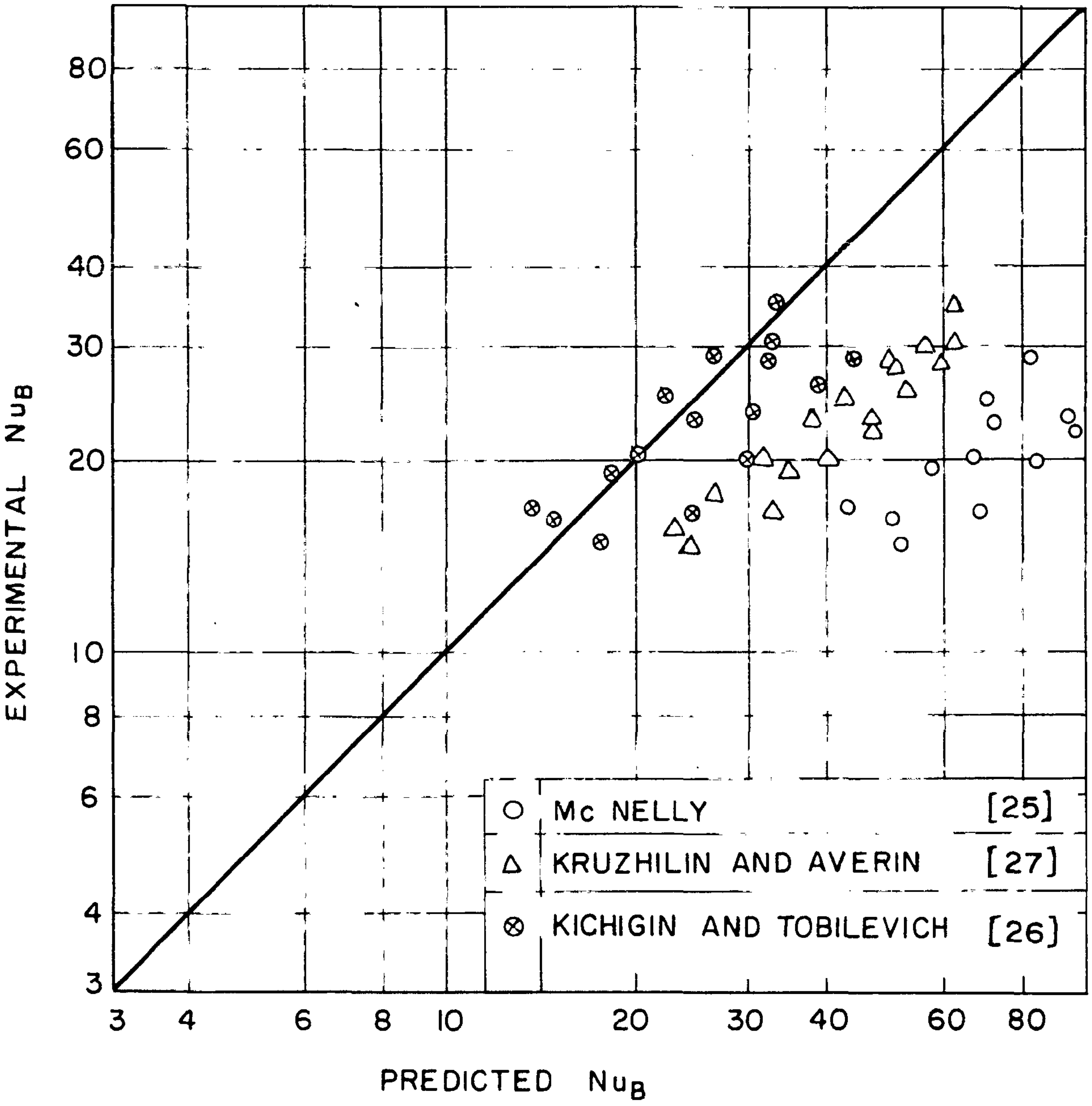

FIG. 4·18 COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED VALUES OF Nu_B USING EARLIER CORRELATIONS FOR SATURATED BOILING OF ETHYL ACETATE.

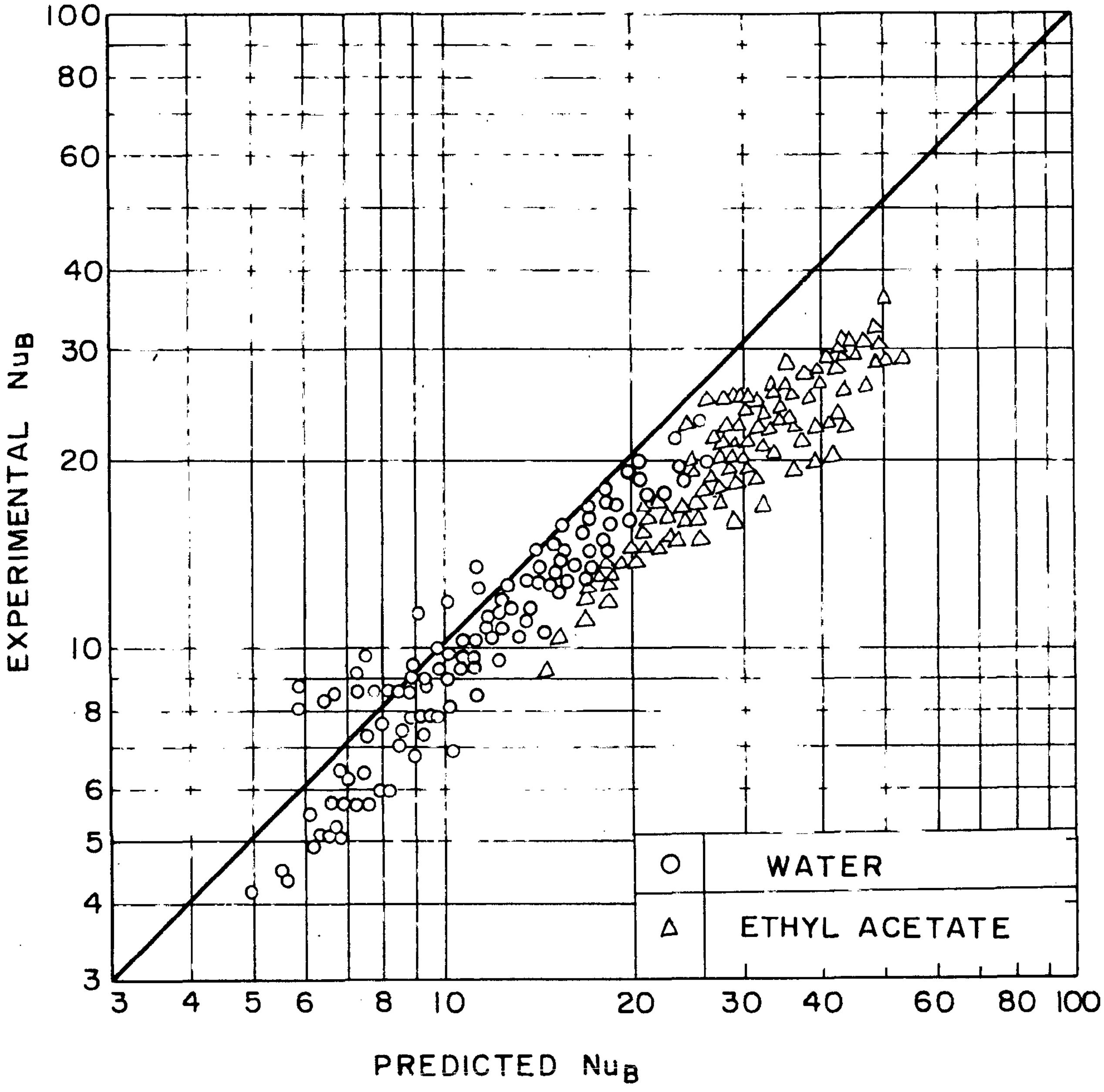

FIG. 4·19 COMPARISON OF EXPERIMENTAL Nu_B FOR SATURATED AND SUBCOOLED BOILING OF LIQUIDS WITH THE PREDICTED VALUES USING THE CORRELATION OF ALAM [24]

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

1. Heat transfer coefficient has been found to increase with increase in the value of heat flux and system pressure.
2. Heat transfer coefficient decreases with the increase in degree of subcooling or K'_{sub}.
3. The experimental data for subcooled and saturated boiling can be correlated by the following equation:

$$Nu_B = 2.17 \times 10^{-4} (Pe_B)^{0.65} (K_P)^{0.65} (Pr)^{-0.45} (K'_{sub})^{-0.5}$$

4. Heat transfer coefficient for saturated boiling can be computed by the following simple and convenient dimensional equations:
   For water, $h = 2.92\ q^{0.7}\ p^{0.16}$
   and
   For ethylacetate, $h = 5.25\ q^{0.6}\ p^{0.35}$

Recommendations:

1. The results of the present investigation suggest the need for a systematic study of other industrially important organic liquids.

2. The study should cover a wide range of pressures both for subatmospheric and superatmospheric.

APPENDIX A

PHYSICAL PROPERTIES OF ETHYL ACETATE

Table A.1 Physical Properties of Ethyl Acetate

Formula: $CH_3COOC_2H_5$, Molecular weight = 88.1

P_c = 39.2 Kg./cm^2, t_c = 250.1°C

1. Density, Viscosity and Surface Tension [35]

t $^\circ$C	ρ_L Kg/m^3	ρ_V Kg/cm^2	μ gm/cm.sec	σx10^4 dynes/cm^2
40	876.2	0.0008	0.380	21.7
50	863.6	0.0012		20.5
60	850.8	0.0018	0.308	19.3
70	837.6	0.00256		18.1
80	824.5	0.00349	0.250	16.8
90	819.2	0.00467		15.6
100	797.2	0.00616	0.212	14.4

2. Specific heat [35,36]

t,$^\circ$C	20	77.1
C $\frac{\text{Kcal}}{\text{Kg.}^\circ\text{C}}$	0.457	0.480

3. Thermal Conductivity [35,37,38]

t,$^\circ$C	20	30	77.1
k, $\frac{\text{Kcal}}{\text{hr.m.}^\circ\text{C}}$	0.101	0.123	0.155

APPENDIX B

EXPERIMENTAL DATA

Table B.1 Experimental Data for Heat Transfer to Water at 725 mm of Hg pressure

Run No.	Temperature, °C t_W	t_L	Run No.	Temperature, °C t_W	t_L	Run No.	Temperature, °C t_W	t_L
	$q=12.44\times10^3 \frac{Kcal}{hr.m^2}$			$q=24.88\times10^3 \frac{Kcal}{hr.m^2}$			$q=37.32\times10^3 \frac{Kcal}{hr.m^2}$	
1	96.20	83.35	28	95.96	72.45	54	94.89	61.55
2	97.00	84.65	29	97.08	74.35	55	100.64	70.90
3	97.70	85.50	30	98.08	76.05	56	104.24	77.80
4	98.45	86.35	31	100.17	79.80	57	105.74	82.15
5	99.83	87.00	32	102.76	83.75	58	106.19	87.35
6	100.26	88.10	33	104.49	90.25	59	106.29	89.20
7	101.43	89.65	34	104.76	91.15	60	106.49	90.90
8	101.95	90.95	35	105.05	93.55	61	106.49	94.60
9.	102.38	91.80	36	105.05	94.65	62	106.02	95.60
10	102.70	93.30	37	105.29	95.65	63	106.12	96.60
11	103.20	94.20	38	105.29	96.80	64	106.24	97.25
12	103.50	95.60	39	105.47	98.30	65	106.24	98.10
13	103.73	96.80	40	105.47	98.80	66	106.24	98.80
14	103.83	97.25						
15	103.83	97.85		$q=31.10\times10^3 \frac{Kcal}{hr.m^2}$			$q=43.54\times10^3 \frac{Kcal}{hr.m^2}$	
16	103.83	98.25						
	$q=18.66\times10^3 \frac{Kcal}{hr.m^2}$		41	97.92	70.70	67	97.53	61.70
			42	99.60	73.25	68	106.93	85.50
			43	102.55	79.30	69	107.23	86.80
17	96.27	76.65	44	103.55	82.35	70	106.83	88.10
18	101.95	85.95						
19	102.35	86.60	45	105.33	88.10	71	107.23	90.95
20	102.79	88.95	46	105.45	90.90	72	106.93	93.80
			47	105.32	92.45	73	106.93	94.20
21	103.42	92.05	48	105.32	94.60	74	106.93	96.00
22	103.52	93.00						
23	104.25	94.80	49	105.72	96.60	75	106.93	97.05
24	104.25	96.60	50	105.85	97.25	76	106.93	98.10
			51	105.92	97.65	77	106.93	98.80
25	104.25	97.85	52	105.95	98.10			
26	104.25	98.10						
27	104.25	98.70	53	105.95	98.80			

Table B.2 Experimental Data for Heat Transfer to Water at 625 mm of Hg pressure

Run No.	Temperature, °C	
	t_W	t_L
	$q=12.44\times10^3$ Kcal/hr.m^2	
78	96.03	83.15
79	97.50	85.70
80	98.25	88.95
81	98.35	89.80
82	99.34	93.40
83	99.86	94.25
	$q=18.66\times10^3$ Kcal/hr.m^2	
84	97.29	82.75
85	98.17	85.55
86	98.77	87.65
87	99.60	90.70
88	100.07	92.85
89	100.38	93.85
	$q=24.88\times10^3$ Kcal/hr.m^2	
90	98.80	84.65
91	99.71	85.95
92	99.88	87.90
93	100.29	89.80
94	100.33	90.90
95	100.79	91.80
96	100.96	93.85
	$q=31.10\times10^3$ Kcal/hr.m^2	
97	100.57	83.15
98	100.78	85.50
99	100.78	86.35
100	101.12	87.25
101	101.20	88.10
102	101.60	89.70
103	101.60	91.60
104	101.60	92.20
105	101.90	94.25
	$q=37.32\times10^3$ Kcal/hr.m^2	
106	101.60	84.00
107	102.16	85.70
108	102.47	87.55
109	102.47	88.75
110	102.47	90.10
111	102.47	90.45
112	102.47	94.25
	$q=43.54\times10^3$ Kcal/hr.m^2	
113	102.38	83.05
114	103.11	86.80
115	103.21	88.50
116	103.31	90.25
117	103.45	92.25
118	103.73	94.25

Table B.3 Experimental Data for Heat Transfer to Water at 470 mm of Hg. pressure

Run No.	Temperature, °C	
	t_W	t_L
	$q=12.44\times10^3$ Kcal/hr.m^2	
119	82.88	76.10
120	84.86	78.45
121	85.95	79.50
122	87.48	81.10
123	88.62	82.65
124	90.42	85.00
125	91.86	85.95
126	92.88	86.60
	$q=18.66\times10^3$ Kcal/hr.m^2	
127	89.45	80.05
128	91.04	82.20
129	91.62	83.60
130	92.82	85.00
131	93.47	86.20
132	93.57	86.60
133	94.07	86.80
	$q=24.88\times10^3$ Kcal/hr.m^2	
134	88.58	76.45
135	90.66	78.20
136	91.96	79.95
137	92.81	81.55
138	93.13	83.65
139	93.63	84.45
140	94.11	85.35
141	94.74	86.80
	$q=31.10\times10^3$ Kcal/hr.m^2	
142	91.48	76.80
143	92.22	77.75
144	93.79	81.20
145	94.82	84.45
146	95.10	86.60
147	95.10	86.80
	$q=37.32\times10^3$ Kcal/hr.m^2	
148	92.56	76.45
149	93.56	78.20
150	95.72	82.15
151	95.81	82.65
152	96.54	83.75
153	96.34	85.00
154	96.34	86.00
155	96.34	86.80
	$q=43.54\times10^3$ Kcal/hr.m^2	
156	94.23	74.85
157	94.46	76.70
158	95.43	78.25
159	96.31	81.30
160	96.38	82.35
161	96.66	83.75
162	96.81	85.70
163	96.81	86.60

Table B.4 Experimental Data for Heat Transfer to Ethyl Acetate at 725 mm of Hg pressure.

Run No.	Temperature, °C		Run No.	Temperature, °C		Run No.	Temperature, °C	
	t_W	t_L		t_W	t_L		t_W	t_L
$q=12.44x10^{3}\frac{Kcal}{hr.m^{2}}$			$q=24.88x10^{3}\frac{Kcal}{hr.m^{2}}$			206	83.37	71.35
						207	83.72	71.85
164	79.02	64.95	185	79.38	61.60	$q=37.32x10^{3}\frac{Kcal}{hr.m^{2}}$		
165	79.42	66.05	186	82.01	64.95			
166	79.77	67.75	187	82.40	67.25	208	82.74	59.55
						209	84.64	65.65
167	79.62	68.55	188	82.54	68.15	210	84.74	67.95
168	79.62	69.25	189	82.62	68.85			
169	79.62	69.55	190	82.82	69.25	211	84.84	68.95
						212	84.64	69.95
170	79.72	70.25	191	83.06	69.75	213	84.64	71.10
171	79.72	71.35	192	82.71	70.45			
172	79.72	71.55	193	82.56	71.35	214	84.84	71.40
						215	85.04	71.85
$q=18.66x10^{3}\frac{Kcal}{hr.m^{2}}$			194	82.83	71.50			
			195	82.83	71.85	$q=43.54x10^{3}\frac{Kcal}{hr.m^{2}}$		
173	79.19	62.65						
174	80.54	64.95	$q=31.10x10^{3}\frac{Kcal}{hr.m^{2}}$			216	78.38	49.65
175	80.97	66.55				217	81.75	52.60
			196	78.20	60.85	218	83.88	59.45
176	80.97	67.60	197	79.28	63.35			
177	80.97	68.15	198	79.48	64.45	219	85.68	63.85
178	81.09	68.65	199	79.68	66.05	220	86.11	66.05
						221	86.75	67.25
179	81.07	69.25	200	79.80	67.95			
180	81.07	69.55	201	79.90	68.15	222	86.38	68.45
181	81.17	69.95	202	82.27	68.45	223	86.75	69.45
						224	86.75	70.45
182	81.19	70.60	203	82.80	70.45			
183	82.07	70.85	204	82.80	70.60	225	86.65	71.60
184	82.55	71.80	205	83.22	70.85	226	86.75	71.85

Table B.5 Experimental Data for Heat Transfer to Ethyl Acetate at 625 mm of Hg Pressure

Run No.	Temperature, °C		Run No.	Temperature, °C		Run No.	Temperature, °C	
	t_W	t_L		t_W	t_L		t_W	t_L
	$q=12.44\times10^3 \frac{Kcal}{hr.m^2}$		248	77.30	65.40		$q=37.32\times10^3 \frac{Kcal}{hr.m^2}$	
			249	77.30	65.85			
			250	77.42	66.05			
227	72.78	58.15		$q=24.88\times10^3 \frac{Kcal}{hr.m^2}$		269	77.93	57.85
228	73.25	59.55				270	79.34	61.05
229	73.85	60.15				271	79.44	62.00
230	74.35	61.10				272	79.59	63.35
			251	74.81	56.95			
231	74.03	61.50	252	75.96	59.05	273	79.59	64.05
232	74.03	62.65	253	76.76	60.15	274	79.49	65.65
233	73.93	63.15	254	77.11	63.15	275	79.59	66.25
234	73.93	63.55						
			255	77.11	63.55			
235	74.03	64.05	256	77.23	64.05			
236	73.96	64.45	257	77.13	64.45		$q=43.54\times10^3 \frac{Kcal}{hr.m^2}$	
237	73.86	64.95	258	77.13	64.95			
238	73.86	65.65						
239	73.92	66.05	259	77.43	65.65	276	74.86	56.70
			260	77.43	65.85	277	79.15	58.75
	$q=18.66\times10^3 \frac{Kcal}{hr.m^2}$		261	77.43	66.05	278	79.85	60.85
						279	80.53	62.65
				$q=31.10\times10^3 \frac{Kcal}{hr.m^2}$		280	81.15	64.25
240	73.54	56.25				281	80.88	65.45
241	74.62	58.35				282	81.05	66.25
			262	76.50	56.50			
242	75.51	61.30	263	78.88	61.05			
243	75.68	62.20	264	79.88	63.10			
			265	79.78	64.05			
244	75.84	63.15						
245	75.74	63.85	266	79.83	64.95			
246	76.42	64.25	267	79.83	65.65			
247	77.33	64.65	268	79.83	66.25			

Table B.6 Experimental Data for Heat Transfer to Ethyl Acetate at 470 mm of Hg pressure

Run No.	Temperature, °C t_W	Temperature, °C t_L
$q=12.44x10^{3}\frac{Kcal}{hr.m^{2}}$		
283	64.58	50.40
284	65.93	51.90
285	66.83	53.95
286	67.20	54.60
287	66.93	55.35
288	66.93	56.05
289	66.83	56.45
290	67.73	57.25
291	67.58	57.85
292	67.86	58.35
293	67.80	58.80
294	68.05	59.15
$q=18.66x10^{3}\frac{Kcal}{hr.m^{2}}$		
295	68.30	51.50
296	69.17	53.95
297	69.22	54.60
298	69.29	56.75
299	70.05	57.25
300	71.09	57.65
301	71.09	58.55
302	71.09	59.00
303	71.09	59.15
$q=24.88x10^{3}\frac{Kcal}{hr.m^{2}}$		
304	66.66	48.50
305	69.11	51.30
306	70.41	54.15
307	70.61	54.85
308	70.65	55.80
309	70.72	56.25
310	71.38	56.95
311	72.26	57.40
312	72.28	58.35
313	72.24	58.80
314	72.24	59.15
$q=31.10x10^{3}\frac{Kcal}{hr.m^{2}}$		
315	68.87	49.90
316	70.38	51.85
317	71.50	54.15
318	71.70	55.55
319	71.78	56.95
320	72.95	58.05
321	72.95	58.80
322	73.05	59.00
323	73.38	59.15
$q=37.32x10^{3}\frac{Kcal}{hr.m^{2}}$		
324	70.76	46.60
325	72.19	52.10
326	72.59	54.15
327	72.72	54.80
328	72.59	55.80
329	73.72	56.45
330	74.04	57.95
331	74.29	58.80
332.	74.29	59.15
$q=43.54x10^{3}\frac{Kcal}{hr.m^{2}}$		
333	71.08	46.60
334	72.70	53.75
335	73.55	55.05
336	73.65	55.80
337	73.65	56.45
338	74.53	57.60
339	75.35	58.80
340	75.38	59.15

APPENDIX C

SAMPLE CALCULATIONS

C.1 GENERAL

a. Calculation of heat transfer surface

Outside diameter of test section $= 25.5\text{x}10^{-3}\text{m}$

Length of test section $=173\text{x}10^{-3}\text{m}$.

Heat transfer area $= \pi\text{x}25.5\text{x}10^{-3} \text{ x } 173\text{x}10^{-3}$

$= \underline{1.382\text{x}10^{-2}}\text{m}^2$

b. Calculation of heat flux

$$q = \frac{0.86W}{A} = \frac{0.86W}{1.382\text{x}10^{-2}}$$

$$= \underline{62.22W} \text{ Kcal/hr.m}^2$$

where W is in watts.

c. Calculation of temperature drop in the wall of test surface

Using the equation of conductive heat transfer for cylindrical test surface, the temperature drop for Run No.90 is calculated as below:

$$\Delta t_w = \frac{q\ d_o}{2k} \ln \frac{d_o}{d_h}$$

where

d_o = O.D. of test surface

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

$$\Delta t_w = \frac{24.88x10^{3}x25.5x10^{-3}}{2x14.012} \ln \frac{25.5}{18+\frac{1}{2}(7.5+2)}$$

$$= \underline{3.44^{\circ}C}$$

C.2 EXPERIMENTAL AND PREDICTED VALUES OF NATURAL CONVECTIVE HEAT TRANSFER COEFFICIENT

Run No.17

Heat flux , $q = 18.66x10^{3}$ Kcal/hr.m^2

Wall temperature , $t_w = 96.27^{\circ}C$

Liquid temperature, $t_L = 76.65^{\circ}C$

a. Experimental h

$$h = \frac{q}{(t_w - t_L)} = \frac{18.66x10^{3}}{(96.27-76.65)}$$

$$= \underline{950\ \text{Kcal/hr}}$$

b. Predicted h

The value of natural convective heat transfer coefficient of water is computed using the following equation:

$$Nu = C\ (Gr\ x\ Pr)^{n}$$

$$Gr = \frac{gd_o^{\,3}}{\nu^{2}} \quad \beta \Delta t$$

$$= \frac{9.81x(2.55x10^{-2})^{3}x6.67x10^{-4}x19.62}{(3.67x10^{-7})^{2}}$$

$$= 1.58x10^{7}$$

$$Pr = 2.02$$

$$(Gr \times Pr) = 1.58\times10^{7}\times2.02$$
$$= 3.185\times10^{7}$$

The value of c and n are taken from Mikheyev [12]

$c = 0.135$

$n = 0.333$

$$h_{pred.} = \frac{0.135 \times (3.185\times10^{7})^{0.333} \times 0.5830}{(2.55\times10^{-2})}$$

$$= \underline{955} \text{ Kcal/hr.m}^{2}.^{\circ}\text{C}$$

$$\text{Percent error} = \frac{955-950}{955}$$

$$= \underline{0.525} \text{ Per cent}$$

C.3 CALCULATION OF Nu_B

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

(i) <u>Experimental Nu_B</u>

$$h = \frac{q}{t_w - t_L} = \frac{24.88\times10^{3}}{100.96-94.25} = 3640 \text{ Kcal/hr.m}^{2}.^{\circ}\text{C}$$

$$Nu_B = \frac{h}{k}\sqrt{\frac{\sigma}{(\rho_L-\rho_V)}} = \frac{3640}{0.5858}\sqrt{\frac{61.50\times10^{-4}}{962.5-0.5}}$$

$$= \underline{15.70}$$

(ii) Predicted Nu_B using correlations of Table 2.4

a. Rohsenow

$$Nu_B = \frac{1}{0.014} (Re_B)^{0.67} (Pr)^{-0.7}$$

$$Re_B = \frac{24.88x10^3}{1.108x543} \sqrt{\frac{61.50x10^{-4}}{962.5-0.5}} = 10.42x10^{-2}$$

$$Pr = \frac{1.008x1.116}{0.5858} = 1.865$$

$$Nu_B = \frac{1}{0.014} (10.42x10^{-2})^{0.67} (1.865)^{-0.7}$$

$$= \frac{1}{0.014} \ x\ 0.220\ x\ 1.546$$

$$= \underline{11.70}$$

b. McNelly

$$\frac{hd}{k} = 0.025 \left(\frac{qd}{\mu\lambda}\right)^{0.69} \left(\frac{Pd}{\sigma}\right)^{0.31} \left(\frac{\rho_L-\rho_V}{\rho_V}\right)^{0.33} \left(\frac{C\mu}{k}\right)^{0.69}$$

$$\left(\frac{qd}{\mu\lambda}\right) = \frac{24.88x10^3x25.5x10^{-3}}{1.116\,x\ 539} = 1.052$$

$$\frac{Pd}{\sigma} = \frac{0.842x25.5x10^{-3}}{61.50x10^{-4}} = 3.575x10^4$$

$$\frac{\rho_L - \rho_V}{\rho_V} = \left(\frac{962.5-0.5}{0.5}\right) = 4810$$

$$Nu_B = 0.025\ (1.052)^{0.69}(3.575x10^4)^{0.31}(4810)^{0.33} (1.865)^{0.69}$$

$$= \underline{10.00}$$

c. Kichigin and Tobilevich

$$Nu_B = 1.04x10^{-4}\ (Pe_B)^{0.7}\ (K_P)^{0.7}\ (Ar)^{0.125}$$

$$Pe_B = \frac{24.88x10^3}{0.5858x539x6.05x10^{-4}} \sqrt{\frac{61.50x10^{-4}}{(962.5-0.5)}}$$

$$= 383.0$$

$$K_P = \frac{0.847x10^4}{\sqrt{61.50x10^{-4}(962.5-0.5)}} = 6.76x10^3$$

$$Ar = \frac{9.81}{(3.42x10^{-7})^2} \left(\frac{61.50x10^{-4}}{(962.5-0.5)}\right)^{3/2} \left(1- \frac{0.5858}{962.5}\right)$$

$$= 1.598x10^6$$

$$Nu_B = 1.04x10^{-4}\ (383)^{0.7}\ (6.76x10^3)^{0.7} (1.598x10^6)^{0.125}$$

$$= \underline{15.95}$$

d. Kutateladze

$$Nu_B = 7.0x10^{-4} (Pe_B)^{0.7}\ (Pr)^{-0.35}\ (K_P)^{0.7}$$

$$= 7.0x10^{-4}\ (383)^{0.7}\ (1.865)^{-0.35} (6.76x10^3)^{0.7}$$

$$= \underline{10.88}$$

e. Borishanskii and Minchenko

$$Nu_B = 8.7x10^{-4}\ (Pe_B)^{0.7}\ (K_P)^{0.7}$$

$$= 8.7x10^{-4}\ (383)^{0.7}\ (6.76x10^3)^{0.7}$$

$$= \underline{16.80}$$

f. Kruzhilin and Averin

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

$$K_t = \frac{427\ (0.5\times543)^2}{1.005\times94.25\times962.5\sqrt{61.50\times10^{-4}(962.5-0.5)}}$$

$$= 142$$

$$Nu_B = 0.082\ (383)^{0.7}\ (1.865)^{-0.5}\ (142)^{0.377}$$

$$= \underline{25.35}$$

g. Labuntsov

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

$$= 0.125(383)^{0.65}\ (1.865)^{-0.32}\ (142)^{0.35}$$

$$= \underline{24.30}$$

h. Rice and Calus

$$Nu_B = 6.3\times10^{-4}\ (Pe_B)^{0.7}\ (K_P)^{0.7}\ \left(\frac{T_{SW}}{T_S}\right)^4$$

$$= 6.3\times10^{-4}\ (383)^{0.7}\ (6.76\times10^3)^{0.7}\ (1)^4$$

$$= \underline{12.18}$$

i. Alam

$$Nu_B = 0.084\ (Pe_B)^{0.6}\ (K_t)^{0.37}\ (K_{sub})^{-0.50}$$

$$K_{sub} = 1.00$$

$$Nu_B = 0.084\ (383)^{0.6}\ (142)^{0.37}\ (1)^{-0.50}$$

$$= \underline{18.80}$$

j. Proposed correlation

$$Nu_B = 2.17x10^{-4}(Pe_B)^{0.65}(K_P)^{0.65}(Pr)^{-0.45}(K'_{sub})^{-0.50}$$

$$= 2.17x10^{-4}(383)^{0.65}(6.76x10^3)^{0.65}(1.865)^{-0.45}(1)^{-0.5}$$

$$= \underline{15.85}$$

(iii) per cent error in the values of Nu_B calculated as above

$$\text{Per cent error} = \frac{(Nu_B)_{calcd.} - (Nu_B)_{exptl.}}{(Nu_B)_{calcd.}}$$

The calculated values of percent error have been shown in Table C.1.

Table C.1 Per cent Error in Predicted Nu_B

Correlation	Per cent error	Correlation	Percent error
a Rohsenow	- 34.20	f Kruzhilin and Averin	+ 38.00
b McNelly	- 57.00	g Labuntsov	+ 35.40
c Kichigin and Tobilevich	+ 1.56	h Rice and Calus	- 26.10
d Kutateladze	- 44.40	i Alam	+ 16.50
e Bonshanskii and Minchenko	+ 6.55	j Proposed	+ 9.45

APPENDIX D

LISTING OF COMPUTER PROGRAMS
AND OUTPUTS

```
C   C  S.C. GUPTA     GENERAL  CALCULATION
C      B1- OUTER SURFACE AREA ,B2- INNER SURFACE AREA ,BM- MEAN AREA
C      W(I) WATTAGE ,Q(I) HEAT FLUX ,DT(I) TEMPERATURE DROP ACROSS
C      WALL  INCORPERATING CORRECTION FACTOR OF 0.6
       DIMENSION W(6), Q(6) ,DT(6)
       READ 1,N
     1 FORMAT (I2)
       READ 2 ,(W(I),I=1,N)
     2 FORMAT (6F4.0)
       B1=3.1414*0.0255*0.1730
       B2=3.1414*0.02175*0.1730
       BM=(B1+B2)/2.0
       DO 3 I=1,N
       Q(I) = 0.86*W(I)/B1
       DT(I)=0.86*W(I)*0.001875/(14.012*BM)
       DT(I) = DT(I) -0.6
     3 PUNCH 4 ,W(I),Q(I),DT(I)
       PUNCH 5,B1,B2,BM
     4 FORMAT (3E 15.5)
     5 FORMAT (3E 15.5)
       STOP
       END
```

DATA INPUT

```
 6
200.300.400.500.600.700.
```

- RESULTS -

```
C   C  S.C. GUPTA     GENERAL  CALCULATION
     0.20000E+03    0.12411E+05     0.11926E+01
     0.30000E+03    0.18617E+05     0.20889E+01
     0.40000E+03    0.24823E+05     0.29852E+01
     0.50000E+03    0.31028E+05     0.38816E+01
     0.60000E+03    0.37234E+05     0.47779E+01
     0.70000E+03    0.43440E+05     0.56742E+01
     0.13858E-01    0.11820E-01     0.12839E-01
0      STOP END AT S. 0005 + 01 L.  Z
```

```
C   C   S C GUPTA    NATURAL  CONVENCTION  CALCULATIONS
        DIMENSION Q(6), TW(6),TL(10),COND(10),B(10), PR(10),DT(10)
        DIMENSION HNEW(10), HCAL(10), HEXP(10), GR(10), ER(10)
        READ 1,N,M,CRIT1,CRIT2, CRIT3
      1 FORMAT (2I6, 3E10.5)
        READ2,(Q(I),I=1,M),D,G
      2 FORMAT(6F7.0,F8.4,F8.2)
        DO 11  J=1,M
        DO 11  I=1,N
        READ3, TW(I),TL(I),COND(I),HNEW(I),B(I),PR(I)
      3 FORMAT(2F7.2,F5.3,2E10.5,F5.2)
        DT(I)=TW(I)-TL(I)
        HEXP(I)=Q(J)/DT(I)
        GR(I)=B(I)*D**3*G*DT(I)/(HNEW(I)**2)
        GR(I)=GR(I)*PR(I)
        IF(GR(I)-CRIT1) 4,4,5
      4 GR(I)=GR(I)**0.125
        HCAL(I)=COND(I)*1.18*GR(I)/D
        GO TO 10
      5 IF(GR(I)-CRIT2) 6,6,7
      6 GR(I)=GR(I)**0.25
        HCAL(I)=COND(I)*0.54*GR(I)/D
        GO TO 10
      7 IF(GR(I)-CRIT3) 8,8,12
      8 GR(I)=GR(I)**0.3333
        HCAL(I)=COND(I)*0.135*GR(I)/D
     10 ER(I)= (HCAL(I)-HEXP(I))/HCAL(I)*100.
        PUNCH 14,HEXP(I),HCAL(I),ER(I)
     14 FORMAT(3E10.3)
     11 CONTINUE
     12 STOP
        END
```

DATA INPUT

```
    2      6.50000E+ 3.20000E+ 8.10000E+14.
12411. 18617. 24823. 31028. 37234. 43440.  0.0255    9.81
  97.70  85.50 .585.32110E- 6.70412E- 3 1.91
  98.45  86.35 .586.30310E- 6.73718E- 3 1.82
  96.27  76.65 .583.34000E- 6.67469E- 3 2.06
 101.97  85.95 .586.31380E- 6.71780E- 3 1.87
  95.96  72.45 .582.34860E- 6.65852E- 3 2.10
  97.08  74.35 .581.34270E- 6.66803E- 3 2.06
  97.92  70.70 .582.34820E- 6.65915E- 3 2.10
  99.60  73.25 .581.34000E- 6.67250E- 3 2.04
  94.89  61.55 .579.37390E- 6.62096E- 3 2.27
 100.64  70.90 .584.34250E- 6.66835E- 3 2.06
  97.53  61.70 .589.36690E- 6.72964E- 3 2.22
 106.93  85.50 .586.30672E- 6.73045E- 3 1.83
  0.103E+04 0.950E+03-0.799E+01
  0.103E+04 0.950E+03-0.799E+01
 0.311E+04 0.102E+04-0.140E+02
```

```
                        - R   E   S   U   L   T   S   -

 0.949E+03 0.104E+04 0.860E+01
 0.106E+04 0.108E+04 0.252E+01
 0.109E+04 0.108E+04-0.803
 0.114E+04 0.114E+04-0.115
 0.113E+04 0.114E+04-0.303E+01
 0.112E+04 0.116E+04 0.395E+01
 0.125E+04 0.119E+04-0.542E+01
 0.121E+04 0.129E+04 0.566E+01
 0.203E+04 0.114E+04-0.780E+02
0     STOP END AT S. 0012 + 00 L.  Z
```

```
C   C   S C G GROUP CALCULATIONS
      PUNCH 10
   10 FORMAT(1X, 3HRN,5X,1HH,7X,3HHNU,7X,3HPEB,7X,4HSUBK,7X,3HHKP,7X,
     13HHKT///)
      IT=1
   16 READ 30, SIG,CON,PV,PL,HV,TS,CP
   30 FORMAT(F10.5,6F10.3)
  100 READ20,NR,TW,TL,Q,PS,EJ
   20 FORMAT(I3,5F10.3)
      DT=TW-TL
      H=Q/DT
      ALPHA=CON/(PL*CP)
      VGR=SQRTF(SIG/(PL-PV))
      HNU=(H/CON)*VGR
      PEB=(Q/(PV*HV*ALPHA))*VGR
      SUBK=1.0+(SQRTF(PL/PV))*((TS-TL)/TS)
      HKP=(PS/SIG)*VGR
      HKTN=EJ*((PV*HV)**2.0)
      HKTD=(CP*TS*PL/SIG)*VGR
      HKT=HKTN/HKTD
      PUNCH 50,NR,H,HNU,PEB,SUBK,HKP,HKT
   50 FORMAT (I4,6F10.3)
      IT = IT+1
      IF(IT-57)100,16,15
   15 IF(IT-97)100,16,12
   12 IF(IT-135)100,100,200
  200 STOP
      END
```

```
                        - R   E   S   U   L   T   S   -

C   C   S C G  GROUP  CALCULATIONS
 RN.       H          HNU         PED          SUBK        HKP          HKT


    1  2224.194      9.595     164.240        1.226    4095.038     1056.183
    2  2075.418      8.953     164.240        1.391    4095.038     1056.183
    3  1886.170      8.137     164.240        1.638    4095.038     1056.183
    4  1790.909      7.726     164.240        1.823    4095.038     1056.183
    5  1571.013      6.777     164.240        2.317    4095.038     1056.183
    6  1379.000      5.949     164.240        2.893    4095.038     1056.183
    7  1320.319      5.696     164.240        3.264    4095.038     1056.183
    8  1173.062      5.060     164.240        3.881    4095.038     1056.183
    9  1128.273      4.867     164.240        4.231    4095.038     1056.183
   10  1010.668      4.360     164.240        4.766    4095.038     1056.183
   11  3027.154     13.059     246.366        1.288    4095.038     1056.183
   12  2908.906     12.549     246.366        1.391    4095.038     1056.183
   13  2433.595     10.498     246.366        1.905    4095.038     1056.183
   14  1970.053      8.499     246.366        2.646    4095.038     1056.183
   15  1769.677      7.634     246.366        3.387    4095.038     1056.183
   16  1637.379      7.063     246.366        3.778    4095.038     1056.183
   17  1345.159      5.803     246.366        5.034    4095.038     1056.183
   18  1182.032      5.099     246.366        6.021    4095.038     1056.183
   19  1163.563      5.019     246.366        6.289    4095.038     1056.183
   20  3721.589     16.055     328.493        1.000    4095.038     1056.183
   21  3462.064     14.935     328.493        1.206    4095.038     1056.183
   22  2923.793     12.613     328.493        1.823    4095.038     1056.183
   23  2561.713     11.051     328.493        2.317    4095.038     1056.183
   24  2386.827     10.297     328.493        2.708    4095.038     1056.183
   25  2158.522      9.312     328.493        3.161    4095.038     1056.183
   26  1823.880      7.868     328.493        4.148    4095.038     1056.183
   27  1743.188      7.520     328.493        4.519    4095.038     1056.183
   28  1305.786      5.633     328.493        7.194    4095.038     1056.183
   29  1218.506      5.257     328.493        8.820    4095.038     1056.183
   30  4339.580     18.720     410.606        1.000    4095.038     1056.183
   31  3952.511     17.051     410.606        1.288    4095.038     1056.183
   32  3751.874     16.185     410.606        1.473    4095.038     1056.183
   33  3607.907     15.564     410.606        1.638    4095.038     1056.183
   34  3402.193     14.677     410.606        1.905    4095.038     1056.183
   35  2894.403     12.486     410.606        2.729    4095.038     1056.183
   36  2410.878     10.400     410.606        3.613    4095.038     1056.183
   37  2132.509      9.199     410.606        4.251    4095.038     1056.183
   38  1800.813      7.769     410.606        5.404    4095.038     1056.183
   39  1463.585      6.314     410.606        7.770    4095.038     1056.183
   40  1334.538      5.757     410.606        9.026    4095.038     1056.183
   41  5004.570     21.589     492.733        1.000    4095.038     1056.183
   42  4574.201     19.733     492.733        1.288    4095.038     1056.183
   43  4141.713     17.867     492.733        1.638    4095.038     1056.183
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44	3911.134	16.872	492.733	1.905	4095.038	1056.183
45	3573.321	15.415	492.733	2.317	4095.038	1056.183
46	3131.539	13.509	492.733	2.729	4095.038	1056.183
47	2388.326	10.303	492.733	4.251	4095.038	1056.183
48	2178.701	9.399	492.733	4.951	4095.038	1056.183
49	1976.327	8.526	492.733	5.712	4095.038	1056.183
50	1619.574	6.987	492.733	7.606	4095.038	1056.183
51	5409.714	23.337	574.859	1.000	4095.038	1056.183
52	4441.718	19.161	574.859	1.720	4095.038	1056.183
53	4048.462	17.465	574.859	2.152	4095.038	1056.183
54	3412.412	14.721	574.859	2.893	4095.038	1056.183
55	3333.845	14.382	574.859	3.058	4095.038	1056.183
56	2319.274	10.005	574.859	5.404	4095.038	1056.183
57	2212.299	9.545	191.142	1.000	3482.237	836.649
58	2089.394	9.015	191.142	1.396	3482.237	836.649
59	1451.579	6.263	191.142	3.072	3482.237	836.649
60	1334.516	5.758	191.142	3.467	3482.237	836.649
61	1051.780	4.538	191.142	4.980	3482.237	836.649
62	963.587	4.158	191.142	6.167	3482.237	836.649
63	3037.031	13.104	286.721	1.000	3482.237	836.649
64	2578.532	11.126	286.721	1.652	3482.237	836.649
65	2091.798	9.026	286.721	2.653	3482.237	836.649
66	1674.191	7.224	286.721	4.072	3482.237	836.649
67	1475.198	6.365	286.721	5.050	3482.237	836.649
68	1280.399	5.525	286.721	6.353	3482.237	836.649
69	3699.404	15.962	382.300	1.000	3482.237	836.649
70	2761.179	11.914	382.300	2.141	3482.237	836.649
71	2632.344	11.358	382.300	2.559	3482.237	836.649
71	2632.344	11.358	382.300	2.559	3482.237	836.649
72	16659.731	71.882	382.300	-1.118	3482.237	836.649
73	2072.037	8.940	382.300	3.956	3482.237	836.649
74	1803.997	7.784	382.300	4.864	3482.237	836.649
75	1754.276	7.569	382.300	5.469	3482.237	836.649
76	4055.948	17.500	477.863	1.000	3482.237	836.649
77	3300.851	14.242	477.863	1.954	3482.237	836.649
78	3102.800	13.388	477.863	2.234	3482.237	836.649
79	2607.395	11.250	477.863	3.118	3482.237	836.649
80	2368.550	10.220	477.863	3.863	3482.237	836.649
81	2237.058	9.652	477.863	4.259	3482.237	836.649
82	2150.243	9.278	477.863	4.678	3482.237	836.649
83	2030.628	8.762	477.863	5.073	3482.237	836.649
84	1781.171	7.685	477.863	6.167	3482.237	836.649
85	4529.684	19.544	573.442	1.000	3482.237	836.649
86	3097.671	13.366	573.442	2.769	3482.237	836.649
87	2713.848	11.709	573.442	3.560	3482.237	836.649
88	2495.576	10.768	573.442	4.119	3482.237	836.649
89	2262.090	9.760	573.442	4.980	3482.237	836.649
90	2115.568	9.128	573.442	5.772	3482.237	836.649
91	4582.278	19.771	669.021	1.000	3482.237	836.649
92	3878.571	16.735	669.021	1.931	3482.237	836.649
93	3326.187	14.352	669.021	2.862	3482.237	836.649
94	2955.102	12.750	669.021	3.672	3482.237	836.649
95	2663.397	11.492	669.021	4.468	3482.237	836.649

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The test surface was stabilized till the experimental data were reproduced. It took a period of about 72 hours of aging and 12 hours of boiling. Before conducting the series of the experimental runs, the test liquid was boiled for a period of about an hour by auxiliary heater. This was done to remove the dissolved air from the liquid. The liquid temperatures were brought back to the desired value. The test surface was energized and the heat flux was adjusted. It took about 20 minutes for attaining steady state. The thermocouple and wattmeter readings were noted. It may be mentioned that no reading was taken just after switching off the auxiliary heater. It took about 10 minutes before the turbulence caused by the auxiliary heater subsided. The heat flux to the heat transfer surface was varied progressively by an autotransformer. The experimental data covered natural convection through surface boiling to saturated boiling. The data were taken for distilled water and ethyl acetate.

The experimental parameters were varied over a respective ranges as enlisted in Table 3.1.