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Experimental study of heat transfer to boiling binaries in a reboiler tube

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Abstract—An experimental investigation of heat transfer to boiling binaries under natural convective flow through a reboiler tube has been carried out to study the effect of composition on heat transfer coefficient. The heat transfer section consisted of an electrically heated stainless steel tube of 25.56 mm i.d. and 1900 mm long. Three binary systems: methanol–water, benzene–toluene and water–ethylene glycol were used for a variety of concentrations. The heat flux values ranged from about 4.1 to 33.0 kW m^{-2}. The liquid submergence levels were maintained around 100, 75, 50 and 30%. A significant reduction in the heat transfer coefficient is observed for binary mixtures attributable to the effect of mass diffusion on heat transfer. The heat transfer coefficients in the non-boiling and boiling regions for all the binary mixtures have been correlated by two separate correlations in terms of dimensionless groups.

INTRODUCTION

Vertical tube thermosiphon reboilers as encountered in petroleum, chemical and petrochemical industries, essentially one-to-one heat exchangers fitted in a U-shaped circulation system. The process fluid entering the tubes of heat exchanger gets heated and moves upwards due to density difference between the liquid and boiling two-phase fluid. The boiling of liquids in vertical tubes of closed loop circulation systems as above, finds its application also extending to refrigeration, power plants and nuclear reactors. This may also serve as a potential means of transferring solar energy requiring efficient heat transfer with little or no forced flow, providing a solution to the problem of transportation and storage of the solar energy available in abundance. Under the present energy crisis and need for better methods of its conservation and economical utilization, the thermosiphon reboilers may receive increasing attention as energy efficient equipments in many other applications.

A typical reboiler tube with flow regimes and corresponding temperature distribution along the heated length has been shown in Fig. 1. The subcooled liquid entering the tube gets heated by single phase convection and moves upwards. The liquid and wall temperatures vary almost linearly and are parallel to each other. As soon as the wall temperature attains particular value, the bubbles begin to grow at the surface. The wall temperature variation deviates from linear behavior while liquid temperature continues to increase till it attains saturation value. The bubbles grow in large numbers and populate whole cross-section (bubbly flow) and finally coalesce into slug flow. The chain of slugs join together forming a core of vapor and liquid film at the wall (annular flow). The annular film is gradually depleted and thinned out resulting in vapor-carrying fine droplets (mist flow). The saturation temperature of single component liquids decreases along the tube length due to the reduction in hydrostatic head. The corresponding wall temperature also decreases but at faster rate. In case of binary mixtures, the liquid temperature, beyond the saturation value (bubble point), increases as a result of the dominant effect of preferential evaporation of more volatile component and the rise in concentration of higher boiling point component in the remaining liquid. The wall temperature in the saturated boiling regime is much larger than that for pure liquid due to the detrimental effect of mass diffusion on the boiling process. The flow patterns distribution resulting from the boiling of liquid and induced flow in the vertical tube depend upon several parameters such as heat flux, inlet liquid temperature, driving liquid head (submergence) and the physical properties of fluids. The various flow patterns affect the corresponding pressure drop and mode of heat transfer. There exists a strong interaction between the hydrodynamics and heat transfer making the process very complex. The nucleate boiling heat transfer coefficient in binary or multicomponent liquid mixtures is strongly influenced by the composition of the mixture as

NOMENCLATURE

a	cross-sectional area of heated tube [m^2]
C	heat capacity [J kg^{-1} °C^{-1}]
C_c	heat capacity of cooling water [J kg^{-1} °C^{-1}]
d	inside diameter of heated tube [m]
F	condenser flow rate [kg s^{-1}]
Gr	Grashof number, $(gd^3\beta\Delta T/v^2)$
h	heat transfer coefficient [W m^{-2} °C^{-1}]
$\bar{h}$	average heat transfer coefficient [W m^{-2} °C^{-1}]
k	thermal conductivity [W m^{-1} °C^{-1}]
K_c	Criterion for concentration term, $[1+(y-x)^2/y(1-y)]$
L	total heated length [m]
m	circulation rate [kg s^{-1}]
M_L	liquid flow rate from separator [kg s^{-1}]
M_v	liquid flow rate from condenser [kg s^{-1}]
Nu	Nusselt number, (hd/k)
Pe_B	Peclet number for boiling, $[q\ \rho_L C_L/\lambda\rho_v\ k_L(\sigma/g(\rho_L-\rho_v))^{0.5}]$
Pr	Prandtl number, $(\mu C/k)$
Q	heat input [W]
q	heat flux [W m^{-2}]
Re	Reynolds' number, $(d\,m/a\,\mu)$
S	submergence [%]
T	temperature [°C(K)]
T_{c1}	inlet temperature of cooling water to condenser [°C]
T_{c2}	outlet temperature of cooling water from condenser [°C]
T_{L1}	inlet temperature of liquid to the tube [°C]
T_{L2}	outlet temperature of the liquid to the tube–saturation temperature of liquid in the tube [°C]
T_{s1}	bubble point of the liquid corresponding to the inlet composition–liquid saturation temperature at $Z = Z_{NB}$ [°C]
T_{s2}	liquid saturation temperature at $Z = L$ [°C]
ΔT	temperature difference, $(T_w - T_L)$ [°C]
ΔT_{sub}	degree of subcooling, $(T_s - T_L)$ [°C]
x^o	vapor fraction
x	mass fraction of component in liquid phase
X_{tt}	Lockhart–Martinelli parameter, $[(1-x^o)/x^o]^{0.9}\ [\rho_v/\rho_L]^{0.5}\ [\mu_L/\mu_v]^{0.1}$
y	mass fraction of more volatile component in vapor phase
Z	distance along the test section [m].

Greek symbols

β	coefficient of volume expansion [°C^{-1}]
λ	latent heat of vaporization [J kg^{-1}]
ρ	density [kg m^{-3}]
v	kinematic viscosity, [m^2 s^{-1}]
μ	dynamic viscosity [Ns m^{-2}]
σ	surface tension [N m^{-1}].

Subscripts

B	boiling
C	convective
L	liquid
M	mixed steam
OB	onset of boiling
NB	non-boiling
s	saturation
v	vapor
w	wall.

observed by a number of workers [1–13] in their boiling studies. The heat transfer coefficients in the above studies were found to be lower than those from the pure component liquids. Similar observations were also made in flow boiling of liquid mixtures by Bennett and Chen [14], Kirschbaum [15], Jung *et al.* [16], Kusumowardhoyo and Hardianto [17], Palen [18], Ponter and Pier [19], Ross *et al.* [20], Thome [21] and Toral *et al.* [22]. With natural circulation boiling of liquid mixtures, as encountered in thermosiphon reboiler, therefore, the composition becomes an additional controlling parameter.

The data on boiling of liquid mixtures are scarce and most of those available give insufficient accurate information about the local heat transfer coefficient and circulation rate under the influence of governing parameters. In spite of the industrial importance of the design of reboilers for distillation columns, the studies on thermosiphon boiling of liquid mixtures in vertical tubes have been reported only by Calus *et al.* [23], Shellene *et al.* [24], Ali [25], Kamil [26] and Kamil *et al.* [27–29].

Therefore, the present experimental study was undertaken to obtain such data for natural circulation boiling of binary mixtures and to study the effect of heat flux and submergence on heat transfer to boiling binaries in a single vertical tube thermosiphon reboiler. As a result of data analysis, generalized correlations have been proposed for predicting heat transfer coefficients.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental reboiler was made of two vertical tubes joined in a U-shape with upper ends connected to a vapor–liquid separator and total condenser

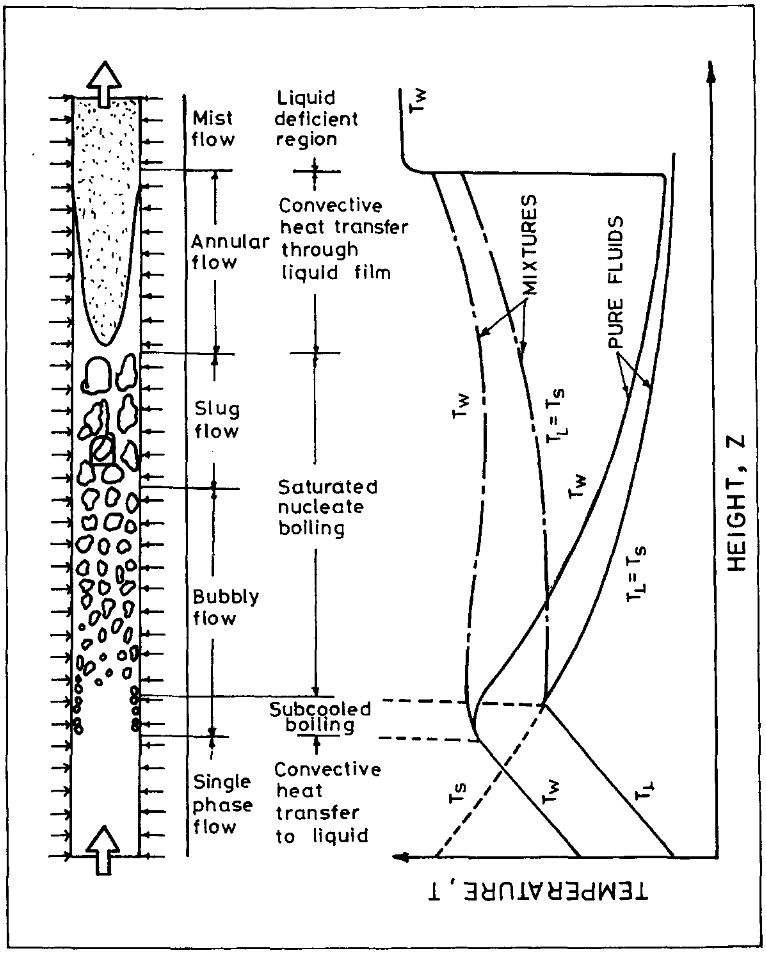

Fig. 1. Flow patterns, boiling regimes and temperature profiles in a vertical tube of thermosiphon reboiler.

vessels forming a thermosiphon loop as schematically shown in Fig. 2. One of the vertical tubes which served as test section was electrically heated. The test liquid boiled in this tube, flowed upwards through a glass section and entered into the separator. The liquid drained down the bottom of the separator while vapors went to a water cooled condenser. The condensate joined the separator liquid near the top end of the other jacketed vertical tube (down flow pipe) through which the total liquid circulated back to the test section through a view port.

The stainless steel tube which served as test section, was of 25.56 mm i.d., 28.85 mm o.d. and 1900 mm long. The stabilized power was supplied through a low voltage high current transformer. The energy input to the test section was measured by calibrated precision type voltmeter and ammeter. In order to monitor the heat transfer surface temperatures along the tube length, 21 copper–constantan thermocouples were spot welded on the outer surface of the tube at intervals of 50 mm upto a length of 200 mm from the bottom end and 100 mm over the remaining length. A copper–constantan thermocouple probe was placed in the view port to measure the inlet liquid temperature. The temperature of the boiling liquid before entry to the vapor–liquid separator was measured by another traversing thermocouple probe. Provisions were also made to measure the flow rates and temperatures in and around the condenser and other strategic locations in the reboiler loop to ensure a reliable computation of circulation rates through the heat balance. Drain cocks were provided at the inlet of test section and exit of the separator and condenser to collect the samples for the measurement of composition of binary liquid mixtures. The entire set up was thoroughly lagged with asbestos rope and glass wool and finally covered with a thin aluminium sheet to reduce the heat losses, which were less than $\pm 2.5\%$.

In order to check the heat balance and reliability of data, a series of runs with forced convection was taken using water. The experimentally measured values of heat transfer coefficient with forced convection agreed well with those predicted using Gnielinski's correlation [30] and Sieder and Tate equation, with correction suggested by Kern and Othmer [31] showing a maximum deviation of $\pm 10\%$. Thus it was ensured that the data generated on the set up are of acceptable standard. After the initial standardization runs, the

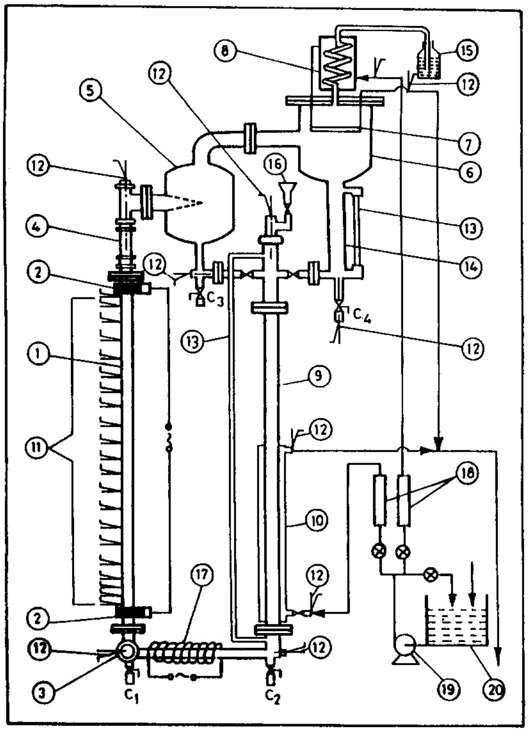

Fig. 2. Schematic diagram of the experimental set-up. Key: (1) test section; (2) copper clamps; (3) view port for inlet liquid; (4) glass tube section; (5) vapor–liquid separator; (6) primary condenser; (7) spiral coil; (8) secondary condenser; (9) liquid downflow pipe; (10) cooling jacket; (11) wall thermocouple; (12) liquid thermocouple probes; (13) liquid level indicator; (14) condenser downflow pipe; (15) bubbler; (16) feeding funnel; (17) auxiliary heater; (18) rotameters; (19) centrifugal pump; (20) cold water tank.

temporary connections of pipe line were removed and reboiler circulation loop was established. The reboiler was filled with distilled water upto the top of the test section. The test section surface was energized and the circulation of coolant water to the condensers was resumed. To avoid any subcooling of the liquid the jacket was emptied, so that the saturated boiling conditions prevailed. The system was kept under operation for many hours followed by aging in order to obtain the stable tube wall nucleating characteristics, which was essential for the reproducibility of data. A few runs were conducted to check the overall heat balance under the conditions of boiling. Care was also taken that once the tube wall was stabilized, it remained fully submerged with liquid as the dry test surface always entraps a very thin film of air.

During the start up of reboiler operation for conducting a series of runs, the test liquid was boiled off for about 8–10 h to remove the last traces of dissolved air which was indicated by the disappearance of the air bubbles in the bubbler. Then a desired heat flux was impressed and cooling water flow rate to the condenser was regulated to give a maximum temperature rise consistent with no loss of vapor due to inadequate condensation. The liquid level in the downflow pipe was adjusted by adding/draining requisite amount of test liquid. When the steady-state conditions were established, the readings of ammeter, voltmeter, thermocouples and rotameters were recorded. The liquid level in the downflow pipe was observed and noted from the level indicator provided for the purpose. The liquid samples from the inlet of the reboiler tube, the vapor–liquid separator and the condensed vapor were withdrawn with the help of a specially designed double-walled sampling device made of glass through drain cocks C_1, C_3 and C_4, respectively. The temperature between the two walls of sampling device was maintained at 0°C by placing melting ice in it. This arrangement proved quite effective for instant and complete cooling of the sample and thus avoiding vapor loss. After cooling the sample, the inner tube was taken out and kept in a refrigerator. The refractive index of the samples were determined and the composition read from the refractive index–composition chart of the system under study. A similar procedure was followed for various compositions of each binary liquid mixture namely methanol–water, benzene–toluene and water–ethylene glycol. The composition of a binary were judiciously selected based on the behavior of $(y-x)$ vs x plot of the system. The maximum liquid head used in the present study corresponded to the liquid level equal to the top end of the reboiler tube. This condition has been termed as 100% submergence. The experimental data were generated at four different levels of liquid submergence and various heat fluxes. While changing over from one system to the other, the circulation system was freed completely from the previous mixture.

The operating parameters with each binary liquid mixture were heat flux, submergence and inlet liquid subcooling. All the runs were conducted at atmospheric pressure. The mixture concentrations and range of other parameters studied are tabulated in Table 1.

DATA PROCESSING

In the experimental reboiler, liquid enters at the bottom of the tube at a temperature below the corresponding saturation temperature. Because of uniform heat flux distribution, the liquid bulk temperature starts to increase and continues upto the saturation value if all the heat added to the system would go to raise the temperature of the liquid only. After that, the liquid bulk temperature would remain constant at the saturation value and all the heat added would go to generate vapor. This is the thermal equilibrium model suggested by Saha and Zuber [32]. Based on this model the circulation rates and liquid bulk temperature distribution in the thermosiphon reboiler have been determined by making a heat balance on the test section. The effective boiling and non-boiling zones over the entire heated length were determined from the amount of net vapor generation. This could be obtained by the vapor condensed in

Table 1. Range of experimental parameters

System	$q \times 10^{-4}$ [W m^{-2}]	S [%]	ΔT_{sub} [°C]	Concentration of more volatile component [wt. %]
Distilled water	0.57–4.3	30, 50, 75, 100	0.5–4.6	100
Methanol	0.41–2.1	30, 50, 75, 100	1.0–3.7	100
Benzene	0.41–2.9	30, 50, 75, 100	0.7–3.6	100
Toluene	0.41–3.2	30, 50, 75, 100	1.9–8.7	100
Ethylene glycol	1.6–3.0	30, 50, 75, 100	5.8–11.6	100
Methanol–water	0.57–2.9	30, 50, 75, 100	0.5–4.6	5, 10, 18, 26, 30, 38, 58
Benzene–toluene	0.41–2.5	30, 50, 75, 100	1.4–8.2	18, 40, 55, 66, 76
Water–ethylene glycol	1.6–3.3	30, 50, 75, 100	0.7–5.1	5, 15, 25, 40, 57

the condenser. A heat balance around the condenser gives:

$$M_v = [FC_c(T_{C2} - T_{C1})]/[\lambda + C_s(T_s - T_v)]. \quad (1)$$

Thus

$$Z_B = \lambda M_v/\pi q d \quad (2)$$

and

$$Z_{NB} = L - Z_B. \quad (3)$$

The rate of liquid circulation was evaluated by making a heat balance over the non-boiling section of the tube

$$Q = \pi d Z_{NB} q = m C_L (T_s - T_{L1}) \quad (4)$$

$$m = \pi d Z_{NB} q / C_L (T_s - T_{L1}). \quad (5)$$

The assumption of linear relationship for liquid temperature distribution for the non-boiling or sensible heating section with the binary mixture was considered valid upto a temperature T_{s1} where the liquid concentration starts changing due to depletion of more volatile component from the liquid. The relevant equation of temperature distribution becomes:

$$T_L = T_{L1} + (T_{s1} - T_{L1})Z/Z_{NB} \quad (6)$$

where $Z \leqslant Z_{NB}$.

Since the change in composition of the more volatile component was very small, (between 1 and 2%), the liquid temperature distribution along the boiling section of the tube was also computed by a linear relationship

$$T_L = T_{s1} + (T_{L2} - T_{s1})Z - Z_{NB}/Z_B \quad (7)$$

where $Z_{NB} \leqslant Z \leqslant L$.

The vapor fraction of the two-phase mixture at the exit of test section is:

$$x^0 = M_v/m. \quad (8)$$

The local heat transfer coefficients in boiling as well as non-boiling sections were calculated as:

$$h = q/(T_w - \Delta T_w - T_L) \quad (9)$$

where the temperature drop, ΔT_w, between the thermocouple bead and the inside surface was estimated using the equation of conductive heat transfer with internal heat generation for a cylindrical wall.

The length-mean values of heat transfer coefficient in the boiling region were calculated as given below:

$$\bar{h}_B = q/\Delta T_B. \quad (10)$$

RESULTS AND DISCUSSION

The wall temperature distributions along the heated length of the test section were obtained from experimentally measured values of the surface temperatures at 21 locations on it. The typical representative plots of these distributions with heat flux and liquid submergence as parameters are given in Figs. 3(a) and (b) for methanol–water and benzene–toluene systems respectively. The variation of liquid temperatures has been shown corresponding to the lowermost curve of wall temperature only. The general characteristic behavior of curves may be observed as follows:

(a) The wall temperature, T_w, rises at a fast rate with Z from its inlet (lower) end up to a point beyond which a steep fall sets in followed by a gradual decrease, over the remaining portion of the heated tube. The shape of the curves is almost similar for other heat fluxes and approximately the same inlet liquid subcooling. However, the curves at higher heat flux values get shifted to higher wall temperatures. The typical behavior, as observed above, remaining the same for all the binary liquid mixtures, the values of wall temperatures, location of peak values and the lengths of various zones are different.

(b) The location of wall temperature peaks get shifted towards the tube inlet and the curves move to lower values of T_w as the liquid submergence is reduced from 100 to 30%. At the submergence of 100 and 75%, all the regimes of heat transfer are present while at lower submergences of 50 and 30% the initial portions of curves before peak are almost absent.

(c) The liquid temperature increases linearly along the tube length as observed for pure liquids, upto a point where it attains the saturation value (bubble point). The liquid temperature remains saturated with its temperature increasing at a very low rate. This may be attributed to the vaporization of liquid accompanied with the decrease in the concentration of low boiling component as the liquid moves upwards. The bubble point thus increases along the tube length inspite of the reduction in hydrostatic head.

The typical variation of wall and liquid temperatures as observed indicates that there exist different regimes of heat transfer in a reboiler tube. The linear rise in the temperature of liquid as it moves upwards through the tube results from sensible heating under uniform heat flux. Since the degree of subcooling in the present study is small, the wall temperatures attain values above saturation right in the close vicinity of the tube inlet. When the minimum wall superheat required is attained, the bubbles start nucleating at the surface but collapse there due to the presence of subcooled liquid core. The onset of subcooled boiling thus creates additional turbulence at the surface. This explains why the linearly increasing wall temperature corresponding to convective heat transfer, starts varying at decreasing rate eventually becoming zero at peak values. Once the bulk liquid temperature attains the saturation value, the bubbles generated at the surface grow to their maximum size and get detached resulting in the existence of vapor phase in the tube. All the heat supplied gets absorbed as latent heat of vaporization converting the liquid to vapor. The two phases flow upwards through the tube with increasing quantity of vapor and hence changing flow patterns. This corresponds to the saturated boiling regime as exhibited by the slowly decreasing wall and liquid temperature profiles. As the value of heat flux is raised, the wall temperature also increases in order to provide adequate temperature difference for transferring the additional heat. In convective mode, this should be almost in the same ratio as that of heat flux change. But in nucleate boiling it is not so because the increased heat flux enables larger number of nuclei for bubble generation becoming active and thus enhancing the heat transfer coefficient and requiring a small temperature difference. This explains the shifting of wall temperature curves with heat flux as observed in Figs. 3(a) and (b).

The effect of concentration on wall temperature distribution has been shown in Figs. 4(a) and (b), respectively. At a given heat flux the nature of variation is similar for all the concentrations of a system. However, the curves get shifted to lower wall temperatures with increase in concentration for saturated boiling as well as initial non-boiling/subcooled boiling regions. There does not seem to be a definite trend near the peak values.

The typical variation of heat transfer coefficient along the test section length with heat flux as parameter for methanol–water system has been shown in Fig. 5(a). The heat transfer coefficient first decreases in the vicinity of tube inlet, and then increases slowly upto a point beyond which it rises very fast with distance along the tube length. At approximately the same value of inlet liquid subcooling and submergence, the characteristic behavior of curves at various heat fluxes remains almost similar. The curves for higher values of heat flux get shifted to higher heat transfer coefficients than those for lower heat flux values. As the heat flux is raised, the initial portions of the curves (decreasing and slowly rising) get shortened shifting the point of steep rise towards tube inlet. Figure 5(b) shows an effect of submergence on the variation of h with Z at a constant heat flux for benzene–toluene system. The curves, at the same value of heat flux, generally shift to higher values of heat transfer coefficient as the submergence is lowered from 100 to 30%. The initial portions of the curves at 100% submergence are quite distinct and longest while they seem to be almost absent at 30%. The point, where saturated boiling sets in, gets shifted to a lower level in the tube as the submergence is reduced from 100% probably due to the change in circulation rates. The decrease in the value of liquid submergence reduces the driving force for liquid circulation and hence its rate through reboiler tube. At a lower rate of liquid circulation the rate of change in its temperature along the tube length becomes higher and the saturation temperature is attained at much smaller length from the inlet. When the submergence is low, the net flow of liquid is small and local circulation between the tube wall and liquid bulk dominates resulting in a condition similar to pool boiling.

The characteristic behavior of h vs Z curves is indicative of heat transfer mechanism governed by various parameters. The initial portions of curves with h decreasing may be assigned to the entrance effect. This is observed to be pronounced at low heat flux values and/or high submergence where the heat transfer is dominantly convective. The increase in h with Z at a slow rate, after the entrance effect may also be due to the convective heat transfer followed by progressively increasing subcooled boiling. The steep rise in the values of heat transfer coefficient correspond to the onset of saturated boiling. The enhancement of transfer coefficient at varying rates along the tube length may be accounted for by the additional turbulence due to nucleation, growth and detachment of vapor bubbles resulting in two phase with different flow patterns. With increase in the value of heat flux larger numbers of nuclei for bubble generation become active enhancing the heat transfer coefficient. The changes in the characteristic behavior of transfer coefficient profiles with submergence seem mainly due to the interaction between circulation rate and bubble dynamics in the tube. The circulation rate increases with S, resulting in the dominant convective heat transfer with appearance of entrance effect and slowly rising h regions. At low submergences, the circulation rate falls and the nucleate boiling dominates showing its effect as observed and discussed.

In order to see the effect of mixture concentration on variation of h with Z, some selected runs at same heat flux and liquid submergence but different mixture concentrations of a system have been plotted in Figs. 6(a) and (b) for methanol–water and water–ethylene glycol systems, respectively. While the main features

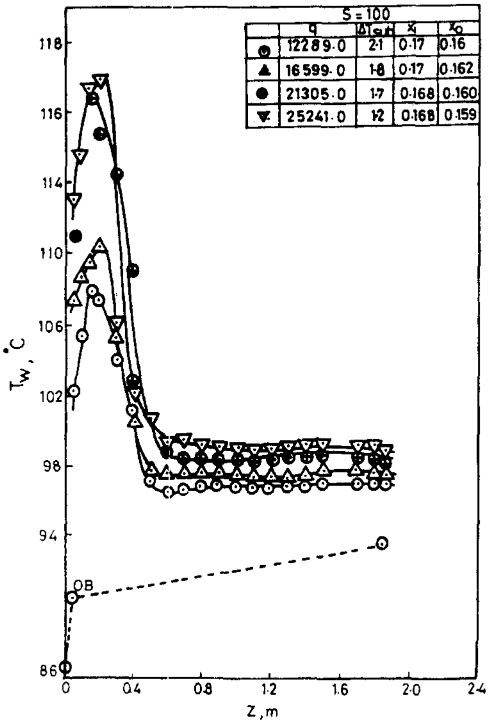

Fig. 3. (a) Variation of wall temperature along the tube length with heat flux as parameter for methanol–water system.

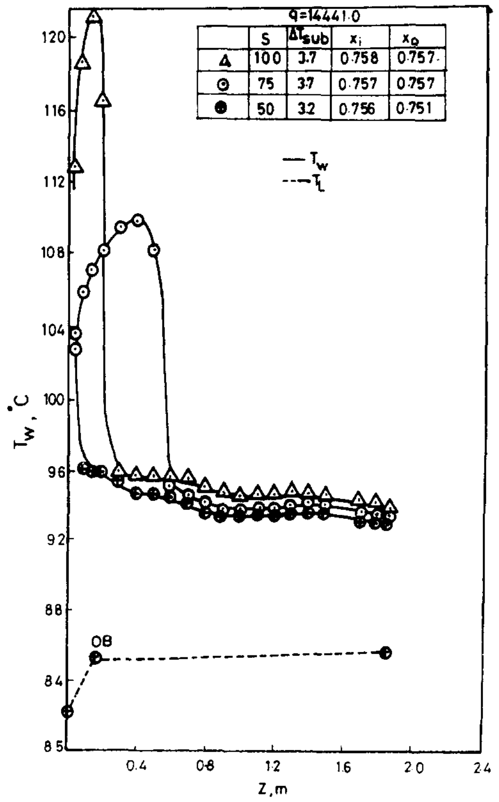

Fig. 3. (b) Variation of wall temperature along the tube length with submergence as parameter for benzene–toluene system.

making the shape of the curves are same at all concentrations and systems as observed earlier, the relative magnitudes, positions of boiling incipience and nature of variations change with composition. The change in the behavior of heat transfer coefficient profiles for binary mixtures may be attributed mainly to the physical properties of mixtures being different from those of their constituents and presumably the effect of mixture composition on the mechanism of the boiling process. Further, with the progress of vaporization, the larger quantities of more volatile component go into the vapor phase reducing its concentration into the liquid phase, the saturation temperature increases and the above effect is intensified. But the higher concentration of vapor phase than that of the coexisting liquid phase in the tube presents the necessary concentration gradient for mass diffusion which might affect adversally the bubble growth rate. Thus the variations of h with Z for binary systems are governed by all the parameters involved for pure components and the additional effect of mass diffusion on bubble growth rate in a very complex manner.

EFFECT OF CONCENTRATION ON AVERAGE HEAT TRANSFER COEFFICIENT

The length–mean values of heat transfer coefficient for saturated boiling of binary mixtures have been plotted against their concentrations in Figs. 7 and 8. These figures clearly demonstrate that $\bar{h}_B$ decreases with increase in concentration of more volatile component in the mixture upto a certain value beyond which it increases showing a minima. The general nature of variation for a system remains essentially same at all heat fluxes and liquid submergences. The shifting of curves with q and S follows the same trend as observed earlier for pure components and mixtures. The mixture concentration at which the heat transfer coefficient becomes minimum is nearly the same at all heat fluxes and submergences for a system. However, each system has its unique value which is observed to be around 20, 40 and 15% for methanol–water, benzene–toluene and water–ethylene glycol systems, respectively. The experimentally obtained values of $\bar{h}_B$ for mixtures are invariably lower than their weighted average at any given concentration. The difference between the two values is maximum at the concentration corresponding to the minimum value of $\bar{h}_B$ for a system.

The different values of heat transfer coefficient for mixtures as compared to the weighted average of the constituent components may be attributed to the change in properties on mixing and the effect of mass diffusion on boiling process. During the boiling of liquid mixtures, the concentration of more volatile component in the vapor bubble becomes higher than

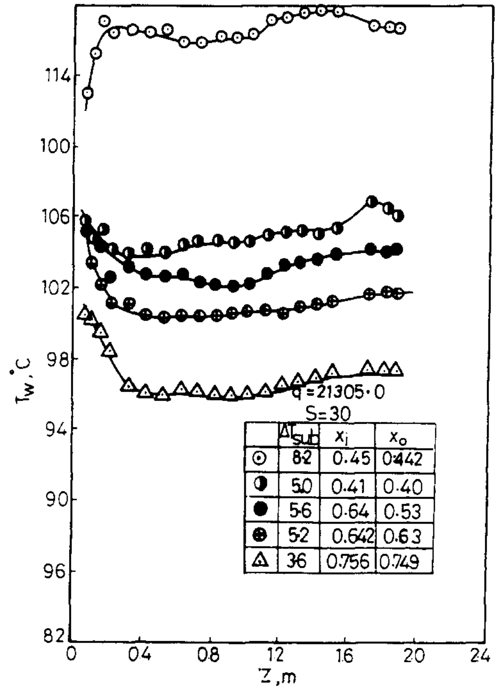

Fig. 4. (a) Variation of wall temperature along the tube length with concentration as parameter for benzene–toluene system.

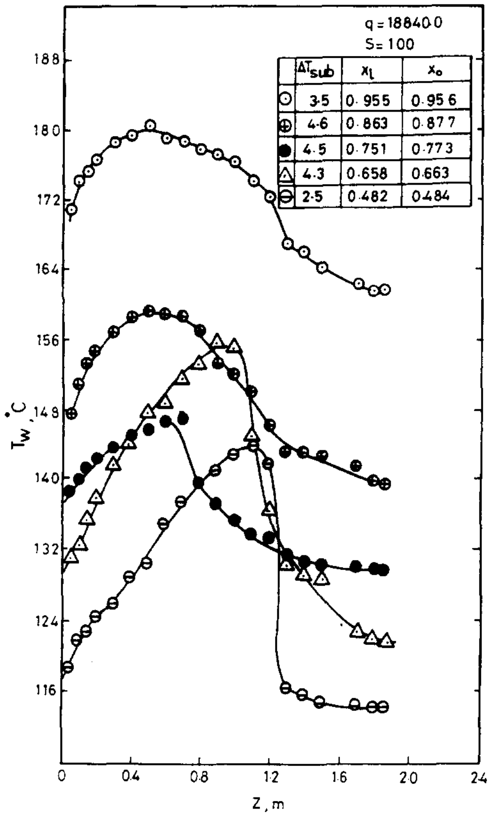

Fig. 4. (b) Variation of wall temperature along the tube length with concentration as parameter for water–ethylene glycol system.

that in the surrounding liquid. The difference between the vapor and liquid phase compositions provides the necessary concentration gradient for the diffusion of more volatile component from the bubble to the liquid. This process being just opposite of the bubble growth and hence the rate of bubble growth gets retarded. The micro-convective contribution to heat transfer, thus gets reduced resulting in a lower heat transfer coefficient than the expected value of weighted average. The rate of diffusion and hence the retardation of bubble growth is maximum at a concentration at which $(y–x)$ is maximum. This is the reason why the values of $\bar{h}_B$ are minimum at the concentrations which are almost same as those corresponding to the maximum value of $(y–x)$ as may be seen in Fig. 9. The above finding is quite similar to those observed in earlier studies [1, 2, 25–29].

CORRELATIONS

It was observed that the point of boiling incipience demarcates the existence of two distinct mechanisms of heat transfer over the vertical tube of thermosiphon reboiler.

(a) *Single phase convection and/or subcooled boiling*
(b) *Saturated boiling*

The variation of h with Z has clearly shown that the values of heat transfer coefficient over the tube length up to the point of boiling incipience have been found to be of lower magnitude than those for saturated boiling over the remaining portion of the tube. Due to the presence of two inherently different mechanisms of heat transfer, it was considered logical to develop separate correlations for the corresponding sections of the tube.

The heat transfer in non-boiling single phase convection is mainly influenced by the induced flow of liquid through the tube. With the rise in temperature of liquid, as it flows upward, the wall temperature also increases at a given heat flux. On attainment of a particular wall superheat, bubbles start nucleating but due to the presence of subcooled liquid core, they remain confined to the surface. The additional turbulence so created is small and the heat transfer coefficient may be governed mainly by the parameters involved in convective heat transfer. The selection of dimensionless groups for the correlation was made based on the earlier studies on single phase closed loop thermosiphon [28, 33–35]. The average values of heat transfer coefficient in this region were well correlated by the following equation with a maximum deviation of ±30% as shown in Fig. 10.

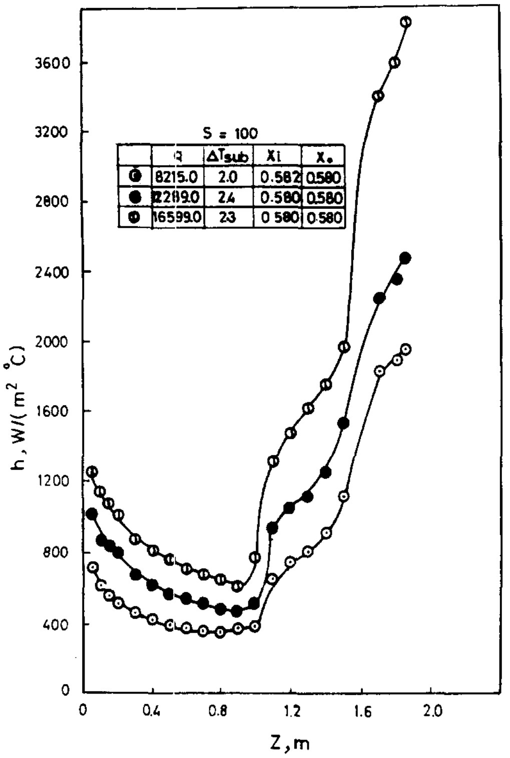

Fig. 5. (a) Variation of heat transfer coefficient along the tube length with heat flux as parameter for methanol–water system.

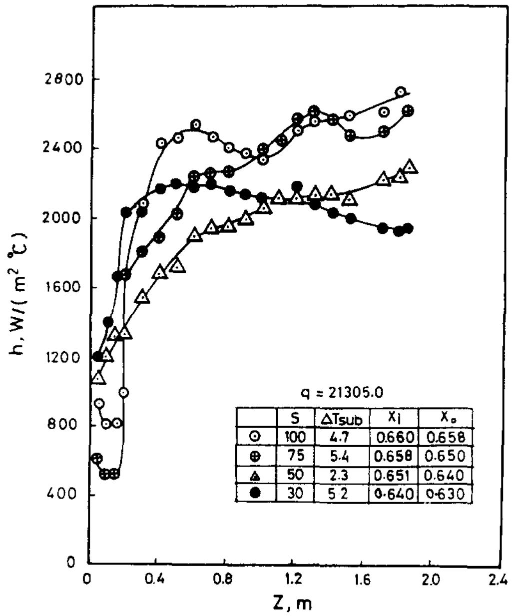

Fig. 5. (b) Variation of heat transfer coefficient along the tube length with submergence as parameter for benzene–toluene system.

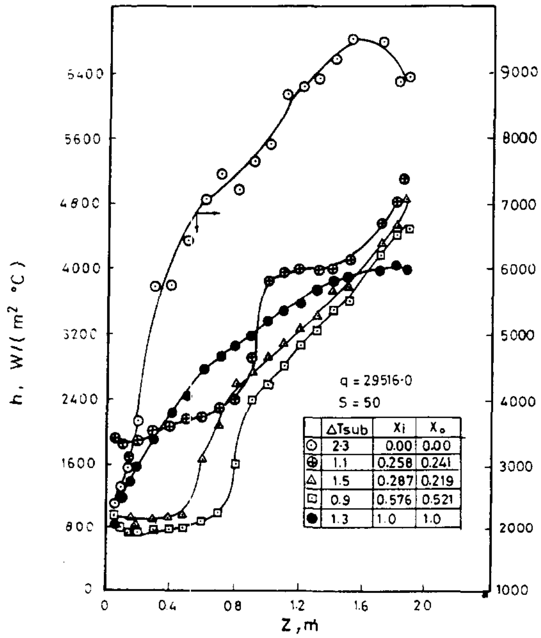

Fig. 6. (a) Variation of heat transfer coefficient along the tube length with concentration as parameter for methanol–water system.

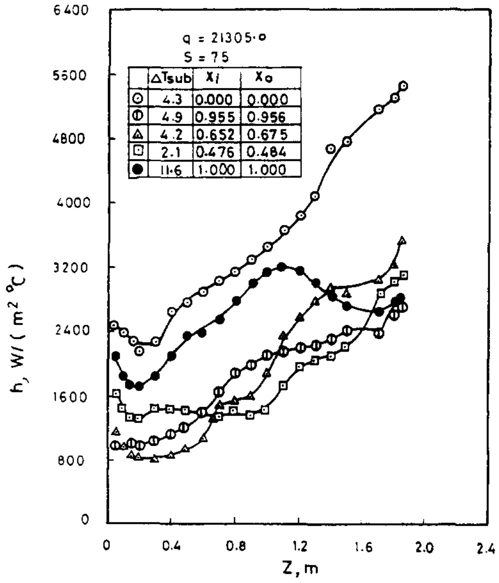

Fig. 6. (b) Variation of heat transfer coefficient along the tube length with concentration as parameter for water–ethylene glycol system.

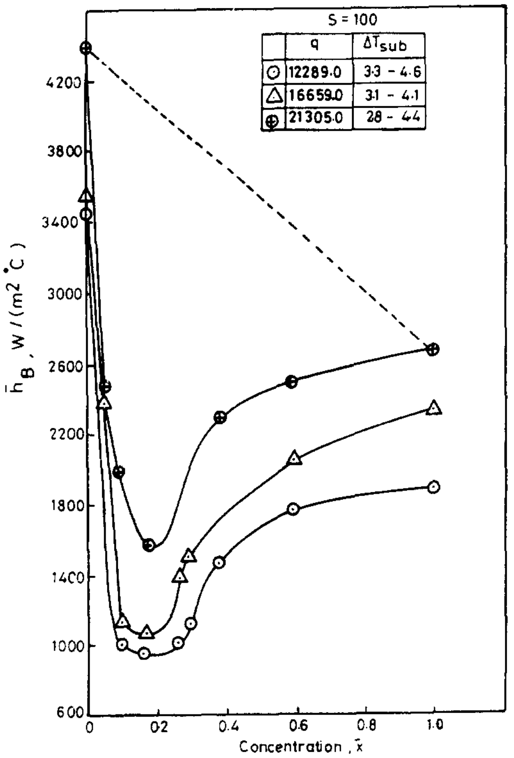

Fig. 7. (a) Variation of average boiling heat transfer coefficient with concentration for methanol–water system.

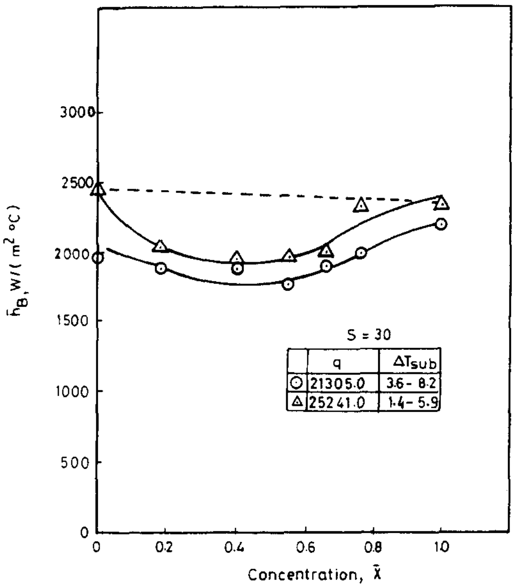

Fig. 7. (b) Variation of average boiling heat transfer coefficient with concentration for benzene–toluene system.

$$Nu_C = 0.6062(Gr)^{0.2017}(Pr)^{0.9587} \times (Re)^{0.063}(Z_{OB}/d)^{0.013}. \quad (11)$$

During the boiling of binary liquid mixtures, the values of heat transfer coefficient have been found to be strongly influenced by the mass diffusion in addition to the microconvection resulting from the

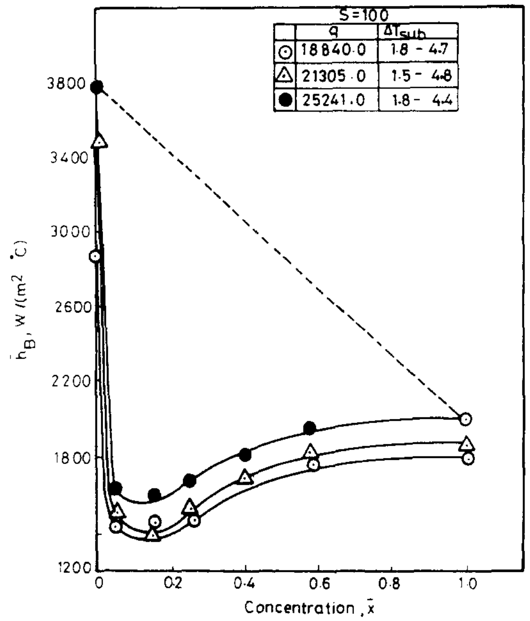

Fig. 8. Variation of average boiling heat transfer coefficient with concentration for water–ethylene glycol system.

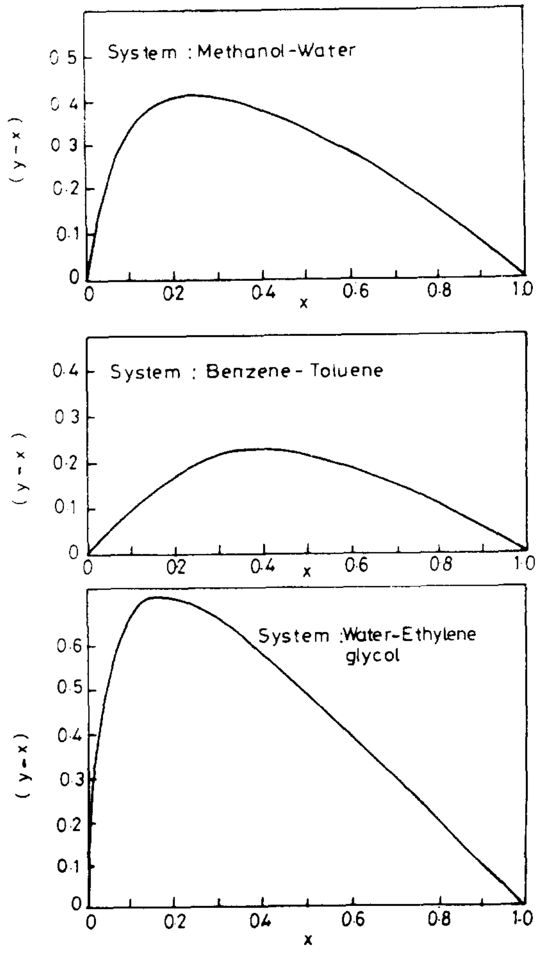

Fig. 9. $(y–x)$ vs x for binary mixtures at $p = 1$ atm.

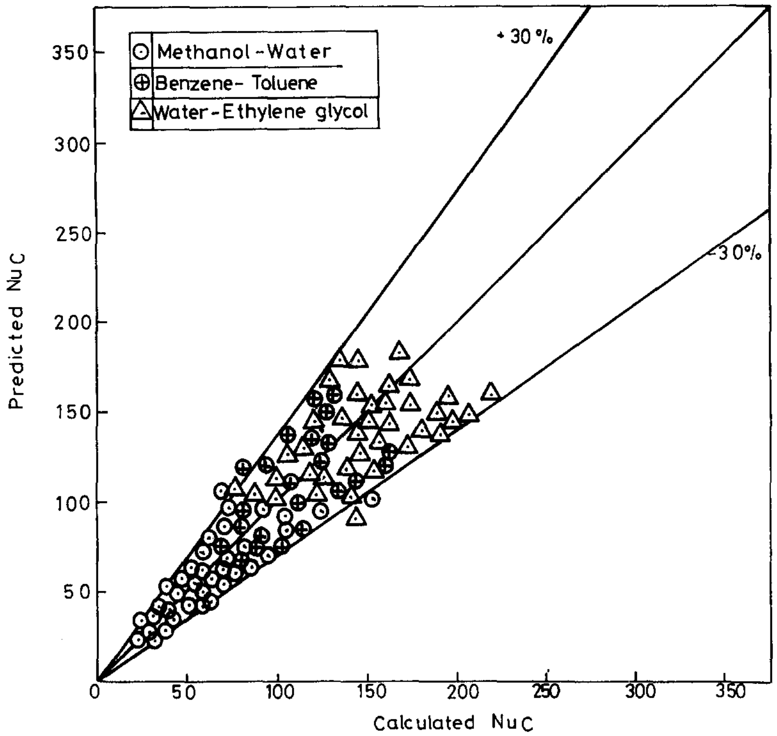

Fig. 10. Comparison of calculated Nu_C and those predicted by equation (11).

bubble nucleation, growth and detachment from the heating surface and macroconvection due to the bulk flow of the two-phase mixture through the tube. The main parameter governing the mass diffusion is the concentration difference (y–x) while the nucleate boiling and convective heat transfer are affected by the heat flux and the mass velocity and flow patterns with varying quality. In order to account for the above mentioned contributions mass diffusion in its dimensionless form as concentration parameter, heat flux as Peclet number for boiling and vapor fraction expressed as Lockhart–Martinelli parameter were identified to correlate heat transfer coefficient as Nusselt number. The correlation developed earlier [26, 35] for the boiling of single component liquids was modified by introducing a criterion for concentration term, K_c, as suggested by Grigorev [4] who extended the Kruzhilins analysis [36] for the boiling heat transfer of binary mixtures. The values of constant and exponents were determined using all the data points of single component liquids as well as binary liquid mixture to obtain the following correlation for average heat transfer coefficient:

$$Nu_B = 7.7297(Pe_B)^{0.4333}(Pr_B)^{0.1772}(X_{tt})^{0.1577} \times (\sigma_M/\sigma_{H_2O})^{0.0074}(K_c)^{0.1225}. \quad (12)$$

A plot between Nusselt numbers predicted by the equation (12) and those experimentally determined is shown in Fig. 11. Almost all the data points were well represented by the above equation with a maximum error of ±30%. The circulation rate through the reboiler tubes may be predicted with the submergence by using the correlation given by Kamil [26] and Kamil *et al.* [37].

CONCLUSIONS

The following important conclusions are drawn from the present study:

(1) The values of heat transfer coefficient during boiling of binary mixtures are generally lower than the weighted average of the pure component values. This reduction may be due to the expected retardation of bubble growth rate by the diffusion of more volatile component from the vapor bubble to the saturated liquid.

(2) The average heat transfer coefficient in the convection dominated section was correlated by equation (11) with a maximum deviation of ±30%.

(3) For the boiling region, almost all the experimental data of the present study were correlated by equation (12) with a maximum deviation of ±30%. It is hoped that the correlation developed will point to certain parameters common to other binary systems, thus at least giving some basis for the speculation about the behavior of other binary liquid systems in flow boiling.

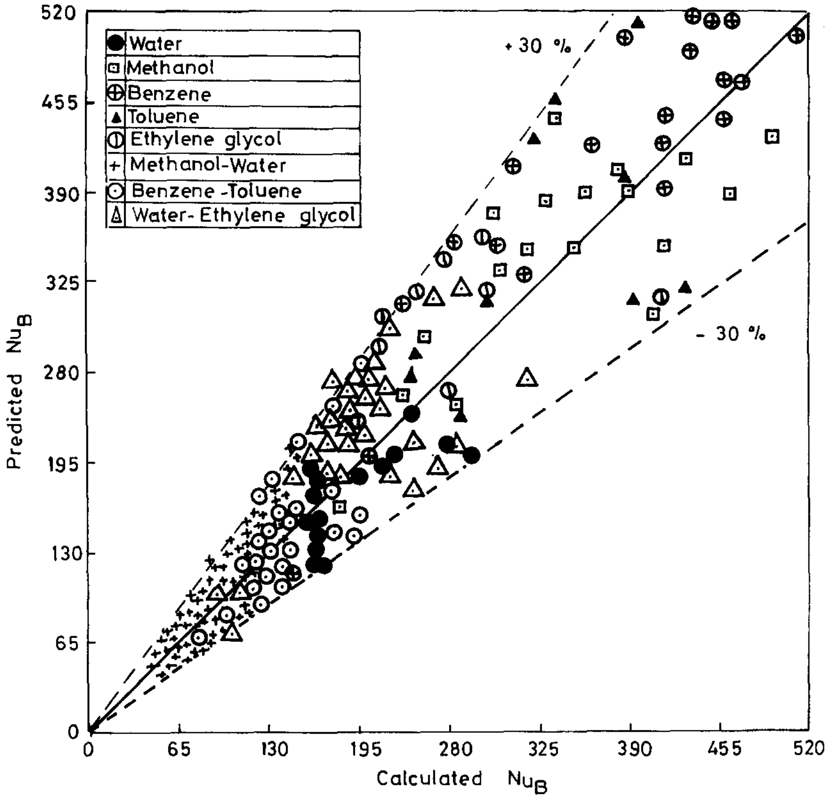

Fig. 11. Comparison of calculated Nu_B and those predicted by equation (12).

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