Circulation rates in thermosiphon reboiler

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An experimental investigation of heat transfer to boiling liquids with natural convective flow has been carried out in a single tube natural circulation reboiler. Three test liquids—water, acetone, and ethylene glycol—were used to cover a wide range of boiling points and thermophysical properties. The heat transfer section consisted of an electrically heated stainless steel tube, 25.56 mm ID and 1900 mm long. The uniform heat fluxes in the range of 3800–40,000 W/m^2 were employed while inlet liquid subcooling varied from 0.2–45.5°C. The liquid submergence levels were maintained around 100, 75, 50, and 30 percent. All the data were generated at 1 atmospheric pressure. The effect of heat flux and submergence on the variation of circulation rates have been graphically presented and discussed. Circulation rates for all test liquids have been correlated in terms of dimensionless groups.

Keywords: thermosiphon; submergence; boiling incipience

Introduction

Thermosiphon reboilers constitute one of the most widely used types of heat transfer equipment in refineries, petrochemical, and chemical process industries where significant capital investment is represented by reboilers, vaporizers, and evaporators. Thermosiphon reboilers owe their popularity to excellent heat transfer rates, mechanical simplicity, and no expenditure of power to circulate the process fluid. The boiling of liquids in a circulation system encountered in a thermosiphon reboiler is applied also to refrigeration systems, pipe stills, power plants, nuclear reactors, and solar energy. In a process industry the equipment is generally a 1-1 exchanger placed vertically, with upper tube sheet close to the liquid of the bottoms in the column. The process fluid entering the vertical tubes of heat exchanger receives the heat from the heat flux supplied. When vaporization takes place in the tubes, the specific volume of the liquid is increased, resulting in its upward movement while the liquid is siphoned from the adjoining cold leg. Thus, a net flow through the circulation loop sets in. The rate of heat transfer and the liquid flow past the heating surface interact with each other under the influence of various governing operating parameters, such as heat flux, inlet liquid subcooling, liquid level in the tube (submergence), and type of fluid. The prediction of rate of liquid circulation and heat transfer is the primary requirement for the design and efficient operation of the thermosiphon reboiler. Several studies have been made to predict the rate of heat transfer during the last two decades, but a very little information is available for the estimation of circulation rates. Johnson[1] carried out an experimental study to measure circulation rates on a 15-inch shell reboiler containing 96 1.0-inch, 12-gauge, 8-ft long tubes. Data were compared with the rates predicted by modification of Kern's method,[2] including the existence of a liquid zone and use of two-phase pressure drop correlation of Martinelli and Lockhart for the vaporization zone. A general method for the estimation of circulation rate through a reboiler tube was first presented by Fair.[3] This method involved a nestle series of trial and error calculations, starting with a rough estimate as a preliminary design. Hughmark[4] discussed the problems in estimating the circulation rate with utilization of a lengthwise temperature profile, and he[5] developed an equation for its prediction in which the two-phase pressure drop was calculated by means of polynomial in terms of the Froude number and volume fraction liquid. Beaver and Hughmark[6] obtained circulating rate data for a single tube thermosiphon reboiler under vacuum and atmospheric pressure and compared with those calculated from a computer program based on gas-liquid two-phase flow correlations developed by Hughmark.[4] Experimental data showed that there was nothing unusual about vacuum operating conditions. The effect of heat flux on the relationship between fluid flow (circulation) and driving force (pressure drop across the tubes) was studied experimentally by Shellene et al.[7] The data were presented graphically and discussed qualitatively. It was found that the regulation of the fluid flow to the reboiler is of importance in maintaining stable operation. Recently, studies have been carried out by Smith,[8] Shah[9] and Agarwal[10] to see the effect of liquid level in cold leg (submergence) on the performance of thermosiphon reboiler. These studies have indicated, qualitatively, that submergence does influence the location of boiling incipience in the tube and operation of the reboiler. Johnson and Yukawa[11] studied the effect of liquid submergence on the circulation rate for vertical thermosiphon reboilers operating under vacuum conditions. The result of this investigation indicated that the optimal practical operating conditions for vacuum reboilers are 50 percent liquid driving head and 50 percent vaporization. The effect of heat flux on circulating flow was observed in a rectangular natural circulation loop, under natural convection condition for water at atmospheric pressure from a vertical tube bundle consisting of seven tubes by Gruszczynski and Viskanta[12] and for a tube bundle

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Received 6 May 1991; accepted 4 October 1991

consisting of 21 tubes by Hallinan and Viskanta.[13] Empirical correlations were developed in terms of dimensionless numbers to govern the fluid flow. Most of these studies were related to water and over a limited range of variables. In spite of the industrial importance of the natural circulation boiling of liquids in vertical tubes where flow and heat transfer interact with each other, no systematic study seems to have been conducted to obtain the effect of governing parameters on circulation rates.

In the present experimental investigation an attempt has been made to study the exclusive effect of heat flux and liquid submergence on circulation rates in a single vertical tube thermosiphon reboiler. As a result of data analysis, an empirical correlation has been developed for the circulation rate in terms of dimensionless number.

Experimental apparatus

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 vessels forming a thermosiphon loop as schematically shown in Figure 1. One of the vertical tubes that served as a reboiler tube was electrically heated. The test liquid boiled in this tube flowed upward 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 reboiler tube through a view port.

The reboiler tube was an electrically heated stainless steel tube, 25.56 mm ID, 28.85 mm OD, 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. Twenty-one copper constantan thermocouples were spot

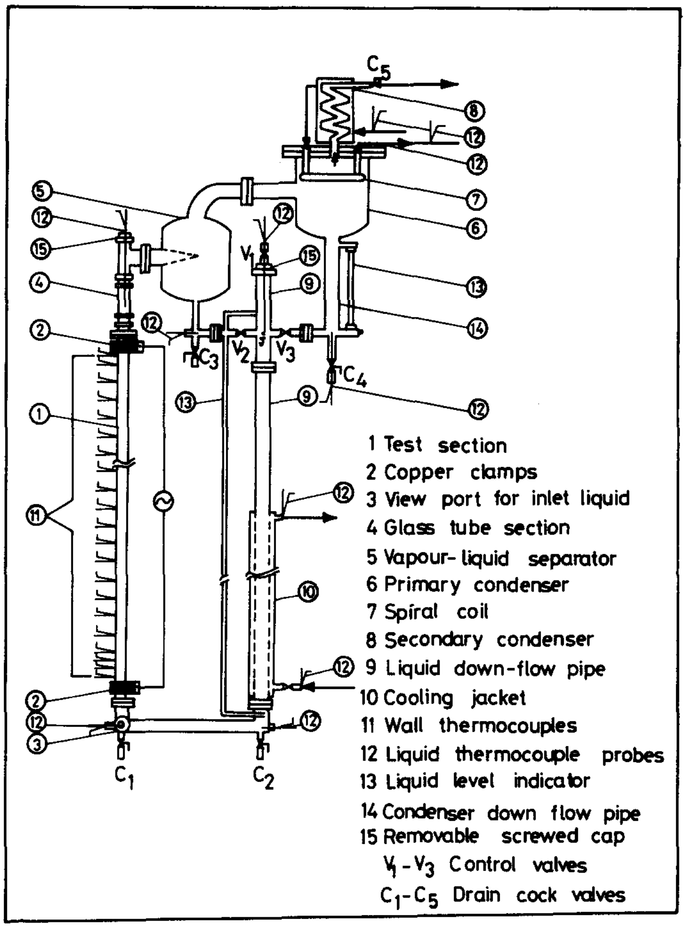

Figure 1 Schematic diagram of the experimental setup

Notation

a	Cross-sectional area of heated tube, m
C	Specific heat, J/kg °C
C_1	Specific heat of cooling water, J/kg °C
d	Inside diameter of the tube, m
F	Cooling water flow rate, kg/s
h	Heat transfer coefficient, W/m^2 °C
k	Thermal conductivity, W/m °C
m	Circulation rate, kg/s
L	Length of tube, m
M_L	Liquid flow rate from separator, kg/s
M_v	Liquid flow rate from condenser, kg/s
q	Heat flux, W/m^2
S	Submergence, percent
T	Temperature, °C
T_1	Inlet temperature of cooling water to condenser, °C
T_2	Outlet temperature of cooling water from condenser, °C
Δt_{sub}	Degree of subcooling, °C
Z	Distance along the test section, m

Greek symbols

λ	Latent heat of vaporization, J/kg
ρ	Density, kg/m^3
μ	Dynamic viscosity, N s/m^2
σ	Surface tension, N/m

Subscripts

B	Boiling
i	Inlet liquid condition
L	Liquid
M	Mixed stream
NB	Nonboiling
OB	Onset of boiling
s	Saturation
v	Vapor
w	Wall

Dimensionless groups

K_{sub}	Subcooling number, $\left(1 + \frac{\rho_L}{\rho_v} \cdot \frac{\Delta t_{sub}}{T_s}\right)$
Pe_B	Peclet number for boiling, $\left[\frac{q}{\lambda} \cdot \frac{\rho_L}{\rho_v} \cdot \frac{C_L}{k_L} \left(\frac{\sigma}{\rho_L - \rho_v}\right)^{0.5}\right]$
Re	Reynolds number, $md/a\mu$

welded on the outer surface of the tube at intervals of 50 mm, up to a length of 200 mm from the bottom and 100 mm over the remaining length in order to monitor the heat transfer surface temperatures. The reboiler tube was electrically isolated from the rest of the setup by means of specially designed flanges and upper glass tube section. The lower end of the flanges was connected to a view port through which the liquid coming out of the downflow pipe, 50 mm ID, could be visually observed to ensure the complete absence of any air or vapor bubbles before its entry to the reboiler tube. A copper constantan thermocouple probe was provided in the viewport to measure the inlet liquid temperature. The visual observation of the boiling liquid emerging out of the test section was made through the upper glass tube section. Another thermocouple probe was inserted in the exit line leading to the vapor–liquid separator. Provisions were also made to measure the flow rate and temperature 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. A glass tube level indicator was provided with downflow pipe to indicate the liquid head (submergence) for the reboiler. The entire setup was thoroughly lagged to reduce the heat losses, which were less than ± 2.5 percent.

Procedure

After the assembly and initial testing of the experimental setup, some forced convection data were collected using water to check the heat balance and standardization of the apparatus. The experimentally measured values of heat transfer coefficient with forced convection agreed well with those computed using the Sieder and Tate equation, with correction suggested by Kern and Othmer,[14] showing a maximum deviation of ± 10 percent. The heat transfer surface was then stabilized for the reproducibility of the experimental data. This was done by boiling distilled water, under the conditions of full submergence and nearly zero inlet degree of subcooling for several hours, followed by aging in order to obtain stable tube wall nucleating characteristics. A few runs were also conducted to check the overall heat balance under the conditions of boiling. Care was taken also that once the tube wall got stabilized, it remained fully submerged with liquid as the dry test surface always entraps a very thin film of air that leaves the surface on heating. Thus, there sets in a microconvection near the heat transfer surface in addition to the macroconvection due to density differences. The test liquid was also boiled off at the start of every experiment to drive out the dissolved air completely, which was indicated by the disappearance of the air bubbles in the bubbler. In an experimental run, the desired heat flux was impressed and submergence adjusted by draining/adding the requisite amount of test liquid. The cooling water rate was regulated to give a maximum temperature rise consistent with no loss of vapor due to inadequate condensation. The system was allowed to attain thermal equilibrium. When the steady-state condition was established, readings of electrical input, wall thermocouples, liquid thermocouple probes, and cooling water were recorded. 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, in the industrial practice, corresponds to the highest possible driving force obtained by using the liquid level equal to the top tube sheet of reboiler and termed as full 100 percent submergence. The driving head could be varied independently by maintaining liquid level at 75, 50, and 30 percent of the full submergence.

Table 1 Range of experimental parameters

System	q (W/m^2)	S (%)	Δt_{sub} (°C)
Water	5998–39,949	30–100	0.2–45.5
Acetone	3800–15,115	30–100	1.05–16.3
Ethylene glycol	15,115–33,654	50–100	3.25–15.8

System and parameter

Water, acetone, and ethylene glycol were used to generate experimental data. They were chosen to cover widely varying and strongly temperature-dependent physical properties because it is these along with transport properties that influence the development of flow and other important parameters of the system involved. Water served as a basis for comparison. Acetone was included to represent the properties of important chemical family ketones. Ethylene glycol was selected to provide experience with high boiling point, high density, high viscosity, and high surface tension fluid.

The operating parameters investigated with each liquid were heat flux and submergence on a fixed geometry and heating surface characteristics. All the data were generated with increasing heat flux and at atmospheric pressure. The range of parameters covered during experimentation on three liquid systems are given in Table 1.

Data reduction

In the experimental reboiler, liquid enters 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 up to 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 remains constant at the saturation value and all the heat added goes to generate vapor. This is the thermal equilibrium model suggested by Saha and Zuber.[15] 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. In order to determine the liquid circulation rate, it was required to know the length of effective nonboiling or sensible heating region over which the liquid temperature varied linearly. The effective boiling and nonboiling zones over the entire heated length were determined from the amount of net vapor generation. This could be obtained by vapor condensed in the condenser.

A heat balance around the condenser gives

$$M_v = FC_1(T_2 - T_1)/[\lambda + C_s(T_s - T_v)] \tag{1}$$

Thus,

$$Z_B = M_v\lambda/\pi qd \tag{2}$$

and

$$Z_{NB} = L - Z_B \tag{3}$$

The rate of liquid circulation, m, from the heat balance over the nonboiling section of the tube is

$$m = \pi Z_{NB}\, dq/C_L(T_s - T_i) \tag{4}$$

The circulation rates could alternatively be evaluated by writing a local material and energy balance around the point, J, (Figure 1) at which the liquid streams from separator and

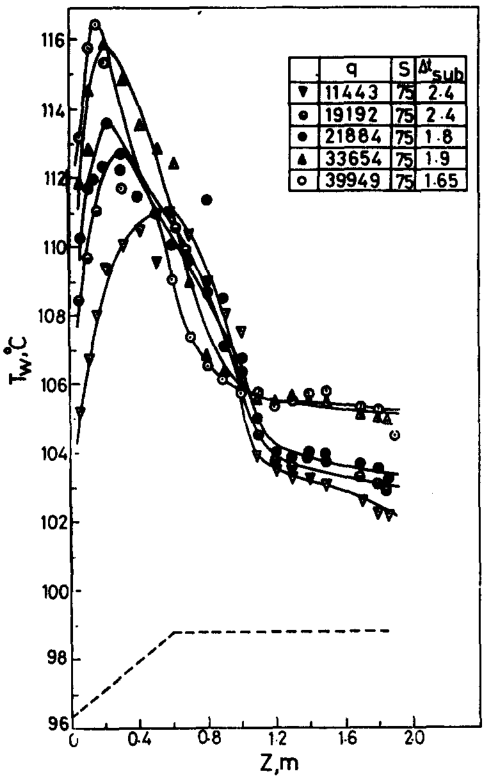

Figure 2 Variation of wall and liquid temperatures along the heated length for water with heat flux as parameter

condenser join together and flow through the liquid downflow pipe. Ignoring the heat losses to the surroundings and assuming a good mixing at the point of junction, the balance may be set up as follows:

Material balance $m = M_L + M_v$ (5)

Energy balance $mC_M T_M = M_L C_s T_s + M_v C_v T_v$ (6)

The values of M_L and m can be evaluated solving the simultaneous Equations 5 and 6 from the knowledge of M_v from Equation 1.

The agreement between the prediction made by two independent methods (Equation 4 and Equations 5 and 6) was found to be within ±6 percent. At lower submergences, the measurements of mixed liquid temperature T_M was not feasible and accordingly the applicability of the method requiring T_M was limited to high submergences only. Hence, the circulation rates for all runs on thermosiphon reboiler were computed using Equations 1–4.

The test liquid temperature distribution along the tube length in the nonboiling section was represented by a linear relationship as given below:

$$T_L = T_i + [(T_s - T_i)Z/Z_{NB}] \tag{7}$$

for $Z \leqslant Z_{NB}$

The temperature distribution along the boiling section of the tube was taken as constant at its saturation value, ignoring the effect of hydrostatic head on boiling point. The error introduced due to this assumption was negligibly small as the length of the test section was not large.

The wall temperature distribution along the heated length of test section was obtained from the experimentally measured values of surface temperatures at 21 locations on it. The liquid temperatures corresponding to the previously mentioned locations were computed using Equation 7. The typical representative plot of this distribution with heat flux as parameter is shown in Figure 2. This distribution was indicative of effective lengths of boiling and nonboiling zones in the reboiler tube and was helpful in verifying the Z_{NB} obtained through the equilibrium model as shown by Ali[16] and Ali and Alam.[17]

The local heat transfer coefficients in boiling as well as nonboiling sections were calculated by dividing wall heat flux with local values of temperature difference between the wall and liquid as expressed by the equation

$$h = q/(T_w - T_L) \tag{8}$$

Results and discussion

The circulation of fluid through the loop and reboiler tube is established by the difference between the hydrostatic head of the liquid in the cold leg and that of the two-phase mixture in the reboiler tube. The hydrostatic head of the two-phase mixture depends directly on its quality, which changes with boiling and generation of the vapor phase.

The rates of liquid circulation through the closed loop thermosiphon system for the experimental runs were computed through heat balance as discussed previously. A typical variation in the value of rates with submergence has been demonstrated in Figure 3 for water. The circulation rate is observed to increase linearly with submergence on the logarithmic plot. The lines get shifted to smaller values of circulation rate as the heat flux is lowered, but they tend to have higher slopes. The liquid submergence provides the driving force for the induced circulation through the heated tube. With the increase in the submergence, lower liquid head in the cold leg is available to balance and push the two-phase mixture through the hot leg—the heated tube. Thus, the rate of net

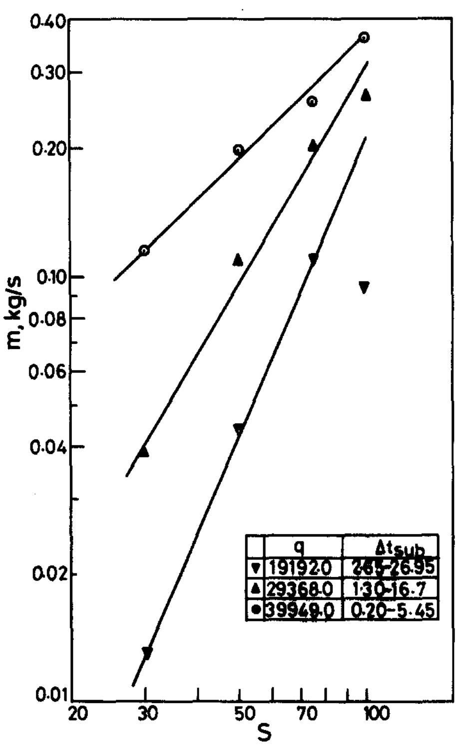

Figure 3 Variation of circulation rate with submergence for water

Table 2 Circulation rates for Figure 4

System	q (W/m^2)	S (%)	Δt_{sub} (°C)	m (kg/s)
Water	29,368	30	1.8	0.039
		50	2.05	0.110
		75	1.30	0.205
		100	1.75	0.253

circulation gets reduced and a larger amount of liquid rising upward in the two-phase mixture falls back. This is confirmed from the computed values of circulation rates as given in Table 2. As a result of increase in the circulation rate with liquid submergence, the change of liquid temperature along the tube length is diminished, and it requires a longer length of tube to attain saturation value. This seems to be the reason why the points of fully developed boiling get shifted to larger Z at higher values of liquid submergence as observed in Figures 4–6. In the experimental runs the inlet liquid subcooling could not be

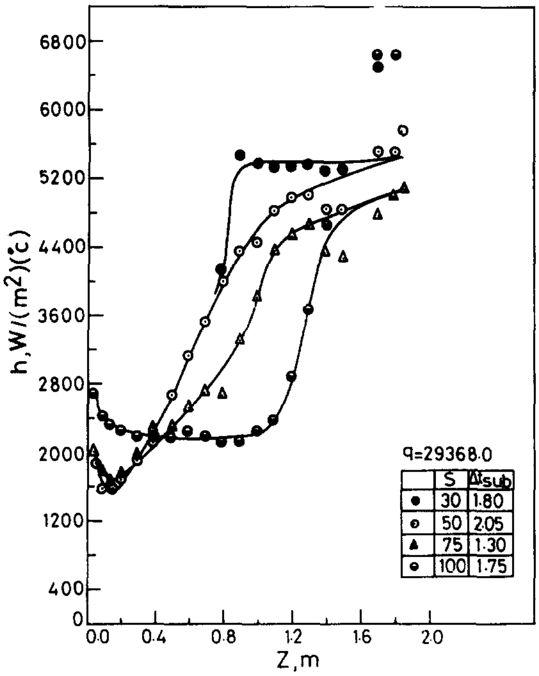

Figure 4 Variation of heat transfer coefficient along the heated length for water with submergence as parameter

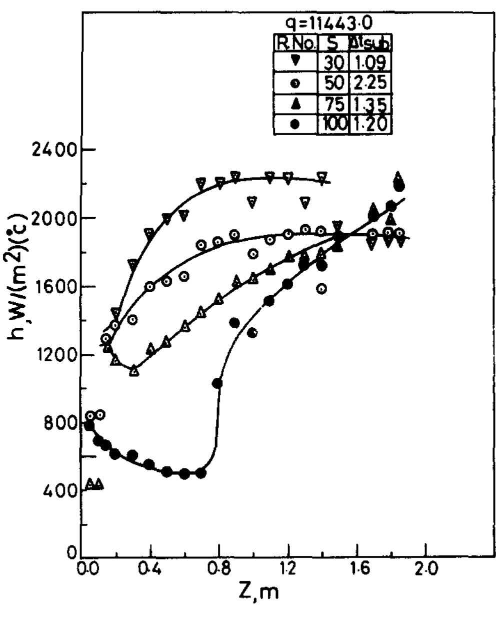

Figure 5 Variation of heat transfer coefficient along the heated length for acetone with submergence as parameter

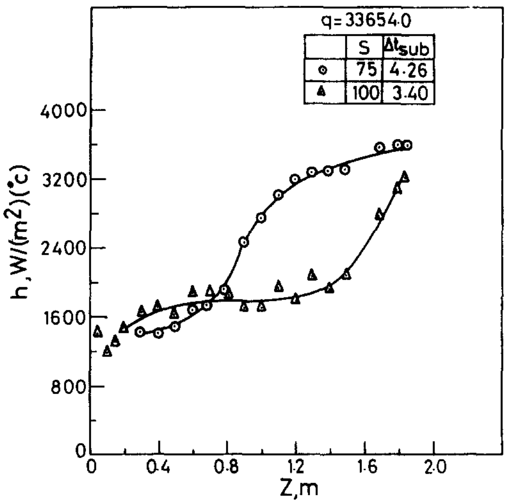

Figure 6 Variation of heat transfer coefficient along the heated length for ethylene glycol with submergence as parameter

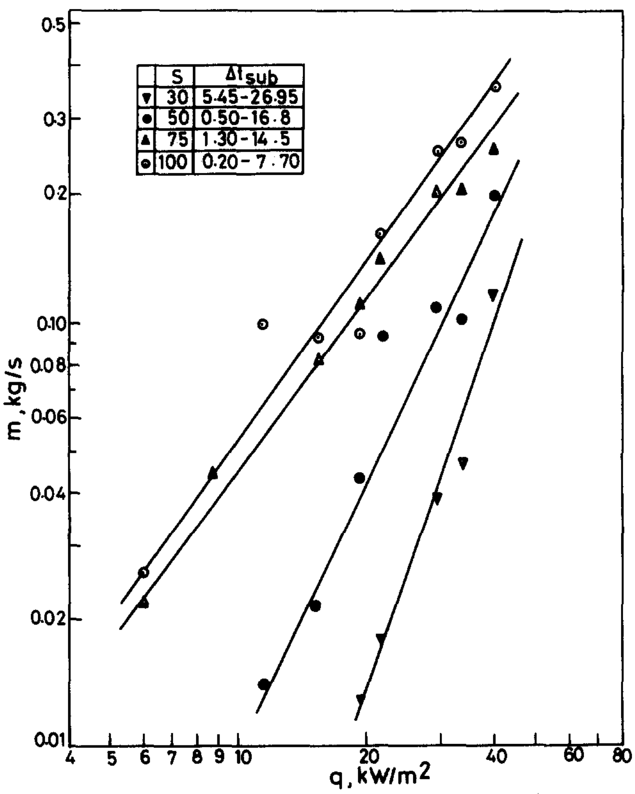

Figure 7 Variation of circulation rate with heat flux for water

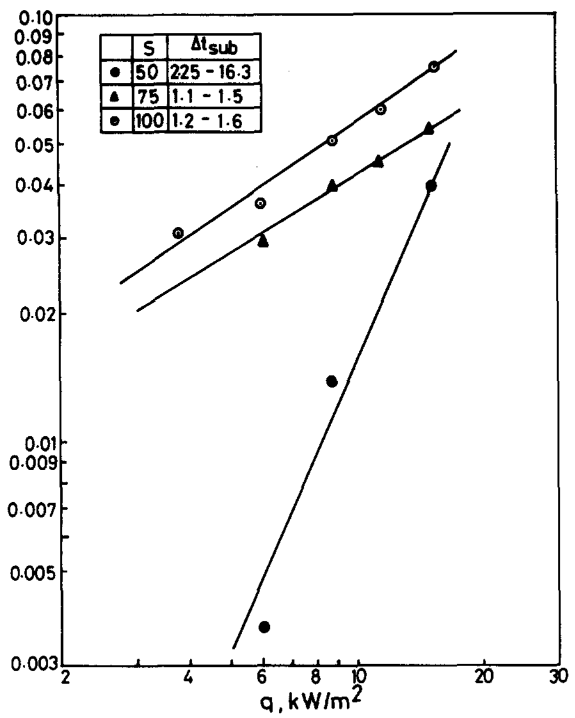

Figure 8 Variation of circulation rate with heat flux for acetone

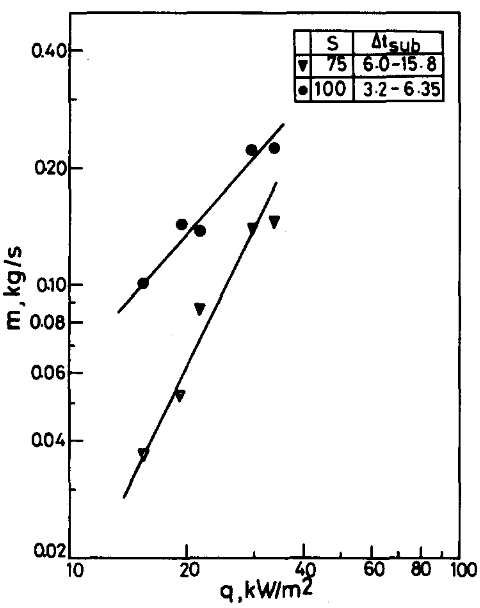

Figure 9 Variation of circulation rate with heat flux for ethylene glycol

Table 3 Range of dimensionless groups in Equation 10

Group	Re	Pe_B	S	K_{sub}
Ranges	1200–62,400	48–587	30–100	7–496

regulated to the desired constant values and these progressively increased on decreasing the heat flux as submergence was varied from 100–30 percent. This seems to be responsible for the scatter of data and variation of slopes of the lines.

The dependence of the circulation rates with heat flux has been represented by Figures 7–9 for water, acetone, and ethylene glycol. The straight lines on the log-log plot suggest the applicability of power law variations similar to Figure 3. At a given submergence, the liquid head in the cold leg remains unchanged, while increasing heat flux shifts the boiling incipience nearer to the tube inlet and saturated boiling occupies a longer length of the tube, resulting in the higher vapor fraction in the reboiler tube. The average density and hence the equivalent head of two-phase mixture gets reduced. Thus, the differential hydrostatic head responsible for fluid circulation increases with q, enhancing the rate as observed in Figures 7–9. At a lower value of liquid submergence the differential head becomes smaller than that at higher S in spite of the increase in the vapor fraction due to more effective saturated boiling in the tube. The effect of unregulated inlet liquid subcooling plays almost the similar role as observed and explained in variation of m with S.

It has been seen that circulation rate through the reboiler tube depends on the wall heat flux, liquid level in the cold leg, and inlet liquid subcooling for a given liquid. In order to account for the previously mentioned contributions, heat flux in its dimensionless form as Peclet number for boiling, inlet liquid subcooling as subcooling number, and submergence were identified to correlate circulation rate as Reynolds number in the following form:

$$\mathrm{Re} = G(\mathrm{Pe}_B)^{n_1}(\kappa_{sub})^{n_2}(S)^{n_3} \tag{9}$$

The value of indices n_1, n_2, n_3 and the constant G were determined by the regression analysis using the experimental data of all the systems and the following equation resulted:

$$\mathrm{Re} = 1.17(\mathrm{Pe}_B)^{0.96}(\kappa_{sub})^{-0.24}(S)^{1.2} \tag{10}$$

A comparison between the calculated Re from Equation 4 with those predicted by Equation 10 has been shown in Figure 10. The experimental data of Agarwal[10] were also plotted in the same figure. Almost all the data points of six test liquids with widely varying physical properties are found to lie along the correlation line, within a maximum deviation of ± 40 percent. The ranges of various groups covered by the experimental data are presented in Table 3. The properties used in the above dimensionless groups are at the saturation temperature of the test liquids.

Conclusion

An effort has been made to develop an empirical correlation to predict the circulation rates in terms of operating parameters. The form of the equation is fairly general; however, its applicability to other systems may have to be substantiated with more data.

The results of the present study may be used in uniform wall temperature problems if the flux profile is known.

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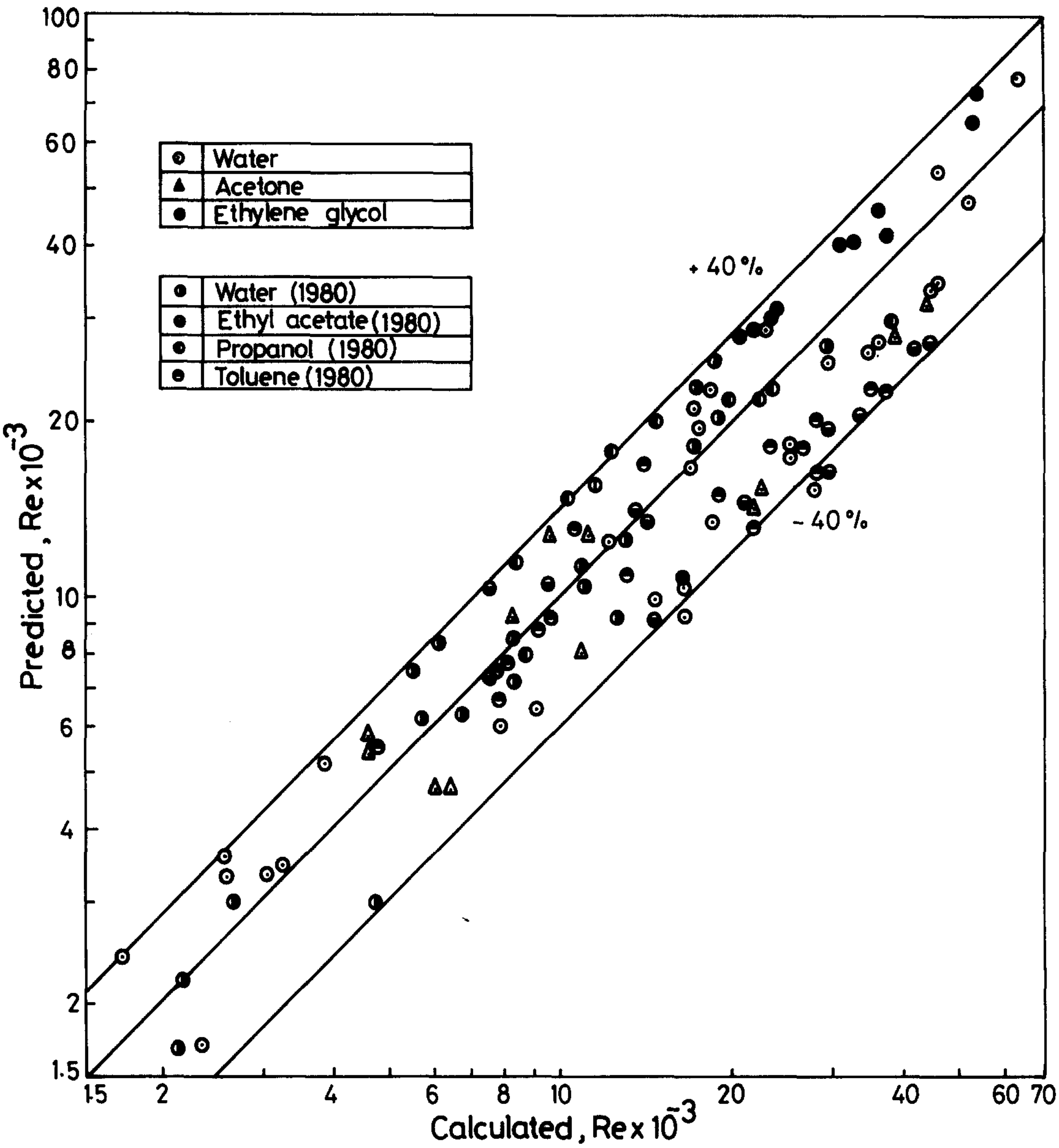

Figure 10 Comparison of calculated Re and those predicted by Equation 10

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