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Nucleate pool boiling performance of acetone–ethanol and methylene chloride–ethanol binary mixtures

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Abstract—Nucleate pool boiling heat transfer coefficients for acetone–ethanol and methylene chloride–ethanol binary mixtures are measured at pressures ranging from 2.0 to 5.0 bar at which the heat fluxes are varied from 10 to 40 kW m^{-2}. Experimental results are tested with the correlations of Happel–Stephan and Schmadl–Bier. Although both correlations are in good agreement with the experimental results, Happel–Stephan's correlation is the more representative form.

1. INTRODUCTION

NUCLEATE boiling of binary liquid mixtures has become one of the most interesting subjects in the scope of heat and mass transfer for the last 20 years. Numerous investigations have been performed, directed both to explain the physical mechanism of boiling, especially the deterioration observed in heat transfer, and to the prediction of the heat transfer coefficient. But, none of these could produce a universal correlation having validity for all practical ranges of conditions and systems, due to the very complex nature of binary mixture boiling phenomena.

In the correlations available in the literature to predict the binary heat transfer coefficient, the variation of the ratio of predicted and ideal heat transfer coefficients was given as a function of physical properties and working conditions. Most of the correlations included the physical properties such as f, α_L, D that were difficult to obtain for mixtures [1–4]. Some others have parameters to be determined experimentally [5, 6]. Thome's [7] very simple correlation, not needing those and modified from that of Stephan–Körner's correlation [5] assumes that the local boiling point rise near the heating surface, which is one of the most important reasons attributed to the deterioration in heat transfer, could be taken equal to the maximum boiling point rise, ΔT_{bp}, as an approximation. It was pointed out that this correlation can be considered as a good prediction, especially at high fluxes, although the boiling point rise may not be equal to ΔT_{bp} even at peak heat flux.

In this paper, the original experimental data on acetone–ethanol and methylene chloride–ethanol mixtures were presented and these were tested with two empirical correlations of the simple form which were proposed recently by Happel and Stephan [6] and Schmadl [8].

2. APPARATUS AND PROCEDURE

The apparatus consists mainly of a reboiler and a condenser. The reboiler of 350 mm i.d. and 150 mm long was made from AISI-316 stainless steel. It has two sight glasses in both sides in order to allow visual observation of the test fluid and the main heater, which is mounted horizontally inside the reboiler. An auxiliary heater of maximum 500 W capacity was placed inside the reboiler to enable boiling conditions to be reached without switching on the test tube heater. The condenser was made from AISI-304 stainless steel with a 210 mm shell i.d. and 700 mm length into which six horizontal tubes of 16 mm o.d. were placed. A heat transfer oil at desired temperatures could be passed through the tubes to condense the vapour coming from the reboiler. The heat transfer area of the condenser can be used at the ratios of 1/3, 2/3 and 3/3 by a valve system at the entrance of the condenser.

The test tube of 8 mm o.d. and 1 mm thickness was made from AISI-304 stainless steel. A copper tube of 4.8 mm o.d. was inserted in the test tube. The annulus was filled with molten lead to reduce the resistance to heat transfer. The heat required for boiling was supplied electrically by a resistance wire of 247 mm length which was tightly placed in the copper tube. The ends of the test tube were insulated to assure uniform temperature distribution along the surface. Finally, the test tube was well polished.

A chromel–alumel thermocouple was placed and soldered in a groove outside the copper tube at the midpoint of the test section. The temperature of the

NOMENCLATURE

A	heat transfer area [m^2]; empirical coefficient
B	empirical coefficient
C	empirical coefficient
D	liquid mass diffusivity [m^2 s^{-1}]
D_1	outside diameter of copper tube [m]
D_2, D_3	inside and outside diameters of stainless steel tube [m]
f	bubble departure frequency [s^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
K_{St}	empirical coefficient
k_{Pb}	thermal conductivity of lead [W m^{-1} K^{-1}]
k_s	thermal conductivity of stainless steel [W m^{-1} K^{-1}]
L	length of resistance wire [m]
m	empirical exponent
p	pressure [bar]
p^*	reduced pressure
Q	heat flow [W]
q	heat flux [W m^{-2}]
T_w	real wall temperature [K]
T_{wm}	measured wall temperature [K]
ΔT	wall superheat [K]
ΔT_{bp}	maximum boiling point rise [K]
x	mole fraction of liquid
y	mole fraction of vapour.

Greek symbols

α_L	thermal diffusivity of liquid [m^2 s^{-1}]
σ	standard deviation.

Subscripts

1	more volatile component
2	other component
ac	acetone
c	calculated
i	ideal
m	measured
mc	methylene chloride.

outer surface was so measured indirectly and its real value was obtained from the measured value and the temperature drop through the lead layer and the steel tube wall by using the following equation:

$$T_w = T_{wm} - \left[\frac{\ln\dfrac{D_2}{D_1}}{2\pi k_{Pb}L} + \frac{\ln\dfrac{D_3}{D_2}}{2\pi k_s L}\right]Q. \tag{1}$$

The temperature of the boiling liquid was measured by two thermocouples immersed in the liquid at a distance of 40 mm above and below the test tube. A Bourdon manometer with a minimum reading of 0.1 bar was used to measure the working pressure. Temperatures were measured with the help of a digital thermometer with an accuracy of ± 0.2 K.

The heat transfer coefficient was obtained by using the definition equation

$$h = \frac{Q/A}{\Delta T} \tag{2}$$

where Q is the electrical power input to the resistance wire. This value was calculated by the potential drop and electrical current. These measurements were made by a digital potentiometer with an accuracy of ± 7 mV. ΔT is the temperature difference between the outer surface and the bulk liquid and A the available heat transfer area of the test section which was measured as 6.8864×10^{-3} m^2.

The samples taken from liquid and vapour phases were analysed by a JGC-1100 gas chromatograph.

3. EXPERIMENTAL RESULTS

The experiments were carried out with binary mixtures of three different mole fractions 0.25, 0.50 and 0.75 with the absolute pressures ranging from 2.0 to 5.0 bar at which the heat fluxes were varied up to 40 kW m^{-2}.

Experimental results showed that the boiling heat transfer coefficients of either the pure liquids or the binary mixtures increased with rising heat flux and/or pressure. Both q and h showed a linear relationship in log–log coordinates. The slopes of the lines decreased as the pressure increased (Figs. 1 and 2).

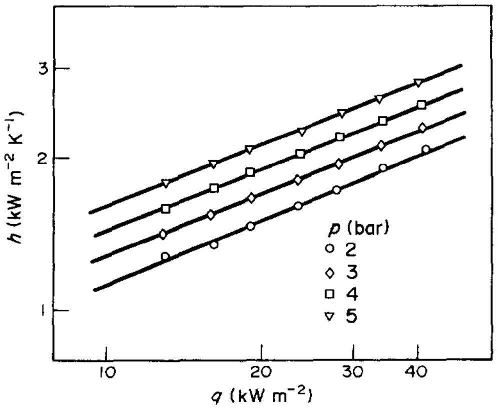

FIG. 1. Variation of boiling heat transfer coefficient with heat flux for acetone for various pressures.

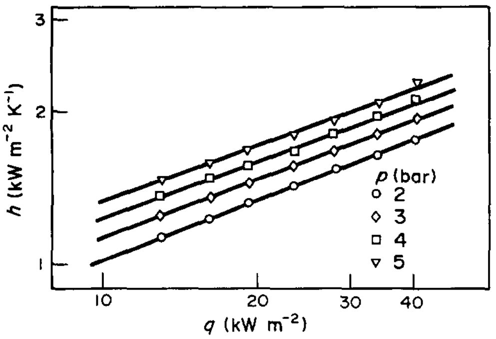

FIG. 2. Variation of boiling heat transfer coefficient with heat flux for acetone–ethanol mixture ($x = 0.50$) for various pressures.

The binary mixture heat transfer coefficients were always lower than the ideal values (Figs. 3 and 4) which are calculated from the heat transfer coefficients of the pure liquids as follows:

$$h_i = h_1 x + h_2(1-x). \tag{3}$$

Finally, the ratios of observed and ideal heat transfer coefficients, which are a measure of the deterioration in heat transfer, were decreased as the heat flux and/or pressure increased at a given concentration (Figs. 5 and 6).

An interesting point is that the maximum deterioration was observed at the concentrations where the absolute concentration differences between vapor and liquid phases were also maximum. This confirmed that the mass transfer resistance to the movement of the more volatile component was also responsible for the decrease in heat transfer.

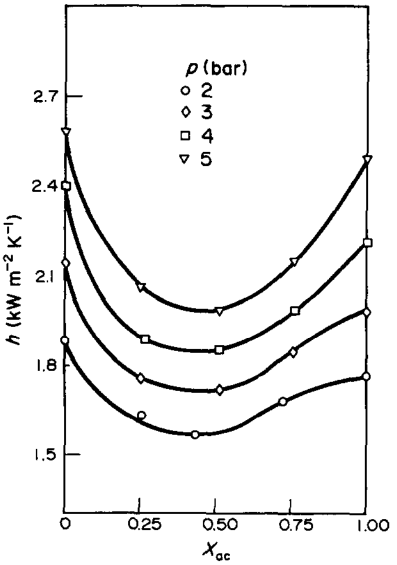

FIG. 3. Variation of boiling heat transfer coefficient with composition for acetone–ethanol mixtures at 30 kW m^{-2} for various pressures.

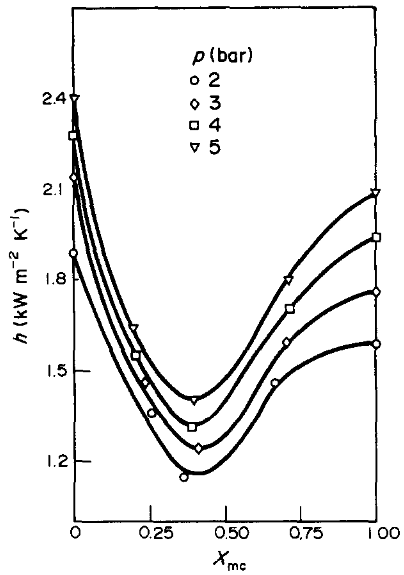

FIG. 4. Variation of boiling heat transfer coefficient with composition for methylene chloride–ethanol mixtures at 30 kW m^{-2} for various pressures.

4. TESTING OF EXPERIMENTAL RESULTS WITH TWO CORRELATIONS

The experimental results were tested with two empirical correlations. The first of these was proposed by Happel and Stephan in the following form:

$$\frac{h}{h_i} = \frac{\Delta T_i}{\Delta T} = 1 - K_{St}|y-x|^m \tag{4}$$

where K_{St} and m are the constants needed to be found experimentally for each system, heat flux and pressure.

Schmadl and Bier gave a similar relation by evaluating K_{St} as a function of reduced pressure, p^*

$$\frac{h}{h_i} = 1 - \left(A + Bp^* + \frac{C}{1-p^*}\right)|y-x|^m \tag{5}$$

where A, B, C and m are the constants depending upon system and heat flux. Critical pressures required for the calculation of reduced pressures were obtained by the Kreglewski–Kay method [9].

All the constants in the correlations, the standard deviations and maximum deviations were determined by means of a regression program. The results are given in Tables 1 and 2 and Figs. 7 and 8 for each binary system measured.

By comparing the standard deviations, it was concluded that Happel–Stephan's correlation represented the experimental results better than the other, although both correlations were found to be in good agreement with the data. It was also determined that the greatest maximum deviations for Happel–Stephan 's correlation are 1.95% for acetone–ethanol and 10.66% for methylene chloride–ethanol mixtures, while they are −3.81 and 9.50%, respectively, for Schmadl–Bier's correlation.

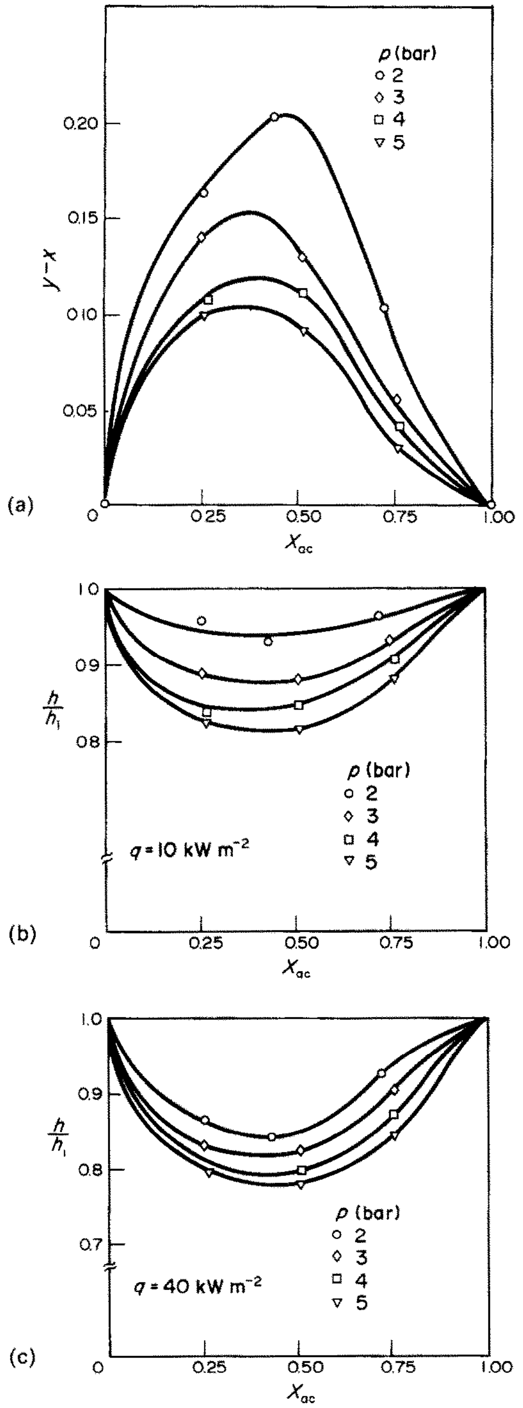

FIG. 5. Variation of concentration difference and normalized heat transfer coefficients with liquid composition for acetone–ethanol mixtures at $q = 10$ and 40 kW m^{-2} for various pressures.

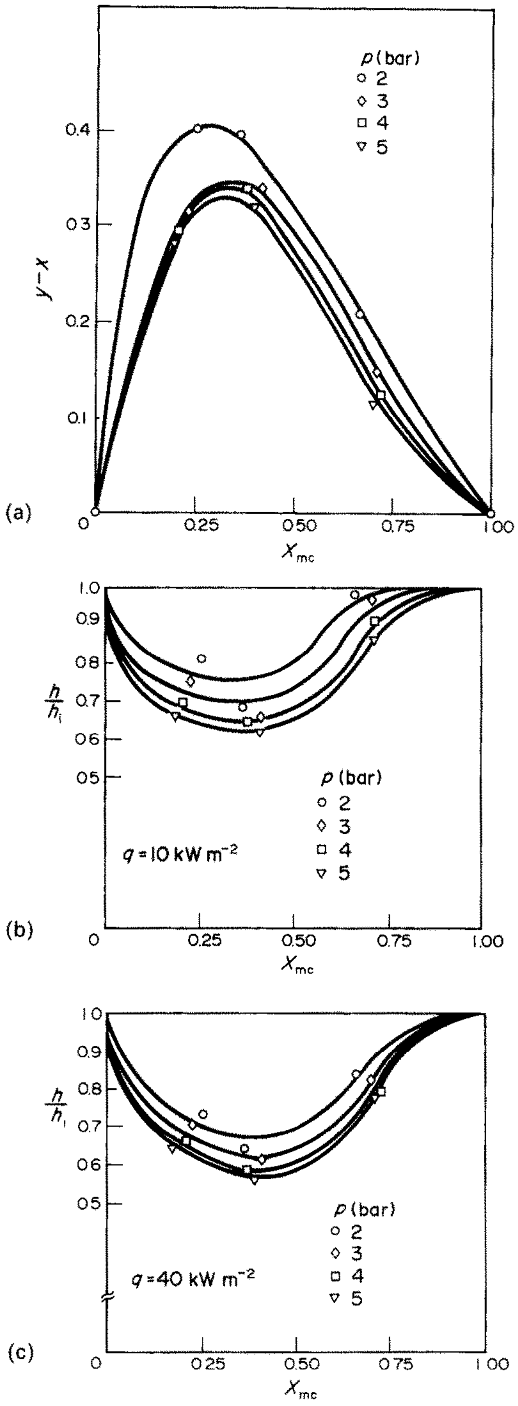

FIG. 6. Variation of concentration difference and normalized heat transfer coefficients with liquid composition for methylene chloride–ethanol mixtures at $q = 10$ and 40 kW m^{-2} for various pressures.

5. SUMMARY AND CONCLUSIONS

(1) Nucleate pool boiling heat transfer coefficients were measured for acetone–ethanol and methylene chloride–ethanol binary mixtures at pressures ranging from 2.0 to 5.0 bar at which heat fluxes were varied up to 40 kW m^{-2}.

(2) Heat transfer coefficients of binary mixtures were always lower than ideal values calculated from the pure liquid data by a linear mixing law.

(3) The deterioration in heat transfer increased as heat flux increased at a given pressure and concentration (Figs. 5 and 6).

(4) The deterioration in heat transfer increased as

Table 1. Comparison of two correlations with experimental results for acetone–ethanol mixtures

		Standard deviation, σ†		Maximum deviation (%)	
p (bar)	q (kW m^{-2})	Happel–Stephan	Schmadl–Bier	Happel–Stephan	Schmadl–Bier
2.0	10	4.523×10^{-3}	8.503×10^{-3}	−0.83	−1.79
2.0	40	3.340×10^{-3}	1.665×10^{-2}	0.69	−3.81
3.0	10	3.444×10^{-3}	6.850×10^{-3}	0.66	1.22
3.0	40	4.724×10^{-3}	9.753×10^{-3}	0.96	0.95
4.0	10	4.200×10^{-3}	1.094×10^{-2}	0.81	2.84
4.0	40	1.504×10^{-3}	9.138×10^{-3}	0.31	2.55
5.0	10	6.117×10^{-3}	8.708×10^{-3}	1.23	−1.54
5.0	40	7.430×10^{-3}	1.405×10^{-2}	1.57	2.69

† Standard deviations were calculated from the measured and calculated (h/h_i) values by the following equation:

$$\sigma = \sqrt{\left(\frac{\sum_{1}^{n}[(h/h_i)_m - (h/h_i)_c]^2}{n}\right)}.$$

Table 2. Comparison of two correlations with experimental results for methylene chloride–ethanol mixtures

		Standard deviation		Maximum deviation (%)	
p (bar)	q (kW m^{-2})	Happel–Stephan	Schmadl–Bier	Happel–Stephan	Schmadl–Bier
2.0	10	4.445×10^{-2}	5.137×10^{-2}	10.66	9.40
2.0	40	3.044×10^{-2}	3.275×10^{-2}	7.67	7.29
3.0	10	9.629×10^{-3}	3.427×10^{-2}	−1.70	9.50
3.0	40	2.169×10^{-2}	2.534×10^{-2}	−5.21	8.65
4.0	10	4.113×10^{-3}	1.286×10^{-2}	1.02	3.04
4.0	40	1.340×10^{-2}	9.275×10^{-3}	−3.5	2.58
5.0	10	1.720×10^{-2}	2.664×10^{-2}	0.44	5.52
5.0	40	1.634×10^{-2}	1.722×10^{-2}	4.24	−5.45

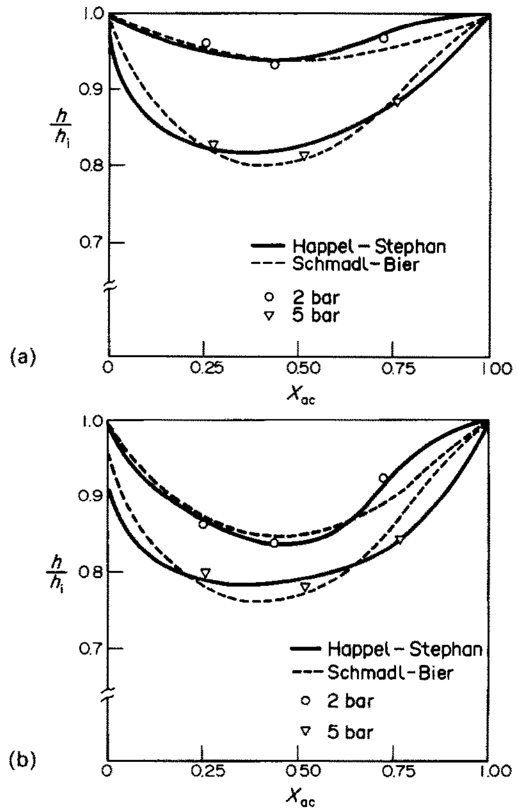

FIG. 7. Comparison of experimental results with two correlations for acetone–ethanol mixtures: (a) $q = 10$ kW m^{-2}; (b) $q = 40$ kW m^{-2}.

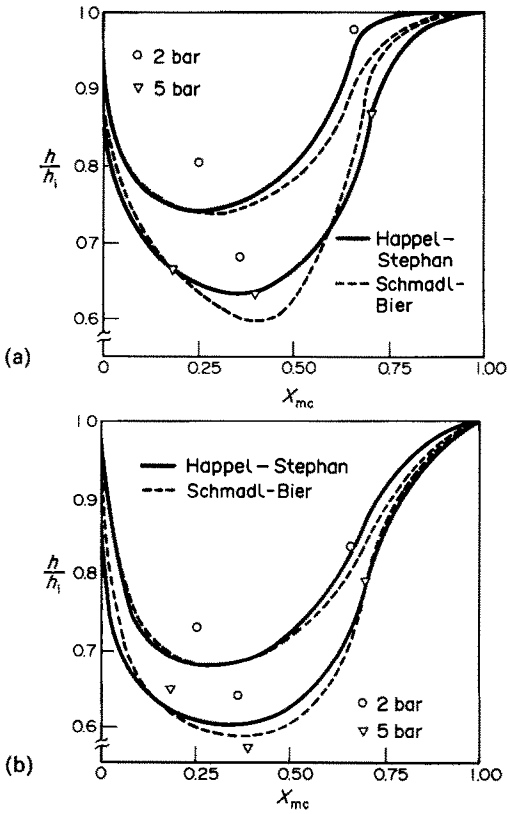

FIG. 8. Comparison of experimental results with two correlations for methylene chloride–ethanol mixtures: (a) $q = 10$ kW m^{-2}; (b) $q = 40$ kW m^{-2}.

pressure increased at a given heat flux and concentration.

(5) The maximum worsening of heat transfer was always observed at the concentration at which $y-x$ values were the greatest.

It follows from Figs. 5 and 6 that, although the concentration difference, $y-x$, decreases with rising pressure, the heat transfer coefficient still deteriorates.

This point, which can be seen as a contradiction at first sight, may be explained as follows.

As the pressure increases, the extent of turbulent motion of liquid near the heating surface decreases due to reduction in bubble size and density difference between liquid and vapour. Both of these effects further complicate the mass transfer which tries to eliminate the reduction in the composition of the more volatile component. As a result of a decrease in mass transfer rate, in the case of fixed surface temperature, the total amount of vaporization and the corresponding heat transfer coefficient decreases. As to fixed heat flux, the surface temperature rises automatically, resulting again in a decrease in heat transfer coefficient.

A similar comment can be made on the effect of heat flux in the decrease of heat transfer. As the heat flux increases, mass transfer of the more volatile component is complicated by crowded bubble population and correspondingly the deterioration in heat transfer.

It follows from the explanation above that the deterioration in heat transfer is greatly affected by governing mass transfer conditions which depend on both pressure and heat flux, besides the $y-x$ difference.

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PERFORMANCE DE L'EBULLITION NUCLEEE EN RESERVOIR POUR DES MELANGES ACETONE–ETHANOL ET CHLORURE DE METHYLENE–ETHANOL

Résumé—Les coefficients de transfert thermique par ébullition nucléée en réservoir sont mesurés pour des mélanges binaires acétone–éthanol et chlorure de méthylène–éthanol, à des pressions entre 2,0 et 5,0 bar et des flux thermiques entre 10 et 40 kW m^{-2}. Des résultats expérimentaux sont confrontés aux formules de Happel–Stephan et de Schmadl–Bier. Les deux formules sont en bon accord avec l'expérience mais celle de Happel–Stephan est la plus représentative.

WÄRMEÜBERGANG BEIM BLASENSIEDEN VON ZWEISTOFFGEMISCHEN AUS AZETON UND ETHANOL SOWIE METHYLENCHLORID UND ETHANOL

Zusammenfassung—Für das Blasensieden (Behältersieden) von Zweistoffgemischen aus Azeton und Ethanol sowie Methylenchlorid und Ethanol werden Wärmeübergangskoeffizienten bestimmt. Gemessen wird bei Drücken von 2,0 bis 5,0 bar und bei Wärmestromdichten von 10 bis 40 kW m^{-2}. Die Ergebnisse werden mit den Korrelationen von Happel–Stephan und Schmadl–Bier verglichen. Obwohl beide in guter Übereinstimmung mit den experimentell ermittelten Werten sind, gibt die Korrelation von Happel–Stephan die Werte besser wieder.

ПУЗЫРЬКОВОЕ КИПЕНИЕ В БИНАРНЫХ СМЕСЯХ АЦЕТОН–ЭТИЛОВЫЙ СПИРТ И ХЛОРИСТЫЙ МЕТИЛЕН–ЭТИЛОВЫЙ СПИРТ

Аннотация—Измерены коэффициенты теплопереноса для случая пузырькового кипения в большом объеме бинарных смесей ацетон–этиловый спирт и хлористый метилен–этиловый спирт при давлении, изменяющемся от 2,0 до 5,0 бар, и соответствующем изменении теплового потока от 10 до 40 кВ м$^{-2}$. Экспериментальные данные проверены при помощи соотношений Хаппедя–Стефана и Шмадля–Бира. Хотя оба соотношения хорошо согласуются с экспериментальными результатами, наиболее приемлемым является соотношение Хаппеля–Стефана.