v_{zr} = fluid velocity in z direction relative to the mean velocity in the z direction
v_m = root-mean-square velocity v_z
v^* = asymptotic peak velocity of tracer
X = cross-sectional space
x_i = i^{th} coordinate in cross-sectional space
z = axial coordinate of the system
z^* = first moment of tracer distribution divided by zeroth moment

Greek Letters

α = fraction of tracer in the moving phase at equilibrium (Example I)
β = fraction of tracer in the stationary phase at equilibrium (Example I)
α = dimensionless parameter (Example II) Equation (51)
β = dimensionless parameter (Example II) Equation (42)
Δ = amplitude of the linear displacement of the moving phase (Example I)
Δ = amplitude of the relative displacement of the plates (Example II)
σ = width of tracer distribution, Equation (3)
ψ = concentration of dispersion substance in the periodic source problem
ν = kinematic viscosity
τ = period of oscillation
ω = angular frequency of oscillation

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Nucleate and Film Pool Boiling of Ethane-Ethylene Mixtures

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Experimental results are presented for saturated nucleate and film pool boiling heat transfer to ethane, ethylene, and three binary ethane-ethylene mixtures containing approximately 25, 50, and 75 mole % ethylene. Data were obtained at reduced pressures from 0.05 to 0.75. The nucleate boiling data are compared with several predictions; the film boiling data are favorably compared with the Sciance, Colver, and Sliepcevich correlation.

This study was initiated to gain further knowledge of saturated pool boiling mixtures in the nucleate and film boiling regimes. The work is part of a continuing series of investigations at the University of Oklahoma on boiling nitrogen (*12*) and pure component liquified hydrocarbon gases (*15, 16*) and their mixtures (*3, 5, 20*).

Probably the earliest nucleate boiling mixture heat transfer data reported in the literature were those of Cichelli and Bonilla (*4*) for several propane–*n*-pentane mixtures. Since that time a limited number of nucleate boiling mixture studies have been reported. However, most of the available data have been obtained at atmospheric pressure for binary mixtures at only one composition or over a very limited composition range. Experimental results have clearly demonstrated that significant differences can exist between the nucleate boiling heat transfer characteristics of pure components and mixtures (*1, 3, 5, 17, 18, 20*). Moreover, it has been suggested (*5, 17*) that mixtures possessing a wide boiling range, that is, mixtures of large relative volatility, can be expected to give considerably higher ΔTs at a given heat flux level than for the mixture's pure components. For two such systems the difference has been shown to be as much as ten- (*3*) to thirtyfold (*17*).

Very little film boiling mixture data have been reported. In fact, results by Brown and Colver for a liquified natural gas (*3*) and a liquified petroleum gas (*5*) at pressures up to the observed critical pressures appear to be the only definitive film boiling mixture data reported to date. These data were correlated extremely well by the film boiling correlation proposed by Sciance, Colver, and Sliepcevich (*16*).

This paper presents experimental results for saturated nucleate and film pool boiling heat transfer to three mixtures of ethane and ethylene, as well as the pure components, over the pressure range from near atmospheric pressure to an approximate reduced pressure $P_r = 0.75$. Data are compared with correlations developed for boiling pure components.

EXPERIMENTAL APPARATUS AND PROCEDURE

Details of the apparatus are discussed in a previous paper (*20*), so only a brief summary is given here. Boiling took place from the gold-plated surface of a 13/16-in. diam. by 3.5-in. long heat transfer element oriented horizontally in a 1-gal. autoclave. The heater body was a copper cylinder, electrically insulated from a graphite electrode by a boron nitride sheath. Heater surface temperatures were determined by extrapolation of internal heater temperature measurements determined with 30-gauge iron-constantan thermocouples. Heat fluxes were determined from electrical current and voltage measurements.

The autoclave was initially filled with each test mixture by first flowing coolant through the reflux condenser and the internal cooling coil and then charging the test fluid to the reflux condenser through the fill line. A special filling procedure was used to ensure that the liquid level did not fall below the heater during operation. The time required for the liquid level to move across the sight glass was measured with a stop watch, and the fill continued for three times the measured length of time. This procedure ensured an initial liquid level about 4 in. above the heat transfer surface.

After filling, the heater was allowed to boil at 27,000 B.t.u./(hr.) (sq. ft.) for 1 hr. to condition the heat transfer surface. This operation was necessary to obtain a stable surface condition for nucleate boiling. All nucleate boiling data were

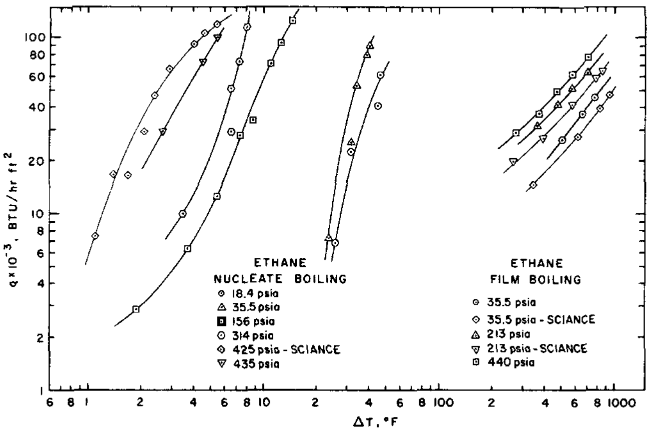

Fig. 1. Nucleate and film boiling data for ethane.

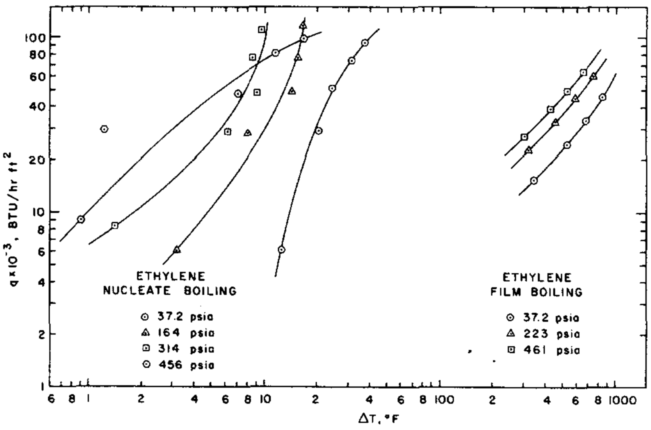

Fig. 2. Nucleate and film boiling data for ethylene.

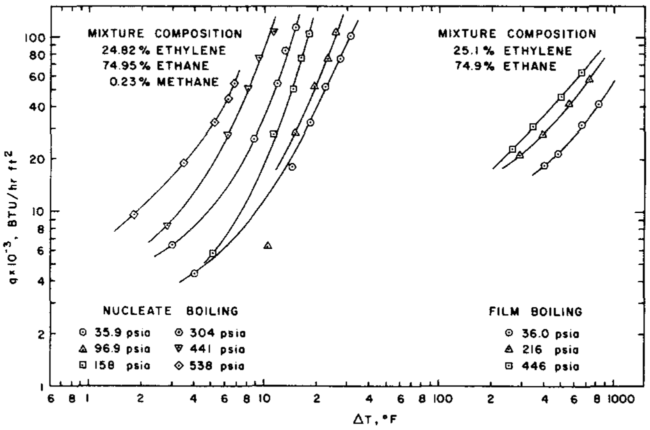

Fig. 3. Nucleate and film boiling data for 25% ethylene-75% ethane mixture.

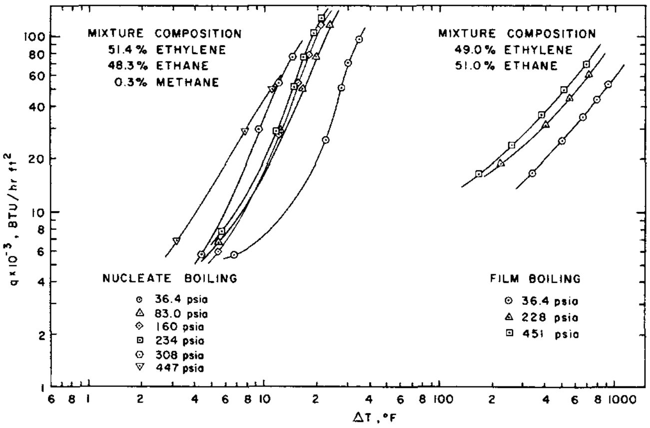

Fig. 4. Nucleate and film boiling data for 50% ethylene-50% ethane mixture.

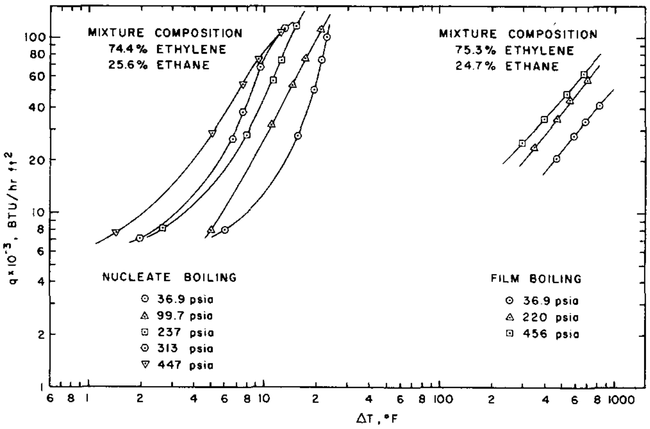

Fig. 5. Nucleate and film boiling data for 75% ethylene-25% ethane mixture.

recorded with increasing heat flux, thus hysteresis effects were not determined. The time required to stabilize the surface temperature after changing the heat flux was about 1 min. for nucleate boiling and 5 min. for film boiling.

Prior to taking film boiling data, the heat flux was set at 70,000 to 80,000 B.t.u./(hr.) (sq. ft.) and then the pressure was allowed to drift upward. Upon reaching the system pressure corresponding to burnout for a given flux, the heat transfer element went immediately into film boiling. Film boiling data were then recorded at either increasing or decreasing heat flux as desired.

All nucleate boiling data were taken prior to initiation of the film boiling data to prevent high-temperature deterioration of the gold-plated surface.

PROPERTY ESTIMATION METHODS

Mixture properties used in the boiling correlations were calculated by techniques utilizing pure component ethane and ethylene properties. All of the mixture property prediction equation were programmed for digital computation. Vapor and liquid densities were calculated using the Benedict-Webb-Rubin equation of state (*13*), which was originally developed from hydrocarbon PVT data. Viscosities were determined using the methods of Wilke (*19*) and Lee, Starling, Dolan, and Ellington (*10*). The method of Lee et al. was especially developed for light hydrocarbon mixtures, and has been quite accurate in testing a number of binary mixtures. The liquid viscosity correlation of Huang, Swift, and Kurata (*7*), which was developed using binary liquid methane-propane data, was also used to calculate liquid viscosities. The method of Filippov and Novoselova (*6*) for binary liquid mixtures was used to determine liquid thermal conductivities. Thermal conductivities in the vapor film were calculated by the technique proposed by Brokaw (*2*) and developed for binary systems. Mixture latent heats and heat capacities were calculated using a linear mixing rule based on pure component values. Surface tensions were estimated using the Macleod and Sugden correlation (*13*).

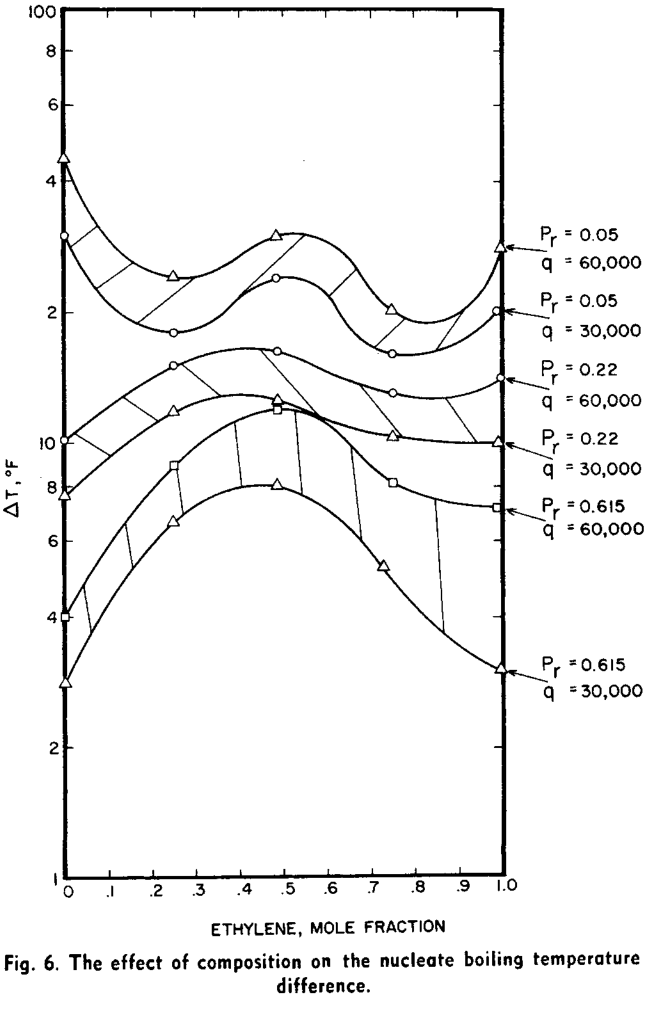

Fig. 6. The effect of composition on the nucleate boiling temperature difference.

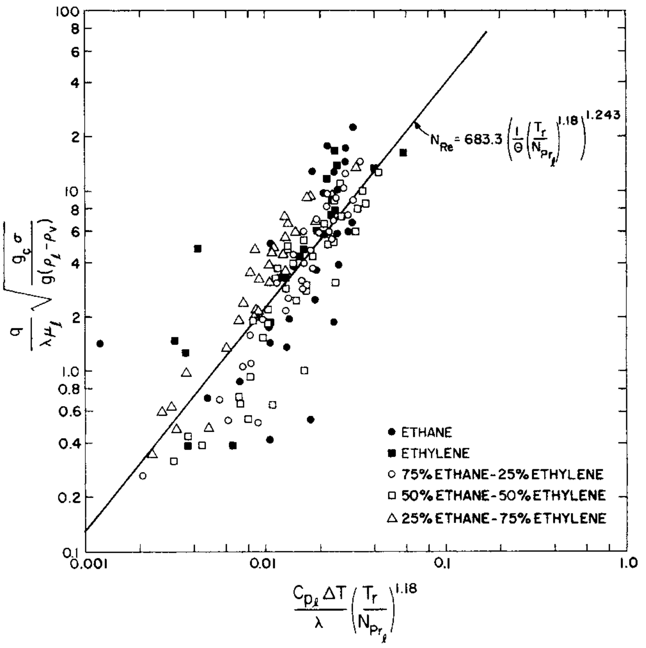

Fig. 7. Modified Rohsenow nucleate boiling correlation for ethane, ethylene, and their mixtures.

RESULTS AND DISCUSSION

Pool boiling data for ethane, ethylene, and three ethane-ethylene mixtures are shown in Figures 1 to 5. The effects of pressure and composition upon the nucleate boiling regime should be noted. In every case there was a regular decrease in ΔT with increasing pressure at a given flux level. The combined effects of pressure and composition are shown quite well in Figure 6. Here the nucleate boiling data at two fluxes are cross-plotted in terms of ΔT versus composition, with reduced pressure as a parameter. Clearly, at a given composition, the ΔT is seen to decrease with increased reduced pressure. Furthermore, the ΔTs at constant flux and reduced pressure show some dependency on composition. For each of the three reduced pressures reported, ΔT goes through a maximum in the range 40 to 50 mole % ethylene. As the reduced pressure increases, the curves also show two minima. It is interesting to note that the ΔT behavior found here corresponds precisely with burnout data for the same mixtures (*20*). Burnout values were found to exhibit maxima between 40 to 50 mole % ethylene while exhibiting minima at about 80 mole % ethylene. On consideration of the equilibrium composition difference between the liquid and vapor at all reduced pressures, it is found (Figure 10 of reference *20*) that maxima occur in the neighborhood of 40 to 50 mole % ethylene. Such behavior, then, supports previous suggestions (*5, 17*) that there is a direct relationship between the relative volatility of a mixture and the nucleate boiling behavior.

The film boiling data for ethane, ethylene, and their mixtures show the expected effects of pressure, but relatively little composition dependence. This latter result, which implies that film boiling is not significantly influenced by the relative volatility of the mixture, is not necessarily unexpected. During film boiling the heater surface is totally covered by a vapor film, indicating that under such conditions the mixture behaves rather like that of a pseudosubstance with properties intermediate between those of the two pure components.

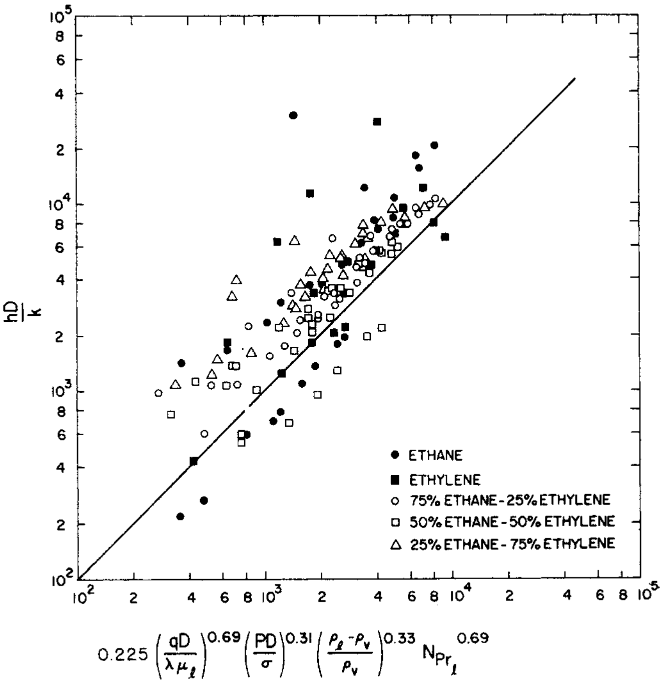

Fig. 8. McNelly nucleate boiling correlation for ethane, ethylene, and their mixtures.

CORRELATION OF DATA

The nucleate boiling data were tested with the correlations of Rohsenow (*14*), McNelly (*11*), Kutateladze (9), and Borishanskii and Minchenko (9). The Rohsenow equation, in the empirically modified form proposed by Sciance et al. (*15, 16*) and found to best correlate hydrocarbon pure component data, was found to correlate all of the data with an average absolute deviation of 55.7%. The best fit line shown in Figure 7 is given by the expression

$$\frac{q}{\lambda\mu_l}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}} = 683.3\left[\frac{C_{pl}\Delta T}{\lambda}\left(\frac{T_r}{N_{Prl}}\right)^{1.18}\right]^{1.243}$$

The other correlations tested were

McNelly:

$$\frac{hD}{k} = 0.225\left(\frac{qD}{\lambda\mu_l}\right)^{0.69}\left(\frac{PD}{\sigma}\right)^{0.31}\left(\frac{\rho_l-\rho_v}{\rho_v}\right)^{0.33}N_{Prl}^{0.69}$$

Kutateladze:

$$\frac{h}{k}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}} = 7\times10^{-4}\left[\frac{q}{\alpha_l\rho_v\lambda}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7}\left[\frac{P}{\sigma}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7}N_{Prl}^{-0.3}$$

Borishanskii and Minchenko:

$$\frac{h}{k}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}} = 8.7\times10^{-4}\left[\frac{q}{\alpha_l\rho_v\lambda}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7}\left[\frac{P}{\sigma}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}}\right]^{0.7}$$

Comparisons of the data with the above correlations are shown in Figures 8 to 10. It is apparent that the accuracy of all three correlations is comparable. Both the McNelly and Kutateladze expressions correlate the data with average deviations of 42%. Although the Borishanskii-Minchenko expression appears to give a better representation of the data (Figure 10), the average absolute deviation is 48.7%. Kosky and Lyon (*8*) found for mixture data of oxygen-nitrogen that the McNelly correlation was the most successful of the above correlations.

The film boiling data are compared in Figure 11 using the following correlation proposed by Sciance et al. (*15, 16*):

$$\frac{q}{k_f\Delta T}\sqrt{\frac{g_c\sigma}{g(\rho_l-\rho_v)}} = 0.369\left[\left(\frac{g_c\sigma}{g(\rho_l-\rho_v)}\right)^{3/2}\frac{g\rho_f(\rho_l-\rho_v)\lambda'}{\mu_f k_f T_r^2\Delta T}\right]^{0.267}$$

The extremely good agreement with the data is apparent. The average absolute deviation of the data is 4.97%. Similar agreement has been obtained for pure component hydrocarbons (methane, ethane, propane, and butane) (*15, 16*), a liquefied natural gas mixture (*3*), and a liquefied petroleum gas mixture (*5*).

SUMMARY

Saturated nucleate and film boiling data are presented for ethane, ethylene, and three binary mixtures having approximate compositions 25, 50, and 75 mole % ethylene. Data were obtained at pressures from 35.5 to 538 lb./sq.in.abs. ($0.05 < P_r < 0.75$).

For a given mixture concentration both the nucleate and film boiling curves generally shifted to lower ΔTs with increased pressure. The nucleate boiling data exhibit a definite concentration effect, with the maximum ΔTs corresponding to mixtures having the highest relative volatilities. All of the nucleate boiling data were compared with the correlations of Rohsenow, (as modified by Sciance et al.), McNelly, Kutateladze, and Borishanskii and Minchenko. The modified Rohsenow correlation and the Borishanskii and Minchenko correlations appear to predict

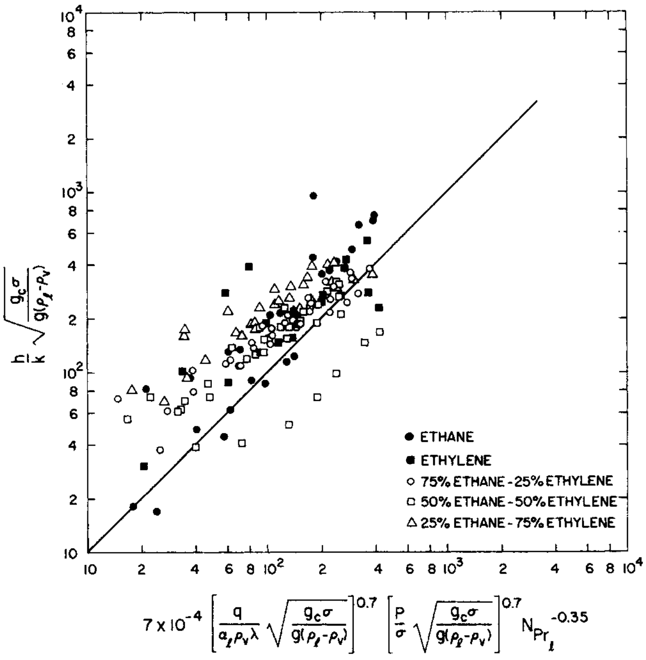

Fig. 9. Kutateladze nucleate boiling correlation for ethane, ethylene, and their mixtures.

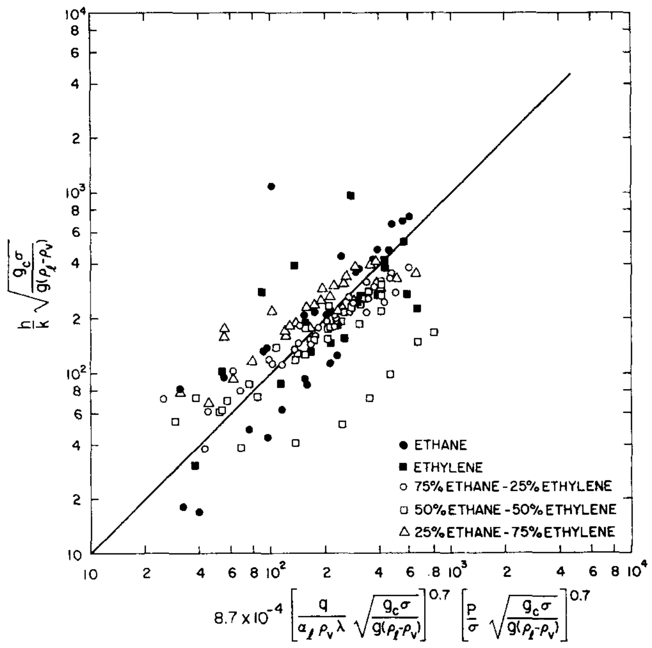

Fig. 10. Borishanskii-Minchenko nucleate boiling correlation for ethane, ethylene, and their mixtures.

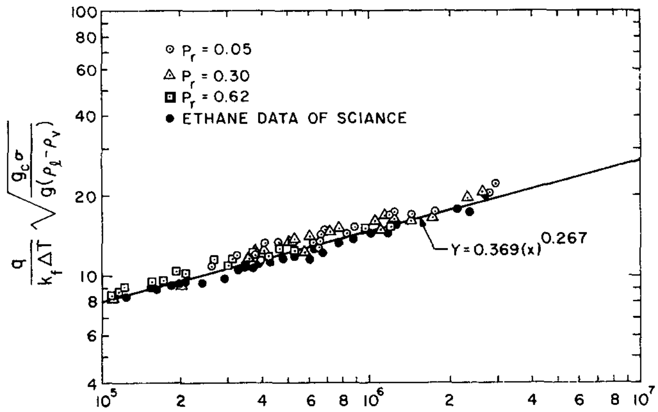

Fig. 11. Sciance et al. film boiling correlation for ethane, ethylene, and their mixtures.

the data most successfully.

The film boiling correlation of Sciance et al. predicted all of the film boiling data exceptionally well.

ACKNOWLEDGMENT

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NOTATION

C_p = heat capacity, B.t.u./(lb.$_m$) (°F.)
D = diameter, ft.
g = acceleration of gravity, ft./hr.^{2}
g_c = unit conversion factor, (lb.$_m$) (ft.)/(lb.$_f$) (hr.^{2})
h = heat transfer coefficient, B.t.u./(hr.) (sq.ft.) (°F.)
k = thermal conductivity, B.t.u./(hr.) (ft.) (°F.)
P = pressure, lb.$_f$/sq.ft.
P_r = reduced pressure, P/P_c
N_{Pr} = Prandtl number, $\frac{C_p\mu}{k}$
N_{Re} = Reynolds number, $\frac{q}{\lambda\mu_l}\left[\frac{g_c\sigma}{g(\rho_l-\rho_v)}\right]^{1/2}$
q = heat flux, B.t.u./(hr.) (sq.ft.)
T = temperature, °F.
T_r = reduced temperature, T/T_c
ΔT = $T_w - T_{\text{liq}}$, °F.

Greek Letters

α = thermal diffusivity, $\frac{k}{C_p\rho}$, cu.ft./hr.
θ = dimensionless group, $\frac{\lambda}{C_{pl}\Delta T}$
λ = latent heat, B.t.u./(lb.$_m$)
λ' = modified heat of vaporization, $(\lambda + 0.5C_{pf}\Delta T)$, B.t.u./lb.$_m$
μ = viscosity, lb.$_m$/(ft.) (hr.)
ρ = density, lb./cu.ft.
σ = surface tension, lb.$_f$/ft.

Subscripts

c = critical
w = wall
l = liquid
v = vapor
f = film

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