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The Peak Boiling Heat Flux in Saturated Ethanol-Water Mixtures

The present work provides original measurements of the burnout heat flux in saturated ethanol-water mixtures, over the full range of concentrations. These data were obtained at atmospheric pressure on horizontal cylinders, ranging from 0.51 to 2.16 mm in diameter. They reveal significant improvements of the peak heat flux for mixtures, over that which would be expected from pure fluids with the properties of the mixture. This improvement is most pronounced at low ethanol mass fractions. McEligot has suggested that the improved heat flux results from a subcooling created by selective distillation at the liquid-vapor interface. Combining this idea with a recent correlation of subcooled burnout, we estimate the extent of effective subcooling qualitatively and discuss the use of this estimate to correlate burnout in binary mixtures. Two dimensionless groups are proposed to characterize this effective subcooling, both based on appropriate characterizations of the phase equilibrium diagram.

Introduction

Boiling in mixtures has been a concern for almost as long as boiling itself has been an active subject of study; the need to understand the *burnout* heat flux, q_{max}, in mixtures has been a major theme from the beginning. This need has been driven by the ubiquitous presence of mixtures in the chemical and process industries.

Reddy (1987) provides a fairly complete critical review of the literature on burnout in binary mixtures since 1941. We provide a brief summary of that review here:

Bonilla provided the first systematic study of boiling in mixtures almost a half century ago. Bonilla and Perry (1946) boiled binary mixtures of water, various alcohols, and acetone (in several combinations) on 9.1 and 6.65-cm-dia flat plate heaters. Additional mixture data by Cichelli and Bonilla (1946) and Bonilla and Eisenberg (1948) signaled to the world that such data displayed certain anomalies and were hard to reproduce.

Van Stralen produced extensive data on small horizontal cylinders in a variety of organic liquid mixtures and aqueous solutions during the 1950's (see Vos and Van Stralen, 1956; Van Wijk et al., 1956; and Van Stralen, 1956, 1959). He noted that burnout could be dramatically increased with small concentrations of alcohol in water. Van Stralen returned to the field later (see Van Stralen, 1966, 1970, and Van Stralen and Sluyter, 1969) with other suggestions for analyzing q_{max} in mixtures. These suggestions have proved to have limited value, for reasons that become apparent subsequently.

Meanwhile, many other observers (Jordan and Leppert, 1959; Dunskus and Westwater, 1961; Huber and Hoehne, 1962; Carne, 1963, 1964; Sterman et al., 1966; Grigor'ev et al., 1968; Wright and Colver, 1968; Van Stralen and Sluyter, 1969) added to the fund of burnout data using a variety of binary organic and aqueous mixtures, on a variety of heaters. Under certain conditions, many of these investigators found a phenomenon that had particularly caught Van Stralen's attention. That was the fact that, in many mixtures, q_{max} reached a local maximum at a low concentration of one component.

Unfortunately, much of the interpretation offered in these studies suffered because the influential roles of geometry and of geometric scale on burnout had not yet been identified or properly diagnosed. The work of Lienhard and several

others—notably Wong, Sun, Bakhru, and Dhir (see, e.g., Lienhard and Dhir, 1973)—during the 1960s and early 1970s finally established two things about burnout in single-phase liquids:

1 The hydrodynamic processes that give rise to burnout cease to occur, and so too does the multivalued character of the boiling curve, when the Laplace number, $R' \equiv R(g[\rho_f - \rho_g]/\sigma)^{1/2}$, is reduced below a value on the order of 0.1, where R is a characteristic dimension of the heater (see, e.g., Bakhru and Lienhard, 1972).

2 When R' is greater than about 1/10, an appropriately nondimensionalized q_{max} varies systematically with R'; and does so in a different way in each of the geometric heater configurations.

There was not yet any basis for separating out the influence of geometry on q_{max} when most of the data were obtained during the 1950s and 60s; yet those influences were present, and many of the data fell in regions of low R'. Therefore, most attempts at interpreting the role of composition were muddied by the unrecognized influences of configuration and geometric scale on burnout.[1]

Two particularly important insights nevertheless did emerge during this period. First, Carne (1964) questioned the use of the equilibrium latent heat of vaporization, h_{fg}. Figure 1 shows a typical phase-equilibrium diagram for a binary azeotropic mixture. The equilibrium h_{fg} is the enthalpy difference between the liquid and vapor at the same temperature. Carne suggested that a flash evaporation process occured at constant *composition* during boiling. This being the case, the appropriate latent heat would be $h_{fg,1}$, the enthalpy difference between liquid and vapor at the same composition. This is sometimes called the "integral latent heat." While it is doubtful that pure flash evaporation occurs during boiling, Thome (1983) subsequently argued that the actual process lies somewhere *between* equilibrium and flash evaporation.

McEligot (1964) provided the second important step toward understanding binary boiling when he noted that evaporation from a liquid-vapor interface leaves the liquid phase at a higher temperature than that at which the vapor condenses.

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[1]The burnout process in a mixture, while it differs in some features from that in a single-component fluid, still involves the same basic hydrodynamic breakdown. Our visual observation of the vapor-removal pattern supports this. We therefore assume R' still correctly compares the buoyant and surface tension forces that are the key to that breakdown; and the criterion, $R' < 0.1$, defines the breakdown in both mixtures and single-component liquids.
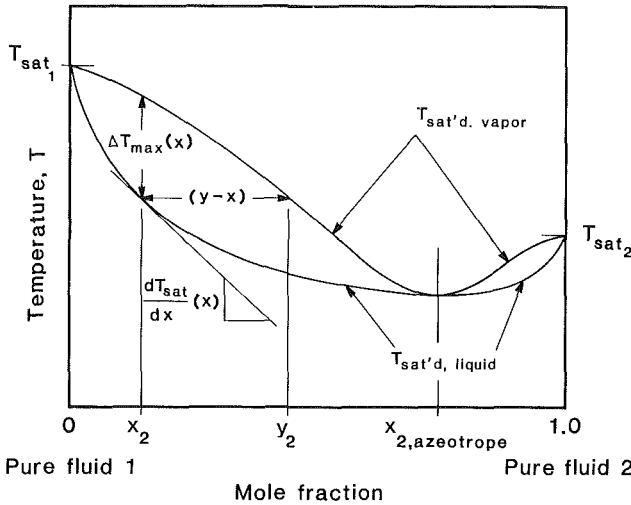
Fig. 1 Schematic phase-equilibrium diagram for a typical binary azeotropic mixture, showing nomenclature

The surrounding liquid—at the original concentration—is thus colder than the temperature at which the liquid actually evaporates. The resulting subcooling is greatest at low alcohol concentrations (owing to the shape of the ethanol-water phase-equilibrium diagram) and so too is the heat flux augmentation.

The idea of this sort of induced subcooling can only be made useful when two things are known. One is the *magnitude* of the induced subcooling and the other is its *effect* on the burnout heat flux. McEligot had access to neither. Indeed, it was not until very recently that Elkassabgi and Lienhard (1988) provided mechanistic accounts (as well as correlations based upon them) of the various influences of subcooling on burnout in pure fluids. The extent of induced subcooling in the interface remains unpredictable. A third piece of information that is also needed is the path of the evaporation process on the phase-equilibrium diagram. Thome's and Shock's (1984) study, 20 years later, provided a cogent discussion of these problems.

Kutateladze et al. (1966) pointed out another element that must be taken into account in binary boiling, namely the shape

of the phase-equilibrium diagram. A glance at the diagram tells us that a variety of pairs of information will characterize the diagram completely. If we identify the liquid and vapor mole fractions of component 1 as x and y, respectively, then $T(x)$ and $T(y)$ would be such a pair, but the complete function would be unmanageable. Kutateladze correlated data with an expression of the following form, which characterizes the role of the equilibrium phase diagram:

$$\text{Ku} = f([y-x]/[y-x]_{\max}) \qquad (1)$$

The term $(y-x)$ is the isothermal difference between y and x and $(y-x)_{\max}$ is the maximum value that $(y-x)$ can reach on the diagram. The Kutateladze number, Ku, is defined as

$$\text{Ku} \equiv \frac{q_{\max}}{h_{fg}\rho_g^{1/2}[g\sigma(\rho_f - \sigma_g)]^{1/4}} \qquad (2)$$

(The denominator of equation (2) is proportional to the Zuber (1958)/Kutateladze (1950) prediction/correlation for $q_{\max}$.) Afgan (1966) also used the more limited expression, $\text{Ku} = f(y-x)$, to correlate data. Of course, neither Afgan nor Kutateladze yet had any way to isolate the influence of geometry in their correlations.

Van Stralen (1970) noted that $q_{\max}$ was maximum where the quantity

$$(x-y)\frac{\Delta T_{\text{sat}}}{\Delta x} \qquad (3)$$

was maximum. ΔT_{sat} is the increase of the liquid saturation temperature resulting from the reduction of concentration, Δx, caused by evaporation at the interface. Since these increments are not known, we would prefer to write them as a derivative, and in so doing obtain another, albeit dimensional, characterization of the phase-equilibrium diagram

$$(x-y)\frac{dT_{\text{sat}}}{dx} \qquad (4)$$

After the mid-1960s, work on burnout in binary mixtures slacked off. The issue did not go away, but the flow of new ideas abated. Ishiki and Nikai (1972) provided more data, but in a range of R' less than 0.1. Matorin (1973), Gaidarov (1975), and Stephen and Preusser (1979) presented additional data and suggested empirical correlations. Frea et al. (1977)

Nomenclature

c_p = specific heat at constant pressure for the boiled liquid

g = gravitational acceleration

$h_{fg}, h_{fg,1}$ = latent heat of vaporization at constant temperature; "integral" or constant-composition latent heat of vaporization

Ja, Ja$_e$ = volumetric Jakob number $= \rho_f c_p \Delta T_{\text{sub}}/\rho_g h_{fg}$; modified volumetric Jakob number based on an effective subcooling (see equation (9))

Ku = Kutateladze number defined in equation (2)

Pe = an effective Peclet number, defined in equation (7)

$q_{\max}, q_{\max,\text{SL}}$ = peak or "burnout" heat flux in saturated boiling; Sun and Lienhard's $q_{\max}$, equation (8)

$q_{\max,\text{sub}}$ = $q_{\max}$ in subcooled boiling

R = radius of heater

R' = Laplace number $= R[g(\rho_f - \rho_g)/\sigma]^{1/2}$

T, T_{sat}, T_w = temperature, saturated liquid temperature, temperature of the wall of a heater

x = mole fraction of ethanol in the liquid phase

y = mole fraction of ethanol in the vapor phase when x is the mole fraction in the liquid phase

α = thermal diffusivity of boiled liquid

$\Delta q_{\max,\text{sub}}$ = $q_{\max} - q_{\max,\text{SL}}$

$\Delta T, \Delta T_{\max}, \Delta T_{\text{sub}}$ = $T_w - T_{\text{sat}}$; $T_g(x) - T_f(x)$ (see Fig. 1); $T_{\text{sat}} - T_{\text{bath}}$

ρ_f, ρ_g = saturated liquid and vapor densities, respectively

σ = surface tension

Subscripts

1, 2 = denoting the two components of a binary mixture

f, g = denoting the saturated liquid and vapor states

Fig. 2 Schematic diagram of the boiling apparatus
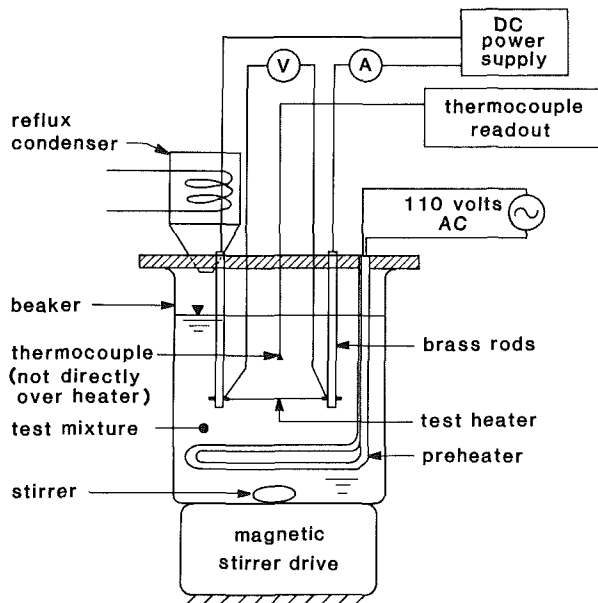

Fig. 3 The ethanol/water equilibrium phase diagram

also gave additional data, but they used a heater configuration that was subject to induced convection influences.

Thome and Shock (1984) presented a broad review of the theoretical bases of the problem, which is serving to revive interest in it. Even more recently Yang (1987) attempted to organize a new correlation of prior data that retains some of the best features of the previous ones. He nondimensionalized the characteristic temperature, equation (4), by making it into a Jakob number. He also included a Lewis number, as was suggested by Gaidarov.

The most recent contribution was Purdy and Avedisian's (1987) clean and careful experimental study of burnout in several organic mixtures. These data are important since they are the first since Cichelli and Bonilla's (1945) study on a large flat plate with vertical sidewalls. By approximating the archetypical infinite plate, Purdy and Avedisian escape geometric complications.

A close look at the accumulated literature on burnout in binary mixtures makes it clear that an accumulation of good ideas has not been fully exploited. The work of Carne, McEligot, Kutateladze, Thome, and Shock, makes it clear that:

1 Evaporation near burnout in a binary mixture is not isothermal.

2 The burnout heat flux in a binary mixture is determined in part by the shape of the equilibrium phase diagram.

3 The component process that increases the burnout heat flux in a binary mixture is subcooling of the *bulk* of the liquid with respect to the vapor—the result of preferential evaporation of the more volatile component at the liquid interface. (This is related to item 1.)

(The idea of an effective subcooling has also been picked up by Yue and Weber (1973, 1974) and by Marschall and Moresco (1977), who have used it to predict increased heat flux during *film* boiling in a vertical plate geometry.)

We therefore seek to obtain a well-controlled set of data that can be rationalized within these facts. We select a mixture (ethanol/water) that is well known to yield a maximum in q_{max}, and for which the best physical property information can be found. We select the geometry (a horizontal cylinder) for which behavior in single-component boiling is best documented. This gives data that stay within the size range $(0.1 \leq R' \leq 0.7)$ for which the hydrodynamic mechanisms are most clearly defined.
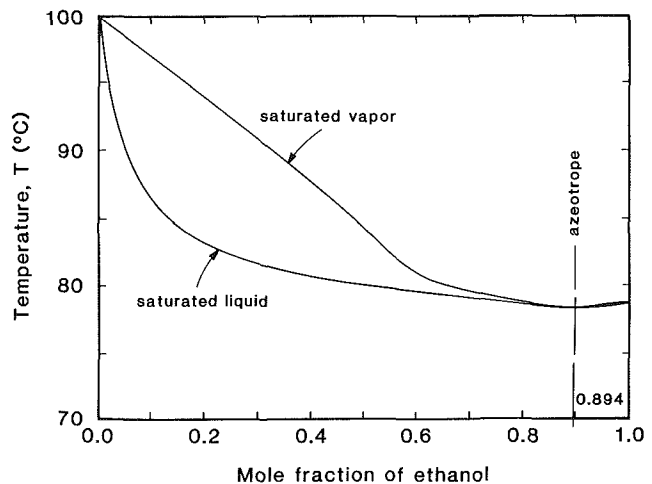
Experiment and Results

The experimental apparatus and procedure are straightforward, and the reader is referred to Reddy (1987) for complete details. The heater is a wire mounted in a beaker as shown in Fig. 2. The copper-plating of electrodes on the smooth wire, the inspection and cleaning procedure, and the d-c power supply are all identical to that used by Elkassabgi and Lienhard (1988) with one exception: In some cases a large d-c motor-generator set was used to reach higher currents.

The cylindrical heaters were nichrome wires with nominal diameters of 0.510, 0.767, 1.016, 1.295, and 1.626 mm; and stainless steel tubes with outer diameters of 1.803 and 2.159 mm. In all cases the active length was within a millimeter of 8 cm. The ethanol/water mixtures were premixed and the composition of the liquid bulk (away from the heater) was checked several times before and after each q_{max} observation with a GOW-MAC Gas Chromatograph. In each case, we turned the stirrer off about 30 s before making an observation. (The disappearance of significant liquid motion was affirmed by bubble movement in the tank.)

Six to eight tests were made at each condition. The probable errors in q_{max} and composition measurements were 5 percent and 1 percent, respectively. As we see in Table 1, the probable error in q_{max} compares favorably with the data scatter.

The phase equilibrium data of Chu et al. (1956), Otsuki and Williams (1956), and Hellwege (1975) for ethanol/water are represented graphically in Fig. 3. We have not plotted the data themselves, but used rational polynomial forms that fit within the accuracy of the data for use in subsequent analyses.

The 108 raw q_{max} data are reported in Table 1 and they are represented in reduced graphic form in Fig. 4 (they are also listed by Reddy (1987)). Two features of these data bear note. The smaller heaters clearly display the local maximum of q_{max} at low alcohol concentrations, while data for the larger heaters become increasingly scattered at low concentrations.

No data from previous sources could be added to this data set. In the first place, not a great deal of work has been done with the ethanol/water system. Those data that do exist represent incompletely documented experiments or R' values that are too small.

Discussion

Means for Identifying the Effective Subcooling. If, as McEligot suggested, the local maximum of q_{max} in x is caused by induced subcooling, it behooves us to evaluate that subcooling quantitatively. That can be done by comparing the in-

Table 1 A complete listing of the present burnout data

Run #	Mole Fraction Ethanol	Peak Heat Flux (MW/m^2) Mean	Peak Heat Flux (MW/m^2) Std. Dev.	Mean dia. (mm)	Run #	Mole Fraction Ethanol	Peak Heat Flux (MW/m^2) Mean	Peak Heat Flux (MW/m^2) Std. Dev.	Mean dia. (mm)
1	0.200	1.586	0.055	0.506	55	1.000	0.531	0.006	1.286
2	0.195	1.238	0.028	0.797	56	1.000	0.509	0.014	1.622
3	0.190	1.275	0.086	1.037	57	1.000	0.395	0.005	2.122
4	0.258	1.548	0.056	0.502	58	0.799	0.566	0.015	1.286
5	0.248	1.232	0.092	0.797	59	0.799	0.542	0.015	1.622
6	0.238	1.241	0.044	1.034	60	0.799	0.402	0.003	2.122
7	0.347	1.416	0.054	0.504	61	0.904	0.541	0.016	1.287
8	0.343	1.228	0.041	0.799	62	0.904	0.526	0.011	1.618
9	0.339	1.152	0.072	1.041	63	0.904	0.401	0.005	2.122
10	0.461	1.176	0.030	0.504	64	0.657	0.688	0.015	1.287
11	0.456	1.026	0.017	0.797	65	0.652	0.660	0.012	1.618
12	0.452	0.990	0.043	1.036	66	0.648	0.654	0.003	2.122
13	0.560	1.059	0.028	0.503	67	0.749	0.624	0.005	1.287
14	0.559	0.927	0.031	0.790	68	0.749	0.585	0.004	1.617
15	0.557	0.842	0.062	1.041	69	0.749	0.455	0.023	2.122
16	0.660	0.939	0.013	0.502	70	0.527	0.861	0.017	1.285
17	0.656	0.814	0.031	0.795	71	0.527	0.861	0.012	1.612
18	0.651	0.753	0.025	1.026	72	0.526	0.880	0.037	1.821
19	0.858	0.600	0.044	0.504	73	0.526	0.762	0.025	2.115
20	0.856	0.564	0.014	0.793	74	0.465	0.926	0.028	1.286
21	0.854	0.628	0.014	1.034	75	0.461	0.921	0.017	1.621
22	0.750	0.693	0.021	0.501	76	0.458	0.990	0.038	1.821
23	0.750	0.668	0.023	0.792	77	0.454	0.894	0.028	2.110
24	0.750	0.666	0.015	1.036	78	0.319	1.065	0.027	1.267
25	1.000	0.593	0.006	0.502	79	0.313	1.096	0.088	1.610
26	1.000	0.550	0.013	0.790	80	0.307	1.295	0.022	1.820
27	1.000	0.611	0.014	1.026	81	0.301	1.117	0.048	2.118
28	1.000	0.544	0.022	1.265	82	0.141	1.278	0.034	1.289
29	1.000	0.512	0.008	1.485	83	0.131	1.340	0.042	1.618
30	0.936	0.586	0.032	0.502	84	0.122	0.943	0.026	1.821
31	0.936	0.557	0.015	0.791	85	0.112	0.898	0.061	2.111
32	0.936	0.616	0.007	1.017	86	0.252	1.165	0.026	1.261
33	0.936	0.565	0.011	1.261	87	0.247	1.246	0.036	1.623
34	0.936	0.541	0.008	1.484	88	0.242	1.267	0.044	1.822
35	0.893	0.593	0.010	0.503	89	0.238	1.162	0.062	2.115
36	0.893	0.583	0.016	0.791	90	0.000	1.411	0.264	1.287
37	0.893	0.588	0.006	1.030	91	0.000	1.545	0.061	1.619
38	0.893	0.587	0.008	1.264	92	0.000	1.349	0.036	1.819
39	0.893	0.537	0.008	1.484	93	0.000	1.237	0.049	2.112
40	0.000	1.532	0.105	0.502	94	0.184	1.306	0.022	1.286
41	0.000	1.442	0.088	1.020	95	0.178	1.240	0.039	1.621
42	0.000	1.643	0.165	0.787	96	0.172	0.964	0.121	1.821
43	0.064	1.953	0.001	0.500	97	0.166	0.899	0.051	2.121
44	0.058	1.535	0.086	0.792	98	0.092	1.333	0.063	1.286
45	0.053	1.605	0.064	1.025	99	0.089	1.424	0.031	1.607
46	0.133	1.691	0.054	0.500	100	0.086	1.176	0.030	1.821
47	0.125	1.662	0.049	0.792	101	0.082	1.020	0.069	2.113
48	0.118	1.614	0.048	1.027	102	0.035	1.070	0.077	1.288
49	0.166	1.543	0.066	0.500	103	0.033	1.462	0.078	1.606
50	0.161	1.418	0.081	0.792	104	0.032	0.734	0.042	1.821
51	0.155	1.540	0.039	1.025	105	0.030	0.632	0.142	2.113
52	0.028	1.794	0.251	0.501	106	1.000	0.390	0.015	1.821
53	0.025	1.906	0.183	0.789	107	0.629	0.825	0.005	1.821
54	0.022	1.879	0.257	1.026	108	0.364	1.189	0.020	1.821

crease of q_{max} over the conventional hydrodynamic value, with the increase of q_{max} that is predicted to occur as a consequence of subcooling.

Elkassabgi and Lienhard (1988) identified three regimes of subcooling for pure fluids: high, low and intermediate. It turns out (after the fact) that the subcoolings induced in binary boiling are all rather low. Thus the only one of their correlations of interest to us is the one for low subcooling

$$\frac{\Delta q_{max, sub}}{q_{max}} = 4.28 \frac{Ja}{Pe^{1/4}} \qquad (5)$$

where $\Delta q_{max, sub}$ is the increase of subcooling over the saturated value, q_{max}, and Ja is a volumetric Jakob number

$$Ja \equiv \rho_f c_p \Delta T_{sub} / \rho_g h_{fg} \qquad (6)$$

and Pe is an effective Peclet number,

$$Pe \equiv \sigma^{3/4} / \{ \alpha [g(\rho_f - \rho_g)]^{1/4} \rho_g^{1/2} \} \qquad (7)$$

To find an effective ΔT_{sub} we next have to decide how much of q_{max} in a binary mixture is an excess over a "saturated" value. To obtain such an "experimental" value of $\Delta q_{max, sub}$, we first use the Sun–Lienhard (1970) prediction for saturated burnout

$$q_{max, SL} = \frac{\pi}{24} \rho_g^{1/2} h_{fg} [\sigma g(\rho_f - \rho_g)]^{1/4} [0.89$$
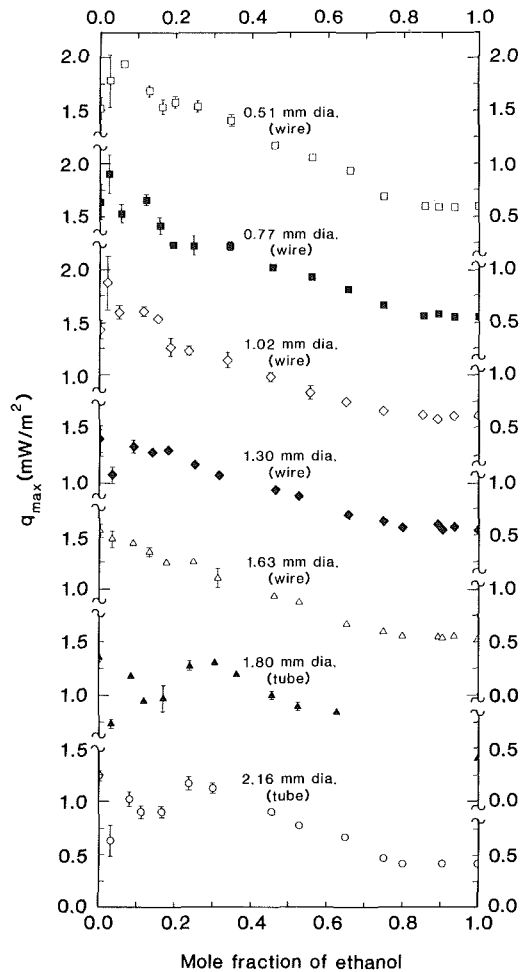$$+ 2.27 exp(-3.44 R'^{1/2})] \qquad (8)$$
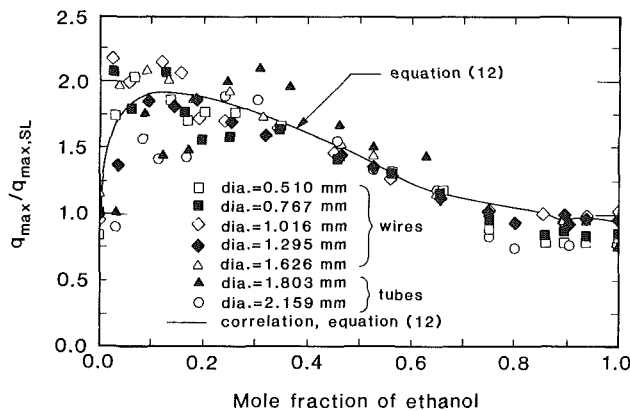
Fig. 4 The complete raw q_{max} data

Fig. 5 The q_{max} data normalized to eliminate the role of geometric scale

(based on properties of the mixture) to obtain a value of q_{max} that would represent the mixture if effective subcooling did not take place. We subtract this $q_{max, SL}$ from the experimental value in each case, to get Δq_{sub}. However, there is a catch. Equation (8) reveals a small systematic error as it is applied to different liquids. It predicts our pure water burnout data very closely, but it overpredicts our burnout values in ethanol by 10 percent. We accordingly use a corrected $q_{max, SL}$: the value given by equation (8), divided by $(1+0.10x)$. This serves to compensate for the systematic overprediction.

Isolating the Influence of Cylinder Geometry. The present q_{max} data have been normalized by $q_{max, SL}$ and plotted in Fig.
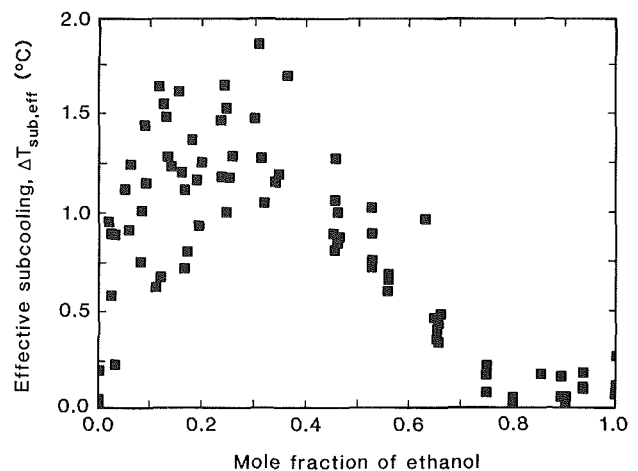

Fig. 6 Effective subcooling inferred from the present data using the low-subcooling correlation of Elkassabgi and Lienhard

5. (We defer discussion of a predictive correlation that is also included in the figure.) The data correlate rather well on these dimensionless coordinates, except at low values of x, where the scatter broadens. However, most of this scatter is introduced by the data obtained using stainless steel tubes, which are generally low. Changing from wires to tubes changes the heat transfer boundary condition from uniform-wall-temperature to uniform-heat-flux and it is clear that burnout is sensitive to this change. For the isothermal wires, however, the modified $q_{max, SL}$ normalizes the data, and therefore takes accurate account of the role of R or R' in burnout, in this case.

An Estimation of the Effective Subcooling. The correlation given in Fig. 5 gives us greater confidence in the use of the modified $q_{max, SL}$ to represent q_{max} when there is no effective subcooling. We can then equate $(q_{max} - q_{max, SL})$ to Δq_{sub} given by equation (5) and solve the result for ΔT_{sub} using mixture properties. (These values, of course, are only inferred. However we have no means for making direct in situ measurements of ΔT_{sub} nor do we see such means on the horizon.)

The resulting values of ΔT_{sub}, plotted in Fig. 6, show a clear trend in x, with ΔT_{sub} vanishing at the azeotrope where effective subcooling can no longer occur. ΔT_{sub} must also remain close to zero for $x > x_{azeotrope}$, since the saturated liquid and vapor curves are very close together in that range (see Fig. 3). The numerical values of ΔT_{sub} look fairly small—all below 2 °C. These, of course, are characteristic values, not actual ones. Furthermore, it is hard to know whether 2°C should really be regarded as a small subcooling within an actual bubble.

Incorporation of Effective Subcooling Into a Burnout Correlation. What factors are missing in the correlation of burnout in a binary mixture? The obvious answer is the composition, x, of the boiled liquid; but the shape of the phase-equilibrium diagram must also be accounted in a correct correlation. The x-dependent shape of the phase equilibrium diagram can be represented using a new effective Jakob number, Ja_e, based on an effective subcooling of the liquid, which varies with x. Two candidate Jakob numbers, based on two representations of the subcooling, are

$$Ja_e \equiv \frac{\rho_f c_p (x-y)}{\rho_g h_{fg}} \frac{dT_f}{dx} \qquad (9a)$$

and

$$Ja_e \equiv \frac{\rho_f c_p [T_g(x) - T_f(x)]}{\rho_g h_{fg}} \qquad (9b)$$
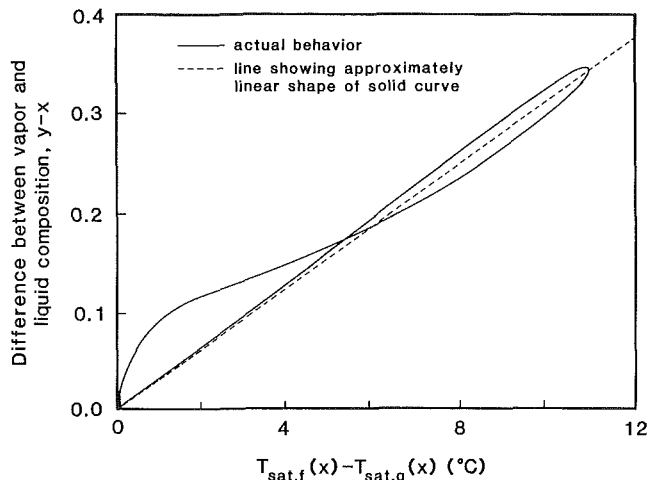
Fig. 7 The approximate linear relation between $|y - x|$ and $(T_g - T_f)$ in the ethanol/water system.

Other Ja_e's could have been created using other characterizations of the subcooling. However, equation (9b) proved to work better than other candidates. The effective subcoolings used here (and the other ones we tried) contain full information about the equilibrium phase diagram.

Before setting a correlation, we look at the dimensional analysis of burnout. The dimensional functional equation for q_{max} is

$$q_{max} = f(h_{fg}, \ g(\rho_f - \rho_g), \ \rho_f, \ \rho_g, \ R, \ c_p, \ (T_g - T_f), \ \alpha, \ \text{mass diffusivity})$$

These ten variables are expressible in N, m, s, °C. Hence the dimensional equation reduces to six dimensional groups

$$Ku = f(R', \ Ja_e, \rho_f/\rho_g, \ Pe, \ Lewis \ No.) \qquad (10)$$

We assume two of these groups are unimportant: Mass diffusivity is normally so slow with respect to boiling processes that it should not play an important role. Hence we drop the Lewis number. Elkassabgi and Lienhard found by least-squares fitting that ρ_f/ρ_g played no role in the kindred problem of burnout in a subcooled, single-component liquids. Binary boiling appears to be sufficiently similar in its vapor removal mechanisms to warrant the use of the same assumption here.

Since Ku and R' can be combined using $q_{max, SL}$, we assume that binary burnout data can be correlated with an equation of the form

$$\frac{q_{max}}{q_{max, SL}} = \frac{1}{1 - f(Ja_e, \ Pe)} \qquad (11)$$

The range of Pe variation in these experiments was not large enough to make its general influence on q_{max} clear. It is only clear that Pe has no noticeable influence when it is varied over the small range represented by the ethanol/water system at 1 atm.

Throughout the present computations, we used actual data for physical properties wherever that was possible. In the few cases that it was not, we used standard prediction techniques of the kind described by Reid et al. (1977) (see Reddy, 1987). A simple least-squares fit of our data then yielded

$$\frac{q_{max}(1 + 0.10x)}{q_{max, SL}} = (1 - 0.170 Ja_e^{0.308})^{-1} \qquad (12)$$

which represents the ethanol/water data for wires alone with an rms deviation of ±8 percent. (With the tube data, the rms error increases to ±15 percent.) Equation (12) is included in Fig. 5.

A Note on the Use of $(y - x)$ to Characterize the Phase-Equilibrium Diagram. We have noted that some authors have tried to characterize the phase-equilibrium diagram using the term $|y - x|$ evaluated at x. This term alone *ought* not be adequate to characterize the diagram fully. However, the use of $[T_g - T_f]$ has proven to be adequate in our effective subcooling model. By plotting $|y - x|$ against $[T_g - T_f]$ (see Fig. 7) for the ethanol/water system we discover a nearly linear interdependence. This is built into the nature of the phase-equilibrium diagram and may work for many other fluids as well. Thus $|y - x|$ fortuitously gives a fairly good characterization of phase-equilibrium behavior.

Accomplishments, Conclusions, and Observations

1 We have provided a carefully measured set of observations of burnout on cylinders in the ethanol/water system over a range of sizes.

2 The Sun-Lienhard burnout prediction may be used to account for size variation when $R' > 0.1$ and when its minor systematic failure for some fluids is compensated.

3 Equation (12) represents these burnout data within an rms error of ±8 percent.

4 The past success of using $|y - x|$ to characterize the phase-equilibrium diagram of ethanol/water is explainable and fortuitous.

5 Further research should be directed at:

• identifying the role of heat diffusion. This can probably be accounted in a relation of the form of equation (11), although it might be necessary to revert to equation (10).

• identifying the role of other geometries in the ethanol/water system (the flat plate would be a prime candidate).

• learning how the heater boundary condition (uniform heat flux as opposed to uniform wall temperature) influences burnout.

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