Pool-Boiling Critical Heat Fluxes For Dimethyl Sulfoxide and Water

W. R. GAMBILL

Oak Ridge National Laboratory, Oak Ridge, Tennessee

COOLANT PROPERTIES

Parker (*1*) has discussed the unusual properties of dimethyl sulfoxide (DMSO) and its solutions. Pure DMSO (CH_3SOCH_3, $M = 78.13$) has a normal boiling point of 189°C. The reagent-grade coolant used in the subject tests was 99.9% pure and exhibited a normal boiling point of 186°C. and a density (25°C.) of 1.098 g./ml. Although pure DMSO has a quite small mammalian toxicity, solutions can be hazardous since pharmacologically active compounds, dissolved in DMSO, can be readily absorbed through the skin and penetrate rapidly through biologic membranes (*2*). Other general characteristics of DMSO include its miscibility with water, *p*H neutrality, high hygroscopicity, ease of supercooling, and pronounced solvation properties. DMSO interacts strongly with water to form highly ordered structures (*1*). Since DMSO has a high dielectric constant (which minimizes electrostatic attraction between anions and cations) and is a good cation solvator (through ion-dipole interaction), precipitation and concentration of dissolved electrolytes on cooling is suppressed.

The physical-property data reported by Melendres (*3*) were the most complete found in the literature and are summarized in Table 1.

Melendres also notes that DMSO undergoes a slight decomposition when it is boiled at atmospheric pressure. Additional data obtained from the Merck Index (*4*) include: $t_f = 95$°C., n_D (21°C.) = 1.4787, and $C_{pl} = 0.7$ cal./g. × °C.

TABLE 1.

Property	@ t (°C.)	Value	Property	@ t (°C.)	Value
t_m	—	18.55°C.	ϵ	20	48.9
t_b	—	189.0°C.	ρ_l	20	1.100 g./ml.
μ	25	2.00 cp.	λ_f	18.6	69.8 B.t.u./lb.
p_v	25	0.600 mm. Hg.	λ	25	291 B.t.u./lb.
σ	20	46.2 *d*/cm.		189	244 B.t.u./lb.*
			ρ_e	20	3×10^7 Ω cm.

* From Trouton's constant = 22.9.

For the purposes of this investigation, it was necessary to calculate C_{pl} and ρ_v at $t = t_b$ and to extrapolate σ and ρ_l from 20°C. to t_b. Application of methods described elsewhere by the writer (*5*) resulted in the values in Table 2.

TABLE 2.

Property	@ t (°C.)	Value	Auxiliary Estimates
ρ_l	186	57.4 lb./cu.ft.	$[P] = 200$
ρ_v	186	0.132 lb./cu.ft.	$T_c = 731$°K.
σ	186	25.7 *d*/cm.	$P_c = 51.3$ atm. abs.
C_{pl}	20	0.496 cal./g. · °C.	
	103	0.600	
	176	0.717	

EXPERIMENTAL SYSTEM

The arrangement was essentially identical to that employed in a previous study of pool-boiling critical fluxes (*6*). Seventeen tests were made at atmospheric pressure ($P_{mn} = 14.4$ lb./sq. in. abs.) with both saturated water and saturated and subcooled DMSO outside a horizontal, a.c. heated, 0.233-in.-O.D. A nickel tube positioned in a 6 × 6 × 9 in. deep pool fabricated of 304 stainless steel and A nickel. A calibrated Sanborn wattmeter was again used to record the instantaneous power dissipation, and an internal ten thermocouple thermopile was distributed so as to monitor the 2.5 in. long central region of the test section. In order to prevent physical burnout of the heater tube, the thermopile signal was used to actuate a circuit breaker when a suitable trip limit was reached. The liquid level above the upper tube surface was 2 (±½) in.

Only two changes were made to the system (*6*) used previously: the sides of the pool were externally insulated with Fiberfrax, and a pyramidal, parallel-plate reflux condenser was placed over the pool during the saturated DMSO tests to avoid excessive vapor concentrations in the experimental area. The condenser coolant was pumped Prestone (97% ethylene glycol, $t_b = 195$ to 196°C.).

At $t > \sim 170$°C., the DMSO slowly changed color from water white to a light yellow or rose hue, indicating some decomposition [as noted by Melendres (*3*)]. Several tests were conducted at this pool temperature (170°C.) to avoid significant degradation of the coolant. The saturated-pool condition of the two final tests was approached relatively rapidly to minimize the exposure time of the DMSO to temperatures exceeding 170°C.

RESULTS

The experimental critical fluxes are listed in Table 3. The average ϕ_c for saturated water is 8.7% higher than that obtained in the earlier study (*6*), when a mean value of 457,000 B.t.u./hr.·sq. ft. (+9%, −11%) resulted from 52 tests (heater no. 3).

The average saturated-DMSO critical flux has been compared with the dimensionless Kutateladze-Zuber equation:

$$(\phi_c)_{sat} = K\lambda \rho_v^{1/2} (\sigma \, g_c \, a \, \Delta\rho)^{1/4} \qquad (1)$$

which was used by the author as an element in his superposition method of correlating critical heat fluxes for flowing liquids (*7*). Average K coefficient values ranging from 0.13 to 0.18 have been proposed, and the available saturated pool-burnout data (*7*) correspond to a maximum K range of 0.08 to 0.23. For the present tests, an average ϕ_c of 130,000 B.t.u./hr.·sq. ft. for DMSO is equivalent to a K value of 0.127.

Another value of $(\phi_c)_{sat}$ may be obtained by applying the subcooling factor of Ivey and Morris (*8*) to the average subcooled ϕ_c whereby:

$$F_{sub} \equiv \frac{(\phi_c)_{sub}}{(\phi_c)_{sat}} = 1 + \left(\frac{\rho_l}{\rho_v}\right)^{3/4} \left(\frac{C_p \, \Delta t_{sub}}{9.8 \, \lambda}\right) \qquad (2)$$

Table 3.

Test No.	Fluid	State	$10^{-3}\ \phi_c$ (B.t.u./hr. sq. ft.)
1	H_2O	saturated	524.4
2	↓	↓	508.2
3			503.4
4			482.5
5			483.0
6			483.0
7			506.0
8			482.0
[Avg. ϕ_c = 496,600 B.t.u./hr.·sq.ft. (+5%, −3%)]			
9	DMSO	subcooled*	214.0
10	↓	↓	236.0
11			220.3
12			242.8
13			225.6
14			242.8
15			204.4
[Avg. ϕ_c = 226,600 B.t.u./hr.·sq.ft. (+9%, −11%)]			
16	DMSO	saturated	127.0
17	DMSO	saturated	133.0
[Avg. ϕ_c = 130,000 B.t.u./hr.·sq.ft. (±2.2%)]			

* Δt_{sub} = 16.3 (±0.3)°C. = 29.3°F.

For the experimental DMSO conditions, $F_{sub} = 1.837$, whence $(\phi_c)_{sat}$ = 123,400 B.t.u./hr.·sq. ft., which is only 5.3% less than the average experimental value and confirms a K value [in Equation (1)] of 0.12 to 0.13 for DMSO.

The preceding observations are summarized in Table 4.

Table 4.

Fluid	Δt_{sub}(°F.)	No. of Tests	$10^{-3}\ (\phi_c)_{avg.}$ (B.t.u./hr.·sq.ft.)	Max. Dev. (%)	K [Equation (1)]	Source
H_2O	0	52	457.0	+9, −11	0.174	6
H_2O	0	8	496.6	+5, −3	0.189	This study
DMSO	0	2	130.0	±2.2	0.127	This study
DMSO	29.3	7	226.6	+9, −11	0.121*	This study

* When $(\phi_c)_{sat}$ is obtained from the average experimental $(\phi_c)_{sub}$ with Equation (2).

CONCLUSIONS

Pool-boiling critical heat fluxes measured with saturated and subcooled DMSO at atmospheric pressure are in good agreement with Equations (1) and (2) when a value of ⅛ is assigned to K. The K value for water, ~0.18, is in accord with earlier measurements.

RECOMMENDATIONS

Because of its strong interaction with water (*1*), critical-flux data for aqueous mixtures of DMSO should be obtained. Such data would provide a good test of McEligot's correlation (*9*) of limited critical-flux data for subcooled dilute binary mixtures:

$$\phi_c = 0.37\,\lambda\,\rho_v^{1/2}(\sigma\,g_c\,a\,\Delta\rho)^{1/4}\left(\frac{h_{la}-h_{lo}}{\lambda}\right)^{1/7} \quad (3)$$

which was proposed for horizontal-plate or large tubular heaters and values of $(h_{la} - h_{lo})/\lambda$ between 0.02 and 0.3. In addition, the possible role of DMSO in reducing heat-transfer-surface fouling by brines could be examined by acquiring boiling data with mixtures of DMSO and aqueous salt solutions.

ACKNOWLEDGMENT

This research was sponsored by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.

NOTATION

- a = local field acceleration
- C_{pl} = specific heat of the liquid (at constant pressure)
- F_{sub} = subcooling factor, Equation (2)
- g_c = mass-to-force conversion constant
- h_{la} = enthalpy of the saturated liquid phase of the less volatile component
- h_{lo} = initial enthalpy of the liquid mixture
- K = coefficient, Equation (1)
- M = molecular weight
- n_D = refractive index (sodium D line)
- P = absolute system pressure
- $[P]$ = parachor
- P_c = thermodynamic critical pressure
- p_v = vapor pressure
- t = temperature
- t_b = normal boiling point
- T_c = thermodynamic critical temperature
- t_f = flash point
- t_m = melting point
- t_{sat} = saturation temperature

Greek Letters

- Δt_{sub} = degree of subcooling, $(t_{sat} - t_{coolant})$
- $\Delta\rho$ = phase density difference, $(\rho_l - \rho_v)$
- ϵ = dielectric constant of liquid
- λ = latent heat of vaporization
- λ_f = latent heat of fusion
- μ = liquid viscosity
- ρ_e = electrical resistivity
- ρ_l = saturated liquid density
- ρ_v = saturated vapor density
- σ = surface tension (liquid-vapor)
- ϕ_c = critical heat flux

Subscripts

- mn = mean
- sat = saturated
- sub = subcooled

LITERATURE CITED

1. Parker, A. J., *Internl. Sci. Tech.*, No. 43, 28 (Aug., 1965).
2. Buckley, A., *J. Chem. Educ.*, 674 (Dec., 1965).
3. Melendres, C. A., *UCRL-16330*, Univ. California, Radiation Laboratory, Berkeley (Sept., 1965).
4. "Merck Index," Seventh Ed., p. 373, Merck & Company, (1960).
5. Gambill, W. R., "Chemical Engineers' Handbook," Fourth Ed., p. 3-213 to 3-231, McGraw-Hill, New York (1963).
6. ———, *AIChE J.*, **10**, 502 (1964).
7. ———, *Chem. Eng. Progress Symposium Ser. No. 41*, **59**, (1963).
8. Ivey, H. J., and D. J. Morris, *At. Energy Estab. (G.B.) Winfrith, Rept. AEEW-R-137* (Jan. 1962).
9. McEligot, D. M., *AIChE J.*, **10**, 130 (1964).