The Interrelation of Surface Effects and Acceleration in the Burnout Heat Flux Problem

C. P. COSTELLO and C. A. HEATH
University of Washington, Seattle, Washington

Most theories of pool-boiling burnout which are based on hydrodynamic instability models indicate that burnout heat flux is proportional to the local acceleration raised to the 0.25 power. The nature of the theories is such that surface effects should alter neither the magnitude of the burnout heat flux nor the extent to which the burnout heat flux is affected by acceleration.

Data collected by Bernath (*1*) and results reported recently (*2*, *3*) have clearly shown that for heat transfer surfaces of practical sizes, surface effects can alter the burnout heat flux, a fact which is in direct contradiction to the hydrodynamic instability theories. Since surface effects are important in the burnout problem, it appears that the extent to which acceleration affects the burnout heat flux should also depend on the surface nature. Data presented in this communication clearly indicate that surface effects are definitely interrelated with acceleration in the burnout heat flux problem.

APPARATUS

The heaters employed were graphite strips (0.3 in. wide, 2.5 in. long with 2-in. between voltage taps, insulated on all but one face) and a platinum wire (0.063 in. in diameter 3 in. long, 2.3 inches between voltage taps). The heaters were mounted at a radius of 2.3 to 2.4 in. in a centrifuge (Figure 1). (Radius was measured to the axis of the wire and to the uninsulated face of the strip.) The heaters were mounted with their long axes parallel to the center line of rotation so that the centripetal acceleration was normally away from the graphite strip.

The acceleration vector was normally away from the inside half of the platinum wire but normally toward the outer half. However, it has been shown (*4*) that in such cases burnout always originates at the inside of the wire, that is, the side from which the acceleration vector is directed. Hence, burnout data from the wire and the strips are comparable.

A fast response potentiometer was used to measure the d.c. voltage across the heaters. With this instrument, it was possible to interrupt the power the instant burnout started and to save the heater. Moreover, because of the rapid interruption of power, the heater surfaces showed no evidence of alteration. The same heater was used for a number of tests, and frequent checks were made at a reference condition (zero revolutions per minute of the centrifuge) to insure that no variation in the surface had occurred.

Fluids employed in the tests were distilled water, distilled water with an additive (see reference *4* for specifications) and 200 proof ethanol. The fluids were maintained at the saturation temperature during the tests by power supplied from the test heaters (*4*). All tests were conducted at pressures close to atmospheric. There were slight pressure increases caused by

(Continued on page 285)

Unsteady Diffusion with First-Order Reaction

E. N. LIGHTFOOT
University of Wisconsin, Madison, Wisconsin

Outlined below is a method for simplification of the solution of diffusion problems involving irreversible first-order reactions. It permits writing the concentration profiles for reactive systems in terms of those for nonreactive systems of the same geometry and similar boundary conditions. The method is valid where fluid flow patterns and concentration boundary conditions are time independent and where the assumptions of constant density and mass diffusivity are acceptable. The useful results of this development are summarized in Equations (31) through (33) and represent a generalization of an earlier development by P. V. Danckwerts (*1*).

Considered here is a binary system, composed primarily of species *A* and *B* and defined by the following equations:

$$\frac{\partial c_A}{\partial t} + (\mathbf{v} \cdot \nabla c_A) = \mathcal{D}_{AB}\, \nabla^2 c_A + k\, c_A \qquad (1)$$

$$c_A(\mathbf{r}, 0) = c_0(\mathbf{r}) \qquad (2)$$

$$c_A(\mathbf{s}, t) = c_s(\mathbf{s}) \qquad (3)$$

$$\mathbf{v} = \mathbf{v}(\mathbf{r}) \qquad (4)$$

$$\rho = \text{constant} \qquad (5)$$

These equations describe unsteady state mass transfer in a system of time-independent velocity profile and boundary conditions for which the mass diffusivity $\mathcal{D}_{AB}$, and total mass density, ρ, are constant.

It is the purpose of this communication to show how the concentration profile for this system may be determined from that of one for which $k = 0$ but is otherwise identical to that described by Equations (1) to (5). The problem may be split into two simpler ones by defining

$$c_A = c_{A1} + c_{A2} \qquad (6)$$

with c_{A1} and c_{A2} described by

$$\frac{\partial c_{A1}}{\partial t} + (\mathbf{v} \cdot \nabla c_{A1}) = \mathcal{D}_{AB} \nabla^2 c_{A1} + k\, c_{A1} \qquad (7)$$

$$c_{A1}(\mathbf{r}, 0) = c_0(\mathbf{r}) \qquad (8)$$

$$c_{A1}(\mathbf{s}, t) = 0 \qquad (9)$$

(Continued on page 282)

(Continued from page 278)

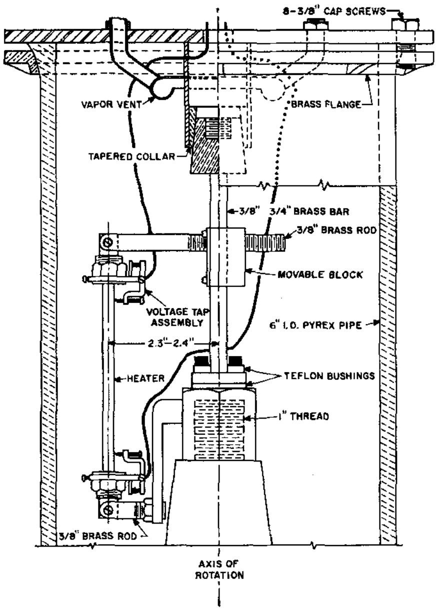

Fig. 1. Experimental apparatus, showing cylindrical heater in place. Graphite strip was mounted with only uninsulated face directed toward axis of rotation.

centrifugal forces, but the pressure increases were insufficient to substantially alter fluid properties (*4*).

The centrifuge, power-measurement equipment, and test sequence are described in reference *4*. In particular, it is noteworthy that according to tests described in reference *4* there were no confounding effects on burnout owing to subcooling, secondary flows, or other effects caused by the use of a centrifuge.

Tests for burnout at local gravity conditions, $a/g = 1$, were conducted with the heaters mounted horizontally in a separate pool. This was done to afford a closer comparison between tests at $a/g = 1$ and with $a/g > 1$.

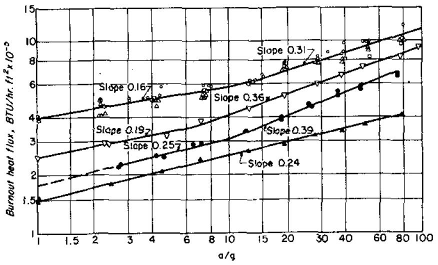

Fig. 2. Burnout heat flux vs. acceleration.

○, △, □ = graphite in pure water (three different heaters)

▽ = graphite in water with surface tension reduced to 72% of that of pure water.

● = graphite in ethanol. (No run taken with heater horizontal at $a/g = 1$. Burnout at $a/g = 1$ for vertical heater, 170,000 B.t.u./hr.sq.ft.)

▲ = platinum wire in ethanol.

Slopes quoted are values of B_2 [Equation (1)].

INFORMATION RETRIEVAL

(Continued from page 284)

A relation between steam quality and void fraction in two-phase flow, Fujie, Hideo, **A.I.Ch.E. Journal, 10,** No. 2, p. 227 (March, 1964).

Key Words: Fluid Flow-7, 8, Void Fraction-8, Channel, Horizontal-10, Channel, Vertical-10, Flow-6, Heat Transfer-6, Quality-6, Pressure-6, Flashing-6, Void Fraction-7, Force Balances-1, Steam-Water-5, Two-Phase-5.

Abstract: Theoretical relationships between steam quality and void fraction are derived from equations of force balance for two-phase flow systems. The relationships yield some insight into the differences between vertical and horizontal flow as well as the effect of mass flow rate on vertical flow. The effects of flashing and heat input, system pressure, and channel geometry are also estimated from the theory. The theory is based upon an annular flow model with three regions being described by simplified force balances. One empirical constant is introduced, and the comparisons between calculated and experimental data over a range of conditions are satisfactory.

Chemical reactor stability by Liapunov's direct method, Berger, Jack Solomon, and D. D. Perlmutter, **A.I.Ch.E. Journal, 10,** No. 2, p. 233 (March, 1964).

Key Words: A. Stability-9, Steady State-8, Dynamic Analysis-10, Liapunov Function-2, Second Method-10, Krasovskii's Theorem-10, Region of Asymptotic Stability-9, Homogeneous Reaction-8, Disturbances-3, Temperature-7, Concentration-7, Well-Stirred Flow Reactor-8, Order of Reaction-6.

Abstract: Stability criteria are developed for a well-stirred flow reactor with chemical kinetics as an arbitrary function of temperature and concentration. By the use of Liapunov's direct method sufficient conditions are found to guarantee a region of asymptotic stability, as well as local stability of a given steady state. A specific solution is presented for nth order kinetics with Arrhenius temperature dependence, together with a qualitative description of the effect of reaction order on the stability criteria. A numerical example is included to illustrate the practical application of the results.

The effect of feedback control on chemical reactor stability, Berger, Jack Solomon, and D. D. Perlmutter, **A.I.Ch.E. Journal, 10,** No. 2, p. 238 (March, 1964).

Key Words: A. Stability-9, Steady State-8, Dynamic Analysis-10, Feedback Control-8, Liapunov Function-2, Second Method-10, Krasovskii's Theorem-10, Region of Asymptotic Stability-9, Homogeneous Reaction-8, Disturbances-3, Temperature-7, Concentration-7, Well-Stirred, Flow Reactor-8, Order of Reaction-6, Computer Control-2.

Abstract: An analysis is made of chemical reactor stability as affected by feedback control. The chemical kinetics are considered to be arbitrary functions of temperature and a single concentration. Liapunov's second method is used to show how the region of asymptotic stability can be expanded by various linear and nonlinear control modes. All the likely manipulating variables of the system are studied singly and/or in combination. Possible applications of computer control are pointed out.

Adsorption rate studies—significance of pore diffusion, Masamune, Shinobu, and J. M. Smith, **A.I.Ch.E. Journal, 10,** No. 2, p. 246 (March, 1964).

Key Words: Nitrogen-1, Helium-1, Vycor-5, Porous Glass-5, Rate-8, Transient Adsorption-8, Adsorption-8, Pore Diffusion-8, Packed Bed-5, Surface Diffusion-9, External Diffusion-9, Sorptometer-10.

Abstract: Adsorption rates were measured by a transient method on beds of porous Vycor glass particles. Nitrogen was adsorbed from a low concentration of helium passed through the bed at atmospheric pressure and liquid-nitrogen temperature.

Analysis of the data showed that external diffusion and surface adsorption were relatively rapid processes so that the overall rate was determined by intraparticle diffusion in the pores of the Vycor. Also the predominant mechanism in the pores was a surface diffusion process.

(Continued on page 288)

RESULTS AND DISCUSSION

Figure 2 shows the observed variations of burnout heat flux with acceleration. All slopes shown on the curve were calculated with an IBM-709 to obtain the least-squares fit to the equation

$$(q/A)_b = B_1(a/g)^{B_2} \qquad (1)$$

where $(q/A)_b$ is the burnout heat flux, B_1 and B_2 are constants, and a/g is the total acceleration divided by the local gravitational acceleration. The individual data points fit the graphite-pure water (topmost) curve within 15% and all other curves within 6.8%.

Measurements from a motion picture study* of ethanol boiling on graphite and on platinum suggest why the acceleration affects the burnout heat flux differently for the two surfaces. Figure 3 and Table 1 show pertinent data from the bubble measurements. Figure 3 clearly indicates that the ethanol wets graphite to a much greater extent than it does platinum; hence, the bub-

Table 1. Summary of Bubble Measurements (Ethanol Boiling on Platinum and Graphite)*

	Platinum	Graphite
Maximum bubble diameter, inches	0.070	0.0467
Average bubble diameter, inches	0.0491	0.033
Average base diameter, inches	0.026	0.012
Ratio, base to max. diameter, average	0.529	0.37
Maximum ratio of base to bubble diameter	0.689	0.500
Minimum ratio, base to bubble diameter	0.303	0.297
Ratio, base to max. diameter on biggest bubble observed	0.490	0.306

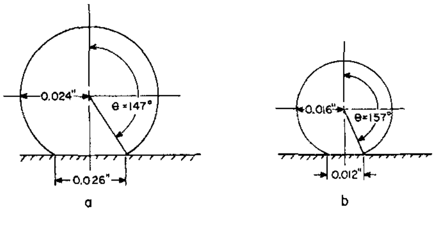

Fig. 3. Average configuration of bubbles measured from motion pictures. *a*. Ethanol boiling on platinum. *b*. Ethanol boiling on graphite.

---

* The study was conducted by photographing the heaters as they were brought from zero heat flux to a flux of 49,000 B.t.u./hr. sq. ft. Twenty-five bubbles were measured on each of the surfaces to obtain meaningful averages.

bles of ethanol on graphite have much smaller bases than do the bubbles on platinum.

When pressure forces around the periphery of bubbles are integrated, it is found that for spherical bubbles the upward buoyancy force is given by

$$F_B = -2\pi \rho \frac{g}{g_c} r^3 \left[\frac{\sin^2\Theta}{2} + \frac{(\cos^3\Theta - 1)}{3} \right] \tag{2}$$

where F_B is the upward buoyancy force, ρ liquid density, g local acceleration, g_c a constant and r the bubble radius. Θ is defined in Figure 3. Because of better wetting (greater value of Θ) the average bubble of ethanol on the graphite heater has one-third greater buoyancy forces per unit mass as compared to ethanol bubbles on platinum. It should be noted that the measurements were made at $a/g = 1$ and increased acceleration will reduce bubble sizes (*4*), but since the surface-to-liquid forces are not functions of acceleration the ethanol will still tend to wet graphite to a greater extent than platinum with $a/g > 1$. Thus, even at higher accelerations and with the vapor distorted into partially columnar shape, buoyancy forces on the vapor will be greater with the graphite surface than with the platinum surface.

Despite the disparity in buoyancy forces, Figure 2 shows that the burnout heat flux on graphite and platinum heaters is almost equally affected by acceleration for $1 \leqq a/g \leqq 10$. This suggests that buoyancy may not be very important in this range of acceleration. For $a/g > 10$, the buoyancy probably becomes more effective for the graphite heater, and the increase in burnout heat flux is proportional to acceleration to the 0.39 power. Apparently, inertial, pressure, and surface-tension forces still dominate the burnout situation on the platinum heater since the effect of acceleration on burnout heat flux is unaltered with $a/g > 10$.

Similar considerations apply to the graphite water curves of Figure 2. Water wets graphite rather poorly and the bubbles have large bases. If the surface tension of the water is reduced by adding a fluid which does not appreciably alter other properties of the water (*4*), the bubbles become smaller, much more numerous, and have very small bases. Such bubbles have greater buoyancy forces per unit mass than bubbles of pure water on graphite. However, the curves of Figure 2 show that the effect of increased acceleration, which directly increases buoyancy forces, is almost the same for both fluids in the range $1 \leqq a/g \leqq 10$.

INFORMATION RETRIEVAL

(Continued from page 286)

Simultaneous radiative and convective heat transfer in an absorbing, emitting, and scattering medium in slug flow between parallel plates, Chen, John C., **A.I.Ch.E. Journal, 10,** No. 2, p. 253 (March, 1964).

Key Words: Heat Transfer-8, 7, Radiation (Thermal)-8, 7, Convection-8, 7, Transport-8, Temperature-6, 7, Emissivity-6, Absorption-6, Scattering-6, Flow-6, Attenuation-7, Analytical Solution-9, Approximation-10.

Abstract: Approximate, analytical solutions in closed form were obtained for combined radiative and convective heat transfer to a medium in slug flow between infinite, parallel plates. The effects of absorption, emission, and scattering within the medium were taken into account. These solutions greatly simplify the task of calculating temperature profiles, radiant fluxes, and heat fluxes. Illustrative examples are presented to indicate the effects of attenuation coefficients, thermal conductivity, flow rate, absolute temperature, and wall emissivities.

Phase-volume relationship at the point of phase inversion in liquid dispersions, Yeh, George C., Fred H. Haynie, Jr., and Rex A. Moses, **A.I.Ch.E. Journal, 10,** No. 2, p. 260 (March, 1964).

Key Words: Phase Inversion-8, Binary Systems-9, Ternary Systems-9, Organic Liquid-9, Water-9, Organic Liquid Mixture-9, Mixing-8, Dispersion Type-8, Water-In-Oil-9, Oil-In-Water-9, Phase-Volume Ratio-7, Phase-Viscosity Ratio-6, Interfacial Composition-6, Interfacial Viscosity-6, Interfacial Adsorption-6, Interfacial Tension-6.

Abstract: The point of phase inversion for twelve binary systems of an immiscible organic liquid and water and five ternary systems of organic liquid mixture and water is investigated by varying the phase-volume ratio and determining the type of dispersion (water-in-oil or oil-in-water) after complete mixing. The phase-volume ratio at the point of inversion is found to be equal to the square root of the ratio of the viscosities of the respective phases at the interface. The theoretical aspects of this relationship are studied along with its limitations.

Force constants for polar substances: their prediction from critical properties, Stiel, Leonard I., and George Thodos, **A.I.Ch.E. Journal, 10,** No. 2, p. 266 (March, 1964)

Key Words: Polar Substances-8, Force Constants-8, Stockmayer Potential-8, Viscosity-9, Thermal Conductivity-9, Diffusivity-9, Transport Properties-9, Critical Constants-9, Critical Temperature-9, Critical Volume-9, Physical Properties-9, Correlations-10.

Abstract: Stockmayer force constants reported for nineteen polar gases have been used to develop relationships for the estimation of these constants from the critical constants of the substance. A dimensional analysis approach was used to establish the correct dependences. The resulting relationships can be applied for the calculation of the transport properties of polar substances.

A numerical method for the solution of the energy equation for steady turbulent heat transfer, Strunk, Mailand R., and Frank F. Tao, **A.I.Ch.E. Journal, 10,** No. 2, p. 269 (March, 1964).

Key Words: Flow-8, Fluid Flow-8, Heat Transfer-8, Mass Transfer-8, Equations-9, Reynolds Number-6, Eigenvalues-7, Temperature-7, Distribution-7, Numerical-10, Methods-10, Techniques-10.

Abstract: A method is presented for solving the basic energy expression for the temperature distribution for turbulent heat transfer in a circular conduit with a digital computer. The method assumes a knowledge of the velocity distribution, the eddy conductivity term as a function of the radial position, and a constant wall temperature. The method, which is also applicable to mass transfer, makes use of known mathematical techniques to determine temperature profiles. Some solutions of the energy equation are presented in graphical and tabular form for illustrative purposes.

The lower burnout heat fluxes for water containing wetting agent compared to burnouts with pure water are no doubt owing to the much greater bubble population caused by a reduction in the liquid surface tension. The great clouds of vapor no doubt prohibit much of the liquid inflow to the heater and cause burnout. This is not the case with the data for ethanol boiling on graphite and on platinum, in which case the better wetting of ethanol on graphite is the result of greater liquid-surface forces. No additive is used, and the bubble population is only slightly greater for ethanol on graphite as opposed to ethanol on platinum.

For $a/g > 10$, buoyancy apparently becomes more significant for both pure water and water with reduced surface tension. However, the latter fluid is more affected by the acceleration because of the greater wetting and the resulting higher buoyancy forces.* If the surface tension is reduced to 45% of that of pure water, the burnout heat flux increases in proportion to a/g raised to the 0.42 power for $a/g > 10$ (*4*).

CONCLUSIONS

1. The effect of acceleration on the burnout heat flux for water and ethanol cannot be predicted without reference to surface characteristics. It is indicated that accelerations above normal gravity have their greatest effect in increasing burnout on well-wetted surfaces and only if $a/g > 10$.
2. It appears that buoyancy is not of great significance in the burnout problem for $1 \leqq a/g \leqq 10$. (This conclusion may be applicable for $a/g \leqq 1$.)

ACKNOWLEDGMENT

The authors are most grateful to the National Science Foundation which provided funds for this project under Grant GP 530. Dr. J. M. Adams, now of Aerojet General, Sacramento, California, was instrumental in obtaining data for this paper while he was at the University of Washington, Seattle, Washington. Dr. Adams's assistance is greatly appreciated.

LITERATURE CITED

1. Bernath, Louis, *Chem. Eng. Progr. Symposium Ser. No. 30,* **56**, p. 95 (1959).
2. Gambill, W. R., *A.I.Ch.E. Journal,* to be published.
3. Costello, C. P., and W. J. Frea, Paper presented at A.I.Ch.E. Boston Meeting (August, 1963).
4. Costello, C. P., and J. M. Adams, *A.I.Ch.E. Journal,* 9, No. 5, p. 671 (1963).

---

* Considerations of this sort appear to indicate that the heat transfer coefficient as well as the burnout heat flux would be affected by acceleration in various ways, depending on the liquid-surface wetability.