

NUCLEATE-BOILING TYPE EVAPORATION OF BINARY-LIQUID
DROPS ON HEATED SURFACES

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ABSTRACT

A binary-liquid drop evaporates on a heated surface in the nucleate-boiling type vaporization regime taking into account the effect of drop geometry. A maximal slowing down of drop evaporation is disclosed together with the occurrence of a minimum surface-drop heat flux at different concentrations of the more volatile component. These phenomena are observed both theoretically and experimentally. Since the nucleate-boiling vaporization regime gives a minimum drop lifetime resulting in quicker vaporization (i.e. the best operating condition) and the rate of vapor formation together with air motion controls the combustion rate, the disclosure may be of some use in application to the regulation of the combustion rate in compression-ignition engines and oil-fired appliances.

Introduction

The boiling paradox in binary liquid mixtures has attracted considerable attention during the last decade. It refers to the curious coincidence of a maximal slowing down of bubble growth rate and departure size, the minimum heat transfer and the occurrence of a maximum critical (i.e. peak) heat flux at the same low concentration of the more volatile component in a binary system. Contributions to the understanding of this peculiar phenomenon by van Stralen [for example, 1, 2], Scriven [3] and Westwater [4] are noteworthy. The slowing down of bubble growth is due to the influence of mass diffusion of the more volatile component towards the bubble boundary, causing an increase in dew point of the vapor. This limits the analogous heat diffusion,

originally controlled by the liquid superheating. In his relaxation micro-layer theory, van Stralen [2] explains nucleate boiling as a relaxation phenomenon of the superheated thermal boundary layer, which is periodically pushed away from the wall due to the rapid growth of succeeding bubbles on nuclei -- the action of the vapor bubbles resulting in an augmentation of convective heat transfer.

Recently, Teshirogi [5] has conducted an experimental study on the lifetime of binary liquid drops on heated surfaces. Theory has been developed in references 6 and 7 to describe the dynamics of evaporation and combustion of liquid drops on heated surfaces for four different regimes classified according to the modes of heat transfer at the drop-surface interface. Theoretical prediction agrees well with test data. The study has concluded that the equations describing heat transfer performance of convection, nucleate boiling and film boiling are also valid for the vaporization of a single drop on a heated surface.

The present paper deals with the nucleate-boiling type vaporization of a binary-liquid drop on a heated surface. Theory is compared with the test data obtained by Teshirogi [5].

Variations of both the nucleate boiling heat flux density and the drop evaporation rate with composition in a binary liquid drop are also investigated.

Theory

Consider a minute drop of binary liquid mixture of radius R_0 is placed on a heated surface at temperature T_w , higher than the boiling point of the binary system T_b . The temperature difference $\Delta T = T_w - T_b$ is restricted to within the range of nucleate boiling. Under this thermal condition, a minute drop is observed to take the form of lens shape on the heating surface [5]. In view of high thermal and mass diffusivities of liquid as compared with those in the vapor phase and relatively slow movement of drop surface during phase change, both heat and mass transfer are treated as steady phenomena. At any time instant t , the drop of instantaneous radius R has uniform temperature and concentration T_b and x , respectively. The ambient has the temperature and concentration (vapor) maintained at T_a and 0, respectively. Due to low thermal conductivity of gas phase, the heat transfer by convection and radiation between the gas ambient and the drop is negligible compared with both the heat transmitted from the heating surface to the drop in the mode of

nucleate boiling and the latent heat of drop vaporization. Hence, the first law of thermodynamics as applied to the drop yields

$$q_b'' A_b = -\rho \lambda \frac{dV}{dt} \quad (1)$$

where q_b'' is the nucleate boiling heat flux; A_b , the drop-wall contact area; ρ , the liquid density; λ , the latent heat of vaporization; and V , the drop volume. The idealized model for a lens-shaped drop consists of a spherical segment of height S and radius of sphere R , as shown in Fig. 1. The area of the curved surface of the segment is $2\pi RS$, while the volume is $V = \pi S^2(3R-S)/3$. The liquid-solid contact area is $A_b = \pi R^2 \sin^2 \varphi$, where φ is the contact angle between the drop and the heating surface. One can write

$$S = R(1 + \cos \varphi) \quad \text{and} \quad V = \eta \pi R^3/3 \quad (2)$$

where

$$\eta = (1 + \cos \varphi)^2 (2 - \cos \varphi) \quad (3)$$

Of several equations available to predict nucleate boiling performance, the Rohsenow correlation is selected for its popularity:

$$q_b'' = \left(\frac{C_p \Delta T}{\lambda \psi Pr^\alpha} \right)^3 \mu \lambda \sqrt{\frac{g(\rho - \rho_v)}{g_c \sigma}} \quad (4)$$

where C_p , Pr and μ are respectively the specific heat, Prandtl number and absolute viscosity of the drop; ρ_v , density of the saturated vapor; g , gravitational acceleration; g_c , conversion factor; σ , surface tension of liquid-to-vapor interface; α , 1.0 for water and 1.7 for all other liquids or mixtures; and ψ , empirical constant which depends on the nature of the heating surface-liquid combination.

The quantity $[g_c \sigma / g(\rho - \rho_v)]^{1/2}$ is considered a characteristic length in boiling heat transfer performance, being interpreted as the departure bubble diameter or the distance between nucleation sites. For a liquid drop in thermal equilibrium with the surrounding gas ambient, a certain radius R can be maintained: with the difference in interfacial tensions between the top and bottom ends of the drop, the gravitational force acting on the drop is balanced with the force caused by surface tension. It yields

$$\left[\frac{\sigma g_c}{6(\rho - \rho_v)g} \right]^{1/2} = \frac{R}{3} \quad (5)$$

$R/3$ corresponds to the characteristic length of a sphere. Equations (1) through (5) are combined. The resulting equation is then integrated subject to the initial condition

$$R(0) = R_0 \quad (6)$$

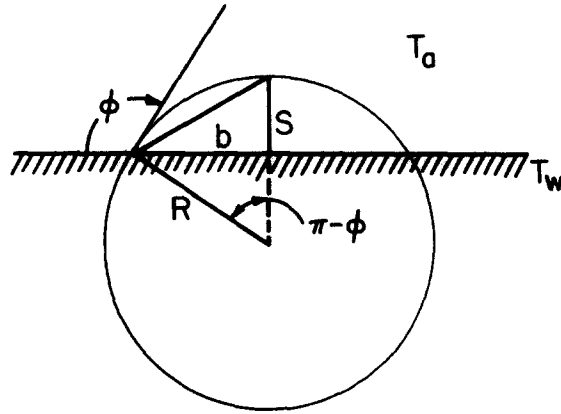


Fig. 1 Model for a lens-shaped drop on a heated surface.

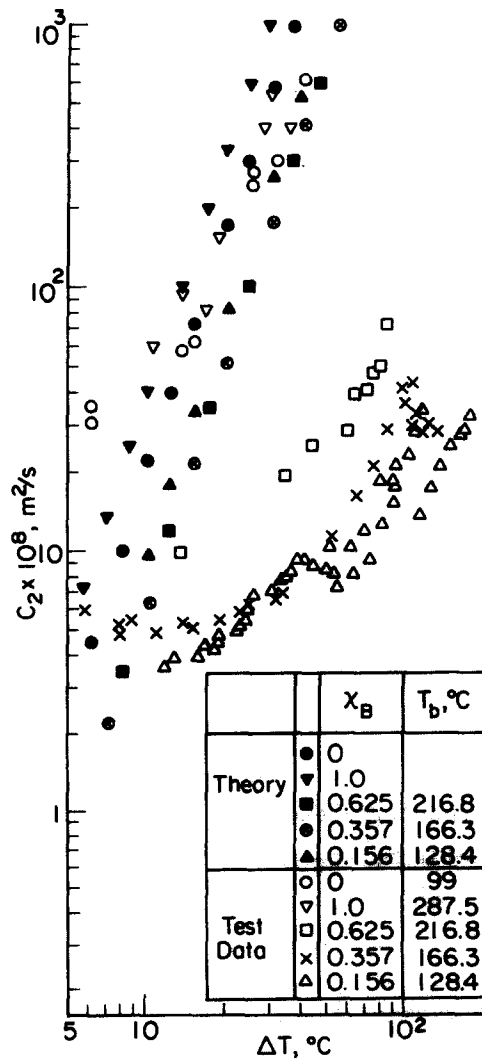


Fig. 2 Comparison of theory and test data for nucleate-boiling type vaporization of C_8H_{18} (A), $C_{16}H_{34}$ (B) and mixture drops.

One gets

$$R_0^2 - R^2 = C_2 t \quad (7)$$

wherein C_2 is the drop evaporation constant defined as

$$C_2 = \frac{\sqrt{6} \mu \sin^2}{\rho \eta} \left(\frac{C_p \Delta T}{\lambda \psi Pr^\alpha} \right)^3 \quad (8)$$

The drop lifetime τ may be obtained from equation (7) as

$$\tau = R_0^2 / C_2 \quad (9)$$

Equations (7), (8) and (9) apply to both single-component and binary-liquid drops. In the latter case, physical properties of the binary system must be employed in equation (8). Methods and equations are described in references 8 and 9 for the prediction of physical properties for both pure liquids and binary liquid mixtures. For example,

$$\mu_m^n = \sum_{i=1}^2 \mu_i^n x_i \quad (10)$$

in which μ_m and μ_i are the viscosities of the mixture and its component i , respectively; and x_i , mole fraction of the component i . The exponent n takes the value of $1/3$ for liquid-mixture viscosity and unity for all other liquid-mixture properties, which can be expressed in the form of equation (10).

Results and Discussion

Theoretical results are obtained for the drop evaporation constant C_2 of equation (8) for isooctane (C_8H_{18} , represented by the symbol A), cetane ($C_{16}H_{34}$, as B), α -methyl-naphthalene ($C_{11}H_{10}$, as C) and their mixtures. Physical properties of pure liquids (except $C_{11}H_{10}$ by approximation) available in reference 10 were utilized together with the methods and equations for predicting physical properties of binary liquid mixtures. Theoretical results are compared with Teshirogi's test data in Figs. 2 and 3. No quantitative information on ψ is presently available for those fluid-surface (aluminum surface was employed in reference 5) combinations. Therefore, the value of ψ for each pure liquid-surface combination was determined by equating one theoretical C_2 to the corresponding experimental C_2 of the same wall superheating ΔT at approximately midpoint in the nucleate-boiling type vaporization regime. The ψ values for the binary liquid mixtures were determined on the mass-fractional average basis. Two most important variables affecting ψ are known to be the surface roughness of the heater and the wettability of the surface with the fluid. Since the same aluminum surface was utilized for the vaporization experiments of pure- and binary-liquid drops

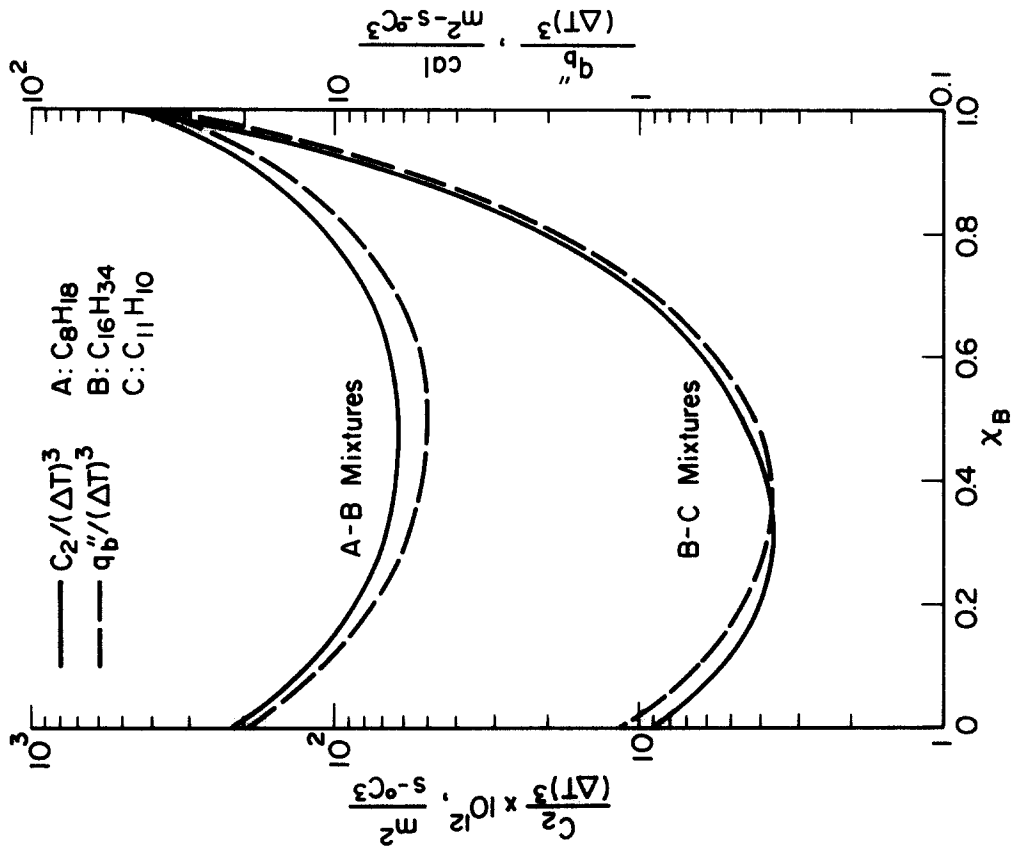


Fig. 4 C/(ΔT)³ and q_b''/(ΔT)³ versus χ_B for nucleate-boiling type vaporization of C₈H₁₈, C₁₆H₃₄, C₁₁H₁₀ and mixture drops.

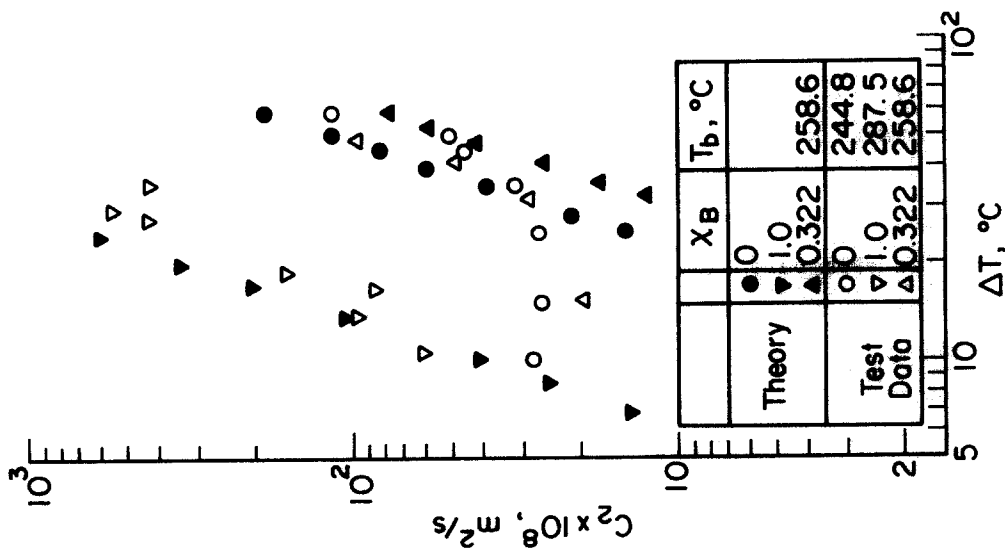


Fig. 3 Comparison of theory and test data for nucleate-boiling type vaporization of C₁₁H₁₀(C), C₁₆H₃₄(B) and mixture drops.

in reference 5, the values of ψ thus determined can be considered very reliable. The contact angle ϕ of 45 degrees was employed for all the fluids and their mixtures in evaluating the theoretical values of C_2 .

Figure 2 illustrates the variation of C_2 with the degree of wall superheating ΔT for C_8H_{18} ($x_B=0$), $C_{16}H_{34}$ ($x_B=1.0$) and their mixtures ($x_B=0.156$, 0.357 , 0.625). The C_2 - ΔT relationship for $C_{16}H_{34}$ ($x_B=1.0$), $C_{11}H_{10}$ ($x_B=0$) and their mixture ($x_B=0.322$) is presented in Fig. 3. Both theory and test data exhibit the slowing down of the vaporization rate of binary-liquid drops. The boiling point of pure liquids was empirical, while that of the binary liquid mixtures was estimated based on mass-fraction average. Theoretical prediction agrees with test data quantitatively in case of pure liquids and only qualitatively in case of binary mixtures. In the latter case, deviation of theory from experiments is, to a certain extent, caused by the errors in ΔT resulting from uncertainty in the value of T_b employed.

Variation of the nucleate-boiling heat flux q_b'' of equation (4) with composition x_B is plotted in Fig. 4 together with the drop evaporation constant C_2 of equation (8). The $q_b'' - x_B$ relationship may also be obtained by the Stephan-Korner method [11] utilizing data for pure components. Both C_8H_{18} - $C_{16}H_{34}$ and $C_{16}H_{34}$ - $C_{11}H_{10}$ mixtures exhibit the occurrence of a minimum value in both the drop evaporation constant and the nucleate-boiling heat flux. The slowing down of the drop evaporation rate is simply due to the reduction in the heat transfer rate resulting from the presence of a second component. Although the minimum values of C_2 and q_b'' fail to coincide at the same composition, both take place at a composition of x_B less than 0.5.

Conclusions

Both theoretical and experimental evidence have indicated that in the nucleate-boiling type vaporization regime, even small amounts of a second component result in considerable reductions in the drop vaporization rate from that measured for the pure liquid drop. The cause of this reduction is simply due to the influence of the second component on the heat transfer rate from the heating surface to the drop. Like in nucleate pool boiling, the heat transfer rate reduces substantially with the presence of a second component in a liquid drop.

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References

1. W.R. van Wijk, A.S. Vos and S.J.D. van Stralen, Heat transfer to boiling binary liquid mixtures, *Chem. Engng. Sci.* 5, 68 (1956).
2. W.J.D. van Stralen, The boiling paradox in binary liquid mixtures, *Chem. Engng. Sci.* 25, 149 (1970).
3. L.E. Scriven, On the dynamics of phase growth, *Chem. Engng. Sci.* 10, 1 (1959).
4. J.E. Benjamin and J.W. Westwater, Bubble growth in nucleate boiling of a binary mixture, 1961 Intern. Heat Transfer Conference, Part II, 212 (1961).
5. N. Teshirogi, Combustion Control of Diesel Engines by Heated Surfaces, Doctor of Engineering Thesis, University of Tokyo, Tokyo, Japan (1975).
6. Wen-Jei Yang, Theory on vaporization and combustion of liquid drops of pure substances and binary mixtures on heated surfaces, ISAS Report No. 535 (Vol. 40, No. 15), 423, University of Tokyo, Tokyo, Japan (Nov. 1975).
7. Wen-Jei Yang, Vaporization and combustion of liquids drops on heated surfaces, presented at the Two-Phase Flow and Heat Transfer Symposium-Workshop, Fort Lauderdale, Florida, Oct. 18-20, 1976.
8. J.H. Perry (Ed.), Chemical Engineers' Handbook, 4th ed., McGraw-Hill, New York (1963), Chap. 3.
9. D.L. Katz (Ed.), Handbook of Natural Gas Engineering, McGraw-Hill, New York (1959), Chap. 4.
10. Phillips 66 reference data for hydrocarbons and petro-sulfur compounds, Bulletin No. 521, Phillips Petroleum Co., Bartlesville, Oklahoma (1962).
11. K. Stephan and M. Korner, Berechnung des Wärmeübergangs verdampfender binärer Flüssigkeitsgemische, *Chemie Ingenieur Technik*, 41, 409 (1969).