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Boiling Heat Transfer in Dilute Emulsions

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Preface

Boiling of dilute emulsions in which the dispersed component has a lower boiling point than the continuous component has received little attention in the literature. These mixtures exhibit several surprising behaviors that were unknown until the 1970s. Boiling of the dispersed component enhances heat transfer over a wide range of surface temperatures without transition to film boiling, but a high degree of superheat is required to initiate boiling. In single-phase convection, the dispersed component has little effect on heat transfer. These behaviors appear to occur in part because few droplets in the emulsion contact nucleation sites on the heated surface. No physically consistent model of boiling in dilute emulsions exists at present.

The unusual behavior of boiling dilute emulsions makes them potentially useful for high heat flux cooling of electronics. High-power electronic devices must be maintained at junction temperatures below ~95 °C to operate reliably, even while generating heat fluxes of 100 W/cm^2 or more. Military avionics is pushing the thermal envelop to junction temperatures of 95 °C and power densities of 1,000 W/cm^3. Current research, generally focusing on single phase convection or flow boiling in small diameter channels, has not yet identified an adequate solution. An emulsion of refrigerant in water would be well-suited to this application. The emulsion retains the high specific heat and thermal conductivity of water, while boiling of the refrigerant enhances the heat transfer coefficient at temperatures below the saturation temperature of water.

We summarize the recent experiments on boiling heat transfer from a heated wire in emulsions of pentane in water and FC-72 in water. These emulsions have properties suitable for practical use in high heat flux cooling applications, unlike most emulsions that have previously been studied. Experiments include enhanced boiling of the continuous component, which has not previously been observed, in addition to boiling of the dispersed component. In both boiling regimes the heat transfer coefficient is enhanced compared to that of water. Visual observation of the boiling process reveals the presence of large attached bubbles on the heated wire, the formation of which coincides with the inception of boiling in the heat transfer data. At very low dispersed component fractions and low temperatures, boiling of individual dispersed droplets is not observed. The large attached bubbles represent a new boiling mode that has not been reported and is, under some circumstances, the dominant mode of boiling heat transfer.

A model of boiling dilute emulsions is described and developed based upon the Euler–Euler model of multiphase flows. The general balance equations are applied to the present situation, thus providing a rigorous and physically consistent framework. The model contains three phases that represent the continuous component, liquid droplets of the dispersed component, and bubbles that result from boiling of individual droplets. Mass, momentum, and energy transfer between the phases are based upon the behavior of and interaction between individual elements of the dispersed phases. A one-dimensional simulation of a single boiling droplet in superheated liquid is used to develop the closure equations of the larger model. Droplet boiling is assumed to occur when a droplet contacts a heated surface or a vapor bubble. Collisions between droplets and bubbles and chain boiling of closely spaced droplets are considered. The model is limited to the dispersed component boiling regime and thus does not account for phase change of the continuous component. It also does not account for large attached bubbles revealed in the experiments. Exercising the model produces several trends observed in the experiments.

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Contents

Symbols

A	Surface area, m^2
A_0	Adjustment parameter in Eq. 2.17
Ar	Archimedes number, $(\rho_{eff} - \rho_b) g \rho d \frac{d_b^3}{\mu_{eff}^2}$
a	Coefficient in discretized differential equations
B	Pre-exponential factor in Eq. 2.2
$\boldsymbol{b}$	Body force per unit mass, N/kg
C_D	Drag coefficient
C_L	Lift coefficient
C_R	Rotation coefficient
C_{sf}	Empirical constant, Eq. 5.3
C_{td}	Turbulent drag coefficient
C_{vm}	Virtual mass coefficient
c_p	Constant-pressure specific heat, J/kg °C
c_v	Constant-volume specific heat, J/kg °C
D	Viscous dissipation, W/m^3
d	Diameter, m
E	Averaged interfacial energy transfer rate, Eq. (A23), W/m^3
e	Specific internal energy, J/kg
F	Source flow strength, m^3/s
$\boldsymbol{F}$	Averaged interfacial force, N/m^3
$\boldsymbol{F}_{ij}$	Averaged interfacial force on phase i by phase j, N/m^3
f	Frequency, Hz
g	Gravitational force, N/kg
h	Heat transfer coefficient, W/m^2 °C
I	Identity matrix
i	Specific enthalpy, J/kg
J	Volumetric nucleation or collision rate, $1/m^3$ s
Ja	Jakob number, $\rho_f c_{p,f} \Delta T / (\rho_g i_{fg})$

K_T	Pseudo-turbulent factor
K	Thermal conductivity, W/m °C
k_B	Boltzmann constant, 1.38065×10^{-23} J/K
l	Eddy mixing length
L	Characteristic length, m
m	Mass, kg
$\dot{m}$	Volumetric mass transfer rate from droplet phase to bubble phase, kg/m^{3}s
N	Number density, 1/m^3
$\boldsymbol{n}$	Outward-pointing unit normal vector
Nu	Nusselt number, hL/k
P	Pressure, N/m^2
Pe	Peclet number, Re · Pr
Pr	Prandtl number, ν/α
Q	Heat transfer, J
$\boldsymbol{q}$	Heat flux vector, W/m^2
q	Heat transfer rate, W
q''	Heat flux, W/m^2
$\boldsymbol{R}_{\mathrm{eff}}$	Effective viscous stress (molecular plus Reynolds), m^2/s^2
$\mathbf{R}_{\mathrm{eff}}^{\mathrm{C}}$	Correction stress component, m^2/s^2
$\mathbf{R}_{\mathrm{eff}}^{\mathrm{D}}$	Diffusive stress component, m^2/s^2
R	Droplet or bubble radius, m
R_G	Gas constant, J/kg K
R_{cr}	Critical bubble radius, m, Eq. 2.1
Ra	Rayleigh number, $\frac{g\beta_{\mathrm{film}}(T_s - T_\infty)d^3}{\nu_{\mathrm{film}}^2}\mathrm{Pr}_{\mathrm{film}}$
r	Radial distance, m
Re	Reynolds number, $\mathscr{U}d/\nu$
$\boldsymbol{S}$	Surface area vector, m^2
S	Heat source per unit mass, W/kg
s	Prandtl number factor, Eq. 5.3
St	Stefan number, $c_{p,d}(T - T_{\mathrm{sat}})/i_{fg}$
T	Temperature, K
ΔT	Temperature difference, $T_\infty - T_{\mathrm{sat}}$
$\mathbf{T}$	Stress tensor, N/m^2
t	Time, s
Δt	Time step size in numerical solver, s
$\mathscr{U}$	Characteristic fluid velocity, m/s
$\boldsymbol{U}$	Velocity vector, m/s
$\boldsymbol{U}_{r,ij}$	Relative velocity vector between phases i and j, $\boldsymbol{U}_j - \boldsymbol{U}_i$, m/s
u	Velocity component, m/s
u^*	Turbulence characteristic velocity, m/s
V	Volume, m^3

v	Specific volume, m^3/kg
X	Phase indicator function
$\boldsymbol{x}$	Position vector

Greek Symbols

α	Thermal diffusivity, m^2/s
β	Volumetric expansion coefficient, m^3/m^3 K
Γ	Averaged interfacial mass transfer rate, Eq. (A24), kg/m^3 s
$\boldsymbol{\gamma}$	Generic diffusive flux, Eq. (A1)
γ	Specific heat ratio, c_p/c_v
Δ	Very small value
δ	Dirac delta function
δ_t	Thermal boundary layer thickness, m
ε	Volume fraction, m^3/m^3
ζ	Generic source density, Eq. (A1)
η	Collision efficiency
θ	Angular direction, radians
κ	Polytropic coefficient
μ	Dynamic viscosity, kg/m-s
ν	Kinematic viscosity, m^2/s
ρ	Density, kg/m^3
σ	Surface tension, N/m
τ	Characteristic time, s
ϕ	Volumetric flux, m^3/s
φ	Number of boiling droplets in a chain reaction
Ψ	Generic conserved quantity, Eq. (A1)

Subscripts

+	Positive portion
–	Negative portion
0	Reference
1ph	Single phase
b	Vapor bubble phase (emulsified component)
c	Continuous phase
coll	Collisions
cond	Condensation
D	Drag
d	Liquid droplet phase (emulsified component) or dispersed phase
eff	Effective value for the emulsion
F	Face-centered value

f	Saturated liquid
fg	Difference between saturated vapor and saturated liquid
film	Evaluated at film temperature, $(T_s + T_\infty)/2$
g	Saturated vapor
I	Interface
inertial	Inertial
init	Initial
i, j	Counting indices, i, j = 1, 2, 3…
L	Lift
M	Minnaert
m	Mixture
max	Maximum value
mol	Molecule
R	Rotational
r	Radial direction
s	Surface
sat	Saturated condition
T	Turbulent quantity
td	Turbulent dispersion
v	Vapor phase
vm	Virtual mass
w	Wall
wire	Heated wire
θ	Tangential direction (in polar coordinates)
∞	Ambient

Superscripts and Other Notation

$\overline{X}$	Average value or phase property
x’	Fluctuating component of x, where $x = x' + \overline{X}$
$\widehat{X}$	Unit vector
$\lvert\mathbf{X}\rvert$	Magnitude of x
δx	Uncertainty in x
x^*	Predicted values of x in PISO algorithm
x^o	Quantity x at previous iteration
x^{Re}	Fluctuation (Reynolds) quantity
$\frac{D_i}{D_t}$	Material derivative for phase i, $\frac{\partial}{\partial_t} + \mathbf{U}_i \cdot \nabla$
$\lvert\lvert\mathscr{L}[x]\rvert\rvert$	Expression arising from implicit discretization of operator $\mathscr{L}$ in terms of x
$\langle X \rangle$	Average of x over adjacent cells
$\mathscr{A}$	Discretized linear system of equations

$\mathscr{A} := \{\ldots\}$	Assignment of the discretized form of the system of linear equations in brackets { … } to $\mathscr{A}$
$\mathscr{A}_D$	Diagonal matrix coefficients of discretized linear system of equations $\mathscr{A}$
$\mathscr{A}_N$	Off-diagonal matrix coefficients of discretized linear system of equations $\mathscr{A}$
$\mathscr{A}_S$	Source vector of discretized linear system of equations $\mathscr{A}$
$\mathscr{A}_H$	H operator, Eq. 4.29