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Microscales of saturated pool film boiling

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Abstract

Two thermal Kolmogorov scales for pool film boiling

$$\eta_\theta^{\mathrm{B}} \sim \left(\frac{\nu\alpha_2^2}{\mathscr{B}}\right)^{1/4}, \quad \eta_\theta^{\mathrm{C}} \sim \left(\frac{\alpha_2^3}{\mathscr{B}}\right)^{1/4},$$

are introduced. Here ν, k and ρ respectively denote the vapor kinematic viscosity, thermal conductivity and density, $\alpha_2 = k/\rho c_{p2}$ and $c_{p2} = h_{fg}/\Delta T$ (a two-phase thermal diffusivity and specific heat) suggested for notational convenience, and $\mathscr{B}$ the rate of buoyant production of turbulent vapor energy. In terms of these scales, the pool film boiling heat transfer is shown to be

$$\frac{\ell}{\eta_\theta^{\mathrm{B}}} \sim Nu \sim Ra_2^{1/3}, \quad \frac{\ell}{\eta_\theta^{\mathrm{C}}} \sim Nu \sim (Ra_2 Pr_2)^{1/3},$$

where ℓ is an integral scale, Ra_2 and Pr_2 are the Rayleigh and Prandtl numbers based on α_2. The microscale foundation of the earlier correlations of the turbulent pool film boiling data of all fluids except for liquid metals is demonstrated in terms of η_θ^{B}. An original correlation in terms of η_θ^{C}

$$Nu = 0.17(Ra_2 Pr_2)^{1/3},$$

is proposed for turbulent pool film boiling data of liquid metals.

1. Introduction

The literature on heat transfer in buoyant films resulting from a phase change go back to Nusselt [1] who obtained in terms of a Rayleigh number based on latent heat,

$$Nu = f(Ra_2), \tag{1}$$

or, explicitly, $Nu \sim Ra_2^{1/4}$ for laminar film condensation, later extended by Bromley [2] to laminar film boiling. These relations ignore the effect of inertial force characterized by a Prandtl number based on latent heat, Pr_2, which suggests

$$Nu = f(Ra_2, Pr_2). \tag{2}$$

The foregoing dimensionless numbers result from a coupling of appropriate (inertial, viscous and buoyant) forces of a momentum balance with enthalpy flow and conduction terms of a thermal energy balance. The objective of the present study is to develop an original correlation for turbulent pool film boiling data of liquid metals in terms of Eq. (2).

The study is divided into four sections. Following this introduction, Section 2 briefly reviews the dimensionless numbers appropriate for two-phase films, Section 3 introduces two thermal microscales for these films and the correlation of pool boiling data in terms of these scales and Section 4 to conclusions.

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Nomenclature

C, C_0	constants
c_p	vapor specific heat
c_{p2}	two-phase specific heat, $h_{fg}/\Delta T$
F_B	buoyant force
F_I	inertial force
F_V	viscous force
g	gravitational acceleration
h	convection heat transfer coefficient
h_{fg}	latent heat
Ja	Jacob number, $c_p\Delta T/h_{fg}$
k	vapor thermal conductivity
ℓ	integral length scale
Nu	Nusselt number, $h\ell/k$
Pe	Peclet number, $V\ell/\alpha$
Pe_B	buoyant Peclet number, $(RaPr)^{1/2}$
Pr	Prandtl number, ν/α
Pr_2	two-phase Prandtl number, Pr/Ja
Q_2	interface enthalpy flow
Q_H	net enthalpy flow
Q_K	conduction heat flux
Ra	Rayleigh number, $(g/\nu\alpha)(\Delta\rho/\rho)\ell^3$
Ra_2	Ra/Ja, two-phase Rayleigh number
S_{ij}	mean rate of strain
s_{ij}	fluctuating rate of strain
T	temperature
ΔT	$T_w - T_{sat}$
U	mean velocity of turbulent flow
u	velocity fluctuation of turbulent flow
V	velocity

Greek symbols

α	thermal diffusivity, $k/\rho c_p$
α_2	two-phase thermal diffusivity, $k/\rho c_{p2}$
ϵ	viscous dissipation
ϵ_θ	thermal dissipation
η_θ^B	Batchelor scale
η_θ^C	Oboukhov–Corrsin scale
λ	Taylor scale
λ_θ	thermal Taylor scale
μ	vapor dynamic viscosity
ν	vapor kinematic viscosity
ρ	vapor density
$\Delta\rho$	$\rho_l - \rho_v$
Θ	mean temperature
Θ_0	saturated liquid temperature
θ	vapor temperature fluctuation

Script symbols

$\mathscr{B}$	buoyant production
$\mathscr{F}$	buoyant force
$\mathscr{P}$	inertial production
$\mathscr{P}_\theta$	thermal production

Subscripts

i, j	tensor index
l	liquid
sat	saturation
v	vapor
w	wall
2	two-phase

2. Two dimensionless numbers

A balance among forces acting on a control volume involving pool film boiling yields

$$F_I + F_V \sim F_B, \tag{3}$$

F_I being the inertial force, F_V the viscous force and F_B the buoyant force. The effect of interface force F_2 (due to density difference between two phase) is usually assumed to be small on heat transfer and is neglected in Eq. (3). A balance of thermal energy for the same control volume gives

$$Q_2 + Q_H \sim Q_K, \tag{4}$$

Q_2 being the interface enthalpy flow, Q_H the net enthalpy flow, and Q_K the conduction. The reasons for retaining Q_2, while neglecting F_2, will be clear shortly.

Two dimensionless numbers resulting from Eq. (3) are

$$\frac{F_B}{F_V}, \quad \frac{F_B}{F_I}. \tag{5}$$

Also, two dimensionless numbers associated with Eq. (4) are

$$\frac{Q_2}{Q_K} + \frac{Q_H}{Q_K} = \frac{Q_2}{Q_K}\left(1 + \frac{Q_H}{Q_2}\right), \tag{6}$$

where $Q_H/Q_2 = c_p\Delta T/h_{fg} = Ja$ is the Jacob number. In the case of liquid metals $Ja \ll 1$ and the effect of sensible heat will be neglected in the following development. [1] On dimensional grounds, in terms of the vapor properties, the density difference $\Delta\rho$ between two phase, the temperature difference ΔT between wall and saturated vapor, and a characteristic length ℓ,

$$\frac{F_B}{F_V} \sim \frac{g(\Delta\rho)\ell^2}{\mu V}, \quad \frac{F_B}{F_I} \sim \frac{g(\Delta\rho)\ell}{\rho V^2}, \quad \frac{F_I}{F_V} \sim \frac{\rho V\ell}{\mu},$$
$$\frac{Q_2}{Q_K} \sim \frac{\rho V\ell h_{fg}}{k\Delta T}.$$

[1] In the case of other fluids Ja may have some effect and may be incorporated into the development by the factor $(Q_2/Q_K)(1 + Ja)$.

However, the foregoing nondimensionalizations depending on a characteristic velocity V are not appropriate for buoyant flows. Velocity is now a dependent variable and should not appear in a dimensionless number describing these flows. Accordingly, one needs to combine Eq. (6) with Eq. (5) for a result independent of V. The only two combinations which eliminate velocity between Eqs. (5) and (6) are

$$\frac{F_B}{F_V}\left(\frac{Q_2}{Q_K}\right) \sim \frac{g(\Delta\rho)\rho h_{fg}\ell^3}{\mu k\,\Delta T} = Ra_2, \tag{7}$$

$$\frac{F_B}{F_I}\left(\frac{Q_2}{Q_K}\right)^2 \sim g(\Delta\rho)\rho\left(\frac{h_{fg}}{k\,\Delta T}\right)^2\ell^3 = Ra_2 Pr_2, \tag{8}$$

where

$$Pr_2 = \frac{\mu h_{fg}}{k\,\Delta T} \sim \frac{F_V}{F_I}\left(\frac{Q_2}{Q_K}\right).$$

Note that a "two-phase specific heat and thermal diffusivity"

$$c_{p2} = h_{fg}/\Delta T, \quad \alpha_2 = \frac{k}{\rho c_{p2}} \tag{9}$$

may for notational convenience be defined as the natural limit of $(\partial h/\partial T)_p$, and ΔT may now be assumed as a temperature jump across interface. Then, in terms of α_2,

$$Ra_2 = \frac{g}{\nu\alpha_2}\left(\frac{\Delta\rho}{\rho}\right)\ell^3, \quad Pr_2 = \frac{\nu}{\alpha_2}, \tag{10}$$

assume the conventional forms of the usual Ra and Pr.

The next section develops explicit forms of Eqs. (1) and (2) for buoyant turbulent films.

3. Turbulent pool film boiling

Recent studies by Arpacı [3–6] develop the original microscales for single-phase buoyant flows and, in terms of these scales, discover the foundations of so far assumed empirical correlations of turbulent heat transfer data. Also, Arpacı and co-workers [7–15] extend these studies to a variety of natural (thermocapillary, rotating, reacting), as well as, pulsating flows. All these references have been recently complied in a concise textbook by Arpacı [16]. Chapter 8 of the text includes a preliminary version of the following development.

Let the instantaneous vapor film velocity and temperature of pool boiling be decomposed into temporal means and fluctuations,

$$U_i + u_i, \quad \Theta + \theta$$

and let U_i and Θ be statistically steady. Then, the balance of the mean kinetic energy of homogeneous velocity fluctuations gives

$$\mathscr{B} = \mathscr{P} + \epsilon, \tag{11}$$

where $\mathscr{B} = -g_i\overline{u_i\theta}/\Theta_0$ is the buoyant production, g_i being the vector acceleration of gravity and Θ_0 the saturated liquid temperature, $\mathscr{P} = -\overline{u_iu_j}S_{ij}$ is the inertial production, S_{ij} being the rate of the mean strain, and $\epsilon = -2\nu\overline{s_{ij}s_{ij}}$ is the dissipation of turbulent energy, s_{ij} being the rate of fluctuating strain. Also, the balance of the root mean square of homogeneous thermal fluctuations involving phase change yields

$$(\mathscr{P}_\theta)_2 = (\epsilon_\theta)_2, \tag{12}$$

where

$$(\mathscr{P}_\theta)_2 = -\overline{u_i\theta}\frac{\partial\Theta}{\partial x_i}$$

is the mean thermal production, and

$$(\epsilon_\theta)_2 = \alpha_2\overline{\left(\frac{\partial\theta}{\partial x_i}\right)\left(\frac{\partial\theta}{\partial x_i}\right)}$$

is the mean thermal dissipation.

First, neglecting inertial effects, consider the case

$$\mathscr{B} \sim \epsilon \gg \mathscr{P} \tag{13}$$

for all fluids except for liquid metals. On dimensional grounds,

$$\mathscr{B} \sim \nu\frac{u^2}{\lambda^2}, \tag{14}$$

where u is the rms value of velocity fluctuations, ℓ is an integral scale and λ is a momentum Taylor scale, and Eq. (12) leads to

$$(\mathscr{P}_\theta)_2 \sim u\frac{\theta^2}{\ell} \sim \alpha_2\frac{\theta^2}{\lambda_\theta^2} \sim (\epsilon_\theta)_2, \tag{15}$$

λ_θ being a thermal Taylor scale. Assuming momentum and thermal boundary layers to be approximately equal, $\lambda \sim \lambda_\theta$, rearranging Eq. (14) in terms of Eq. (15), and solving the result for λ_θ, yields

$$\lambda_\theta \sim \ell^{1/3}\left(\frac{\nu\alpha_2^2}{\mathscr{B}}\right)^{1/6}. \tag{16}$$

For the isotropic flow, the foregoing development (from Eqs. (14)–(16)) repeated in terms of only one length scale, say η_θ, leads to a thermal Kolmogorov scale,

$$\eta_\theta^B \sim \left(\frac{\nu\alpha_2^2}{\mathscr{B}}\right)^{1/4}. \tag{17}$$

A special case of this scale for $\alpha_2 = \alpha$, expressed in terms of dissipation rather than production, is the Batchelor scale [17] introduced for single-phase flows with $Pr \geqslant 1$.

As demonstrated in Section 2 leading to the development of Ra_2 and Pr_2, a dimensionless number appropriate for buoyant flows cannot depend on velocity which is a dependent variable. Since $\mathscr{B}$ depends on velocity, Eq. (17) cannot be the ultimate form of a microscale for buoyant flows. To eliminate velocity, consider $\mathscr{B}$ in terms of a buoyant force $\mathscr{F}$. On dimensional grounds,

$$\mathscr{B} \sim u\mathscr{F} \tag{18}$$

which may be rearranged in terms of the isotropic velocity obtained from Eq. (15),

$$u \sim \alpha_2/\eta_\theta, \tag{19}$$

as

$$\mathscr{B} \sim \alpha_2\mathscr{F}/\eta_\theta. \tag{20}$$

In terms of $\mathscr{F} = g(\Delta\rho/\rho)$, Eq. (17) becomes

$$\eta_\theta^{\mathrm{B}} \sim \left(\frac{\nu\alpha_2}{g(\Delta\rho/\rho)}\right)^{1/3}, \tag{21}$$

or, relative to an integral scale, as

$$\frac{\ell}{\eta_\theta^{\mathrm{B}}} \sim Nu \sim Ra_2^{1/3} \tag{22}$$

and, including the effect of sensible heat, as

$$Nu = C[(1 + C_0 Ja)Ra_2]^{1/3}. \tag{23}$$

Beginning with the second half of the past century and extending beyond the following four decades, several researchers [18–34] have correlated experimental data on pool film boiling involving three basic geometries and a variety of fluids (see [35] for an earlier review and [36] for a latest review). These correlations are customarily assumed empirical rather than having any microscale foundation demonstrated by the foregoing development leading to Eq. (23). After Frederking and Clark [19] the numerical value of C_0 is usually assumed to be 0.5 and C is found to be in between 0.13 and 0.20. One of the latest works by Bui and Dhir [26] correlated by Chu [33] leads to

$$Nu = 0.14[(1 + 0.5Ja)Ra_2]^{1/3}.$$

Next, neglecting viscous effects, consider the case

$$\mathscr{B} \sim \mathscr{P} \gg \epsilon \tag{24}$$

for liquid metals. On dimensional grounds,

$$\mathscr{B} \sim \frac{u^3}{\ell}, \tag{25}$$

where ℓ is an integral scale. Now, rearranging Eq. (25) in terms of Eq. (15), and solving the result for λ_θ, yields

$$\lambda_\theta \sim \ell^{1/3}\left(\frac{\alpha_2^3}{\mathscr{B}}\right)^{1/6}. \tag{26}$$

For isotropic flow, the foregoing development repeated in terms of only one length scale, say η_θ, leads to a thermal Kolmogorov scale,

$$\eta_\theta \sim \left(\frac{\alpha_2^3}{\mathscr{B}}\right)^{1/4}. \tag{27}$$

A special case of this scale for $\alpha_2 = \alpha$, expressed in terms of dissipation, is the Oboukhov–Corrsin scale [37,38] introduced for single-phase flows with $Pr \ll 1$. Recalling Eq. (20) and $\mathscr{F} = g(\Delta\rho/\rho)$, Eq. (27) may be rearranged as

$$\eta_\theta^{\mathrm{C}} \sim \left(\frac{\alpha_2^2}{g(\Delta\rho/\rho)}\right)^{1/3}, \tag{28}$$

or, relative to an integral scale, as

$$\frac{\ell}{\eta_\theta^{\mathrm{C}}} \sim Nu \sim (Ra_2 Pr_2)^{1/3}. \tag{29}$$

Fig. 1 shows a correlation of the old mercury data of Korneev [39] and Lyon [40] which lead, in terms of Eq. (29), to

$$Nu = 0.17(Ra_2 Pr_2)^{1/3}. \tag{30}$$

The figure includes also the limited and old potassium data of Padilla [41]. Vapor properties at the film temperature of the liquid metals are taken from [42,43]. The buoyancy is based on the difference between the saturated liquid temperature and the vapor film temperature. The integral scale is replaced with a characteristic length (height or diameter, depending on geometry).

It is interesting to note that a balance between buoyant and inertial forces, $g(\Delta\rho)\ell^3 \sim \rho V^2\ell^2$, leads to a characteristic velocity,

$$V \sim \left[g\left(\frac{\Delta\rho}{\rho}\right)\ell\right]^{1/2},$$

for buoyant flows involving fluids with $Pr \ll 1$. Then, the usual definition of the Peclet number,

$$Pe = \frac{\text{Enthalpy flow}}{\text{Conduction}} = \frac{V\ell}{\alpha},$$

in terms of the foregoing velocity, leads to a *Peclet number for buoyant flows*,

$$Pe_{\mathrm{B}} = \frac{[g(\Delta\rho/\rho)\ell^3]^{1/2}}{\alpha} = (Ra\,Pr)^{1/2}.$$

An extension to pool films is readily obtained by replacing α with α_2 in Pe_{B}. In terms of this Peclet number, say $(Pe_{\mathrm{B}})_2$, the correlation given by Eq. (30) becomes

$$Nu = 0.17(Pe_{\mathrm{B}})_2^{1/3}.$$

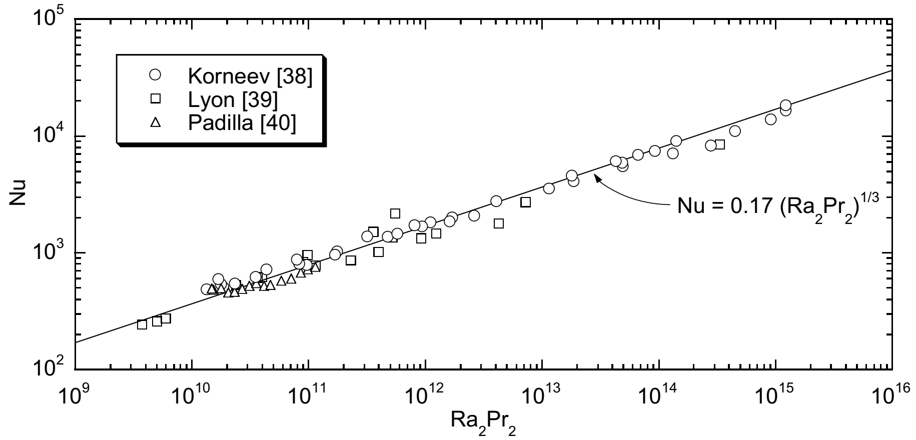

Fig. 1. Nu vs. $Ra_2 Pr_2$; Korneev [39] and Lyon [40] data for mercury pool film boiling on a horizontal cylinder at 1 atm, and Padilla [41] data for potassium pool film boiling on a horizontal surface at 0.08–0.4 atm.

4. Concluding remarks

The present study provides a microscale foundation to all existing, and so far assumed empirical, correlations of turbulent pool film boiling data. Two thermal microscales are introduced. The 1/3-power law of the well-known correlation of turbulent pool film boiling data for heat transfer involving all fluids except for liquid metals is explained with one of these scales. A new correlation based on the other scale and depending also the same power law is introduced for turbulent pool film boiling data of liquid metals.

An important conclusion emerging from the present study is that the heat transfer in an actual (nonhomogeneous) buoyant flow is apparently characterized by a Kolmogorov sublayer.

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