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Boiling heat transfer on a sphere with turbulent vapour film

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ABSTRACT

The theoretical study investigates turbulent film boiling on a sphere immersed in the stagnant liquid. It begins by assuming the surface temperature of the sphere is isothermal. The result shows that the boiling heat transfer under the turbulent vapour shows that both the temperature and the velocity present a non-linear distribution. Besides, the increase of the thermal radiation, wall temperature and buoyancy effects can enhance the heat transfer efficiency. Furthermore, a comparison between the results of the present study and those reported in a previous theoretical study of laminar film boiling is provided. It is found that turbulent film boiling with higher Rayleigh number will have higher Nusselt number.

1. Introduction

Heat transfer of phase-change is widely considered in the design of heat exchanger, power plant and cooling of electronic elements. Significant efforts have been directed towards researches into related fields; for example, stable film boiling has received considerable attention since the pioneering analysis of Bromley [1]. After Bromley's research, there were many related studies reported. In 1966, Nishikawa et al. [2] analyzed two-phase boundary-layer treatment of free-convection film boiling. The theoretical study has been made of film boiling from an isothermal vertical plate and a horizontal cylinder without considering radiative effects. Jordan [3] investigated both the laminar film boiling and transition boiling. The intermediate region which separated the two boiling mechanisms had also been discussed in his work. Sakurai et al. [4,5] presented a theoretical and an experimental investigation into pool film boiling on a horizontal cylinder, in which the analytical heat transfer model was based on laminar boundary theory and took account of radiation effects, while the experimental data were based on a variety of working fluids, including water, ethanol, iso-propanol, Freon-113 Freon-11, liquid nitrogen, and liquid argon. Studies of the heat transfer process often consider the case of a spherical body. Farahat [6] investigated the natural film boiling on spheres under saturated liquids. The integral methods of boundary-layer used in the analysis combined both the analytical approach and the experimental judgment. For film boiling from a sphere to a sub-cooled liquid, Burmeister [7] presented generalized predictions for the film pressure's frequency of oscillation and maximum excursion. Furthermore, Tou et al. [8] investigated the modeling of film boiling on spheres. The analytical model of Nusselt number for laminar film boiling from a sphere is expressed as:

$$Nu_m = C_1(Ra/Ja)^{1/4} + 2. \tag{1}$$

Besides, for the condensation heat transfer on a sphere, Hu [9] investigated the turbulent film condensation on a spherical body with variable wall temperature under the effect of local shear stress.

Since laminar boiling heat transfer on a cylinder or a sphere and turbulent film condensation heat transfer on a sphere have been widely discussed in published literature, there is also some development on the researches of turbulent film

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Nomenclature

C_p	specific heat capacity (J/kg K)
D	diameter of sphere, $2R$
D^+	shear parameter, Du^*/v_s
Gr_D	modified Grashof number of buoyancy effects, $\frac{gD^3}{v_s^2}\frac{\rho_l-\rho_s}{\rho_s}$
G	acceleration due to gravity (m/s^2)
H	heat transfer coefficient (W/(m^2 K))
h_{fg}	latent heat (J/kg)
k	thermal conductivity (W/m K)
k^+	$k(T)/k(T_s)$, Eq. (12)
N_u	local Nusselt number, hR/k_s
Nu_m	mean Nusselt number for whole sphere surface
NR	radiation parameter $\varepsilon\sigma T_s^3 R/k_s$
Pr	Prandtl number $C_p\mu/k$
R	radius of sphere (m)
Ra	modified Rayleigh number, $Gr_D Pr[0.5 + 1/S(T_r - 1)]$
S	heat capacity parameter, $C_pT_s/(\mathrm{Pr}h_{fg})$
T	temperature (K)
T_r	temperature ratio, T_w/T_s
T^+	dimensionless temperature, $(T - T_s)/(T_w - T_s)$
u	vapour velocity in x-direction (m/s)
u^*	shear velocity, $\sqrt{\tau_w/\rho}$
u^+	dimensionless velocity, u/u^*
v	velocity normal to the direction of flow (m/s)
x	peripheral coordinate (m)
y	coordinate measured distance normal to sphere surface (m)
y^+	dimensionless distance, yu^*/v_s

Greek symbols

δ	vapour film thickness (m)
δ^+	dimensionless film thickness, $\delta u^*/v_s$
μ	absolute viscosity (kg/ms)
μ^+	Eq. (10), μ/μ_s
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
θ	angle measured from bottom of sphere
ε_m	eddy diffusivity for momentum
ε_h	eddy diffusivity for energy
ε	emissivity
σ	Stefan–Boltzmann constant (W/m^{2}K^4)

Subscripts

l	liquid
s	vapour at saturation temperature
v	vapour
w	sphere wall
X	x-direction
δ	vapour–liquid interface

boiling. For example, Sarma et al. [10] presented turbulent film boiling under uniform heat flux condition on a horizontal cylinder. In their research, the assumption of the interfacial shear stress at the vapour–liquid interface is of the same order as that which would prevail at the solid boundary. Through the comparison between the theoretical model and the experimental studies [11,12], they found the assumption was reasonable. About the turbulent film boiling on a horizontal isothermal circular cylinder, Sarma et al. [13] presented turbulent film boiling on a horizontal cylinder. The analysis compared the theoretical results with previous experimental results, and found that their results were in a good agreement with the experimental data [11,12].