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Heat transfer during pool boiling based on evaporation from micro and macrolayer

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Abstract

An analytical model of heat transfer based on evaporation from the micro and macrolayers to the vapor bubble during pool boiling is developed. Evaporation of microlayer and macrolayer during the growth of individual bubbles is taken care of by using temporal and spatial variation of temperature in the liquid layer. Change of bubble shape during the entire cycle of bubble growth and departure is meticulously considered to find out the rate of heat transfer from the solid surface to the boiling liquid. Continuous boiling curve is developed by considering the bubble dynamics and decreasing thickness of liquid layer along with the increase of dry spot radius. Transient variation of macrolayer and microlayer thickness is predicted along with their effect on CHF. Present model exhibits a good agreement with reported experimental data as well as theories.

Keywords: Microlayer; Macrolayer; Dry out radius; Critical heat flux; Bubble; Pool boiling

1. Introduction

Boiling heat transfer finds extensive applications in a variety of industries. Metallurgical processing, thermal and nuclear power generation refrigeration, cryogenics and space applications, electronic component cooling are a few to name. Yet boiling heat transfer is one of the least understood topics in thermal engineering. Though a large number of experimental investigations have been made over the years the processes like nucleation, boiling crisis, transition etc. cannot be well explained from the first principle. As a result no well-established theory exists for predicting the rate of heat transfer during boiling. Nevertheless, because of the practical importance of boiling heat transfer, thermal engineers have proposed various phenomenological models based on the insight gained from the experimental observations. In general, these models contain one or more empirical constants and have different level of accuracies for different data sets. Till the complex physics of boiling is understood, there remains a scope for improving such mechanistic models.

Nukiyama [1] first developed the basic understanding of the physical processes that occurs during boiling by heating a nichrome wire in a saturated pool of water. He distinguished different modes of pool boiling such as partial nucleate boiling, fully developed nucleate boiling, transition boiling and film boiling. Out of these fully developed nucleate boiling exhibits a very high rate of heat transfer and the absence of local hot/dry spots—which is very suitable for a large number of industrial processes. Though in most of the heat exchange processes convective boiling is encountered enough efforts have been spared to study pool boiling to develop an understanding of the boiling process as such. Rohsenow [2] was the first to propose a physical model of nucleate boiling as well as a theoretical expression of heat transfer coefficient containing two empirical constant (C_{sf}, s).

$$\frac{c_{pl}\Delta T_{sat}}{h_{fg}Pr^{s}} = c_{sf}\left[\frac{q_w}{\mu h_{fg}}\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}}\right]^{0.33} \quad (1)$$

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Nomenclature

A_d	maximum cross sectional area at the time of departure (m^2)
A_{mi}	microlayer area (m^2)
c_1	change of degree of superheat (K/s)
c	constant stated in Eq. (4) (dimensionless)
C_{pl}	heat capacity (KJ $(kg\,K)^{-1}$)
C_s	empirical constant for bubble departure diameter (dimensionless)
C_{sf}	empirical constant used in Eq. (1) (dimensionless)
d	diameter of the bubble at the end of initial phase (m)
D_d	bubble departure diameter (m)
F_{sy}	surface tension force (N)
F_{duy}	unsteady growth force (N)
F_b	buoyancy force (N)
F_l	lift force (N)
g	acceleration due to gravity ($m\,s^{-2}$)
h_{fg}	latent heat ($J\,kg^{-1}$)
k_l	thermal conductivity ($W\,(m\,K)^{-1}$)
K	empirical constant used in Eq. (25) (dimensionless)
n	empirical constant used in Eq. (25) (dimensionless)
Pr	liquid Prandtl number (dimensionless)
$q(r,t)$	wall heat flux as a function of r and t ($W\,m^{-2}$)
q_w	wall heat flux ($W\,m^{-2}$)
q_c	heat flux due to thermal boundary layer ($W\,m^{-2}$)
q_{CHF}	critical heat flux ($W\,m^{-2}$)
r	radial coordinate (m)
r_d	dry out radius (m)
r_c	radius at which superheated boundary layer touches the bubble (m)
R	instantaneous radius of the bubble (m)
R_d	bubble departure radius (m)
s	empirical constant used in Eq. (1) (dimensionless)
t	time (s)
t_d	bubble departure time (s)
t_g	initial growth period (s)
t^*_{mg}	time at which boundary layer touches the liquid vapor interface (s)
T_0	incipient boiling wall temperature (K)
T_w	instantaneous wall temperature (K)
u_b	velocity of the bubble front ($m\,s^{-1}$)
V_b	instantaneous bubble volume (m^3)

Greek symbols

ΔT_{sat}	degree of superheat (K)
α	liquid thermal diffusivity ($m^2\,s^{-1}$)
δ_{mi}	microlayer thickness (m)
δ_{ma}	macrolayer thickness (m)
δ_c	thickness of superheated boundary layer (m)
μ	liquid dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ_l	liquid density ($kg\,m^{-3}$)
ρ_v	vapor density ($kg\,m^{-3}$)
σ	surface tension of liquid solid combination ($N\,m^{-1}$)
Φ	contact angle

Subscripts

0	initial
l	liquid
v	vapor
d	at a radial position $d/2$

In 1958 Zuber [3] developed a theoretical approach to describe the methodology for determining critical heat flux based on hydrodynamic instability that is known as far field model.

As the process of nucleation depends essentially on the surface condition and the wetting property of the boiling fluid, Mikic and Rohsenow [4] suggested a heat transfer model for flat surfaces which considers micro-conduction only at the nucleation site and natural convection elsewhere.

Katto et al. [5] realized the importance of evaporative heat transfer from thin liquid layers adjacent to the bubbles. They were first to propose a heat transfer model based on macrolayer evaporation. Haramura and Katto [6] and Pan et al. [7] developed their macrolayer model further stating that instability at the macrolayer interface termed, as near field phenomena is the main controlling parameter throughout the boiling process. Among the other efforts of near field model Pasamehmetoglu et al. [8] described the phenomena by the dry out of microlayer (liquid layer of very small thickness below the growing bubble) and macrolayer. Brief reviews stating all these models have been presented by Katto [9] and Lienhard [10].

Lay and Dhir [11] used a vapor stem model which is also based on the evaporation of the microlayer. Currently, Zhao et al. [12] predicted critical heat flux based on a dynamic microlayer model for steady and transient boiling heat transfer. They calculated the microlayer thickness varying with time and space ignoring the heat transfer from macrolayer.

Shoji et al. [13] numerically derived the transient macrolayer thickness and finally predicted the total boiling curve. They considered three-dimensional transient heat conduction to investigate the spatial variation of wall temperature.