Chemical Engineering Science 181 (2018) 326–340

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

A numerical investigation on heat transfer dynamics of a periodically forced boiling channel in low amplitudes

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HIGHLIGHTS

- Mechanism of wall heat transfer dynamics in a vertical boiling channel under periodic forcing.
- Role of chaotic bubble dynamics and bubble mixing in wall heat transfer.
- Effect of forcing amplitude and frequency on boiling heat flux.
- Effect external flux on wall heat flux.

ARTICLE INFO

Article history:
Received 10 November 2017
Received in revised form 26 January 2018
Accepted 20 February 2018

Keywords:
Heat transfer
Subcooled boiling
Boiling channel
Periodic forcing
Drift flux model

ABSTRACT

In this article, the authors report wall-heat transfer characteristics of a periodically forced vertical boiling channel with the help of numerical simulation based on four-equation drift flux model. The periodic forcing on the boiling channel was initiated by the sinusoidal perturbation of the inlet velocity. The effect of the frequency ω and the amplitude $\tilde{a}$ of the forcing on the heat transfer enhancement were studied to formulate a mechanism for the enhancement of wall heat flux q''_w. q''_w increases with $\tilde{a}$ in the range of ω less than a critical value ω_{crit}. The comparison of the numerical solution and the asymptotic solution of a reduced-order model through harmonic balance method (HBM) shows that both the solutions for the amplitude of exit mixture enthalpy decrease with ω consistently and asymptotically, when ω is greater than the characteristic frequency ω_c of the channel. The enhancement is also facilitated by chaotic instability (mixing) at higher $\tilde{a}$ and higher external heat flux.

1. Introduction

Studies on boiling heat flux from the heated surface under flow oscillations or unstable conditions have been an interesting subject of research in many applications which involve transfer of a large amount of heat. In particular, the applications include fast heat removal from nuclear fuel rods (pins) in maintaining thermohydraulic safety of nuclear reactors (Tong, 1967; Bergles, 1999; Kakac, 1999; Sinha and Kakodkar, 2006; Saha et al., 2013) and cooling of extremely hot bodies in metal industries (Chattopadhyay et al., 2002; Warrier and Dhir, 2013). Subcooled nucleate boiling is practiced in the water-cooled nuclear reactors for safe and fast heat removal despite the highly complex mechanism of the subcooled boiling. High fuel-surface heat flux can be facilitated by several heat transfer mechanisms (Tong, 1967). Improving the heat transfer in these applications adds an appreciable amount of economic return. Jet impingements and liquid droplet spray are being successfully used in metal industries for high heat removal.

The effect of flow oscillations on the wall heat flux in single-phase and two-phase flow, studied by many authors (West and Tayor, 1952; Baird et al., 1966; Cheng and Zhao, 1998; Bouhadji and Djilali, 2003; Chen et al., 2010; Okawa et al., 2010; Wang et al., 2013; Chen et al., 2016; Paruya et al., 2016) causes to facilitate the heat transfer. West and Taylor reported 60–70% increase in single-phase heat transfer rate in pulsating flow. Cheng and Zhao concluded that pulsating flow or periodic flow could cause a significant increase of single-phase heat transfer. Bouhadji and Djilali performed a two-dimensional simulation of the unsteady separated flow over a bluff rectangular plate subjected to an oscillatory bulk flow over a broad range of forcing amplitudes and frequencies up to the 60th harmonic of the natural vortex shedding frequency. They showed that the periodic forcing had a significant impact on the heat transfer and an appreciable enhancement of local Nusselt number. Chen et al. (2010) experimentally investigated the effect of the forced periodic flow rate of refrigerant using a triangular wave function on flow boiling heat transfer characteristics and

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https://doi.org/10.1016/j.ces.2018.02.037
0009-2509/

Nomenclature

a	interfacial heat transfer area, m^2/m^3
a_{2F}	fraction of wall area occupied by bubbles
a_n	surface density of active nucleation sites, m^{-2}
$\tilde{a}$	amplitude of velocity perturbation, m/s
C_o	void distribution parameter
cf	correction factor
d_{bw}	bubble departure diameter, m
d_b	mean bubble diameter, m
D	diameter of channel, m
f_{bd}	bubble departure frequency, s^{-1}
g	acceleration due to gravity, m/s^2
G	mass flux, kg/m^2-s
G_c	condensation rate, $kg/s\text{-}m^3$
$\overline{G_c}$	space-averaged condensation rate, $kg/s\text{-}m^3$
H	height of boiling channel, m
h	enthalpy, J/kg
j	volumetric flux of mixture or superficial velocity, m^3/m^2-s
k	thermal conductivity, W/m-K
L	length, m
p	local pressure, Pa
Pr	Prandtl number
q''_w	wall heat flux, W/m^2
$\overline{q''_w}$	space-averaged wall heat flux, W/m^2
q''	uniform external heat flux to the wall, W/m^2
q''_c	single-phase heat flux, W/m^2
q''_e	evaporative heat flux, W/m^2
q''_q	quenching heat flux, W/m^2
q'''	volumetric heating rate, W/m^3
R	space-averaged and time-averaged ratio
Re	Reynolds number
t	time, s
T	temperature, K
$\bar{T}$	space-averaged temperature, K
u	phase velocity, m/s
W	mass flow rate, kg/s
x	vapour quality
z	axial distance, m

Greek letters

α	void fraction
Δ	difference
Γ	boiling rate, $kg/s\text{-}m^3$
Γ_h	rate of vaporization due to heating, $kg/s\text{-}m^3$
Γ_f	rate of vaporization due to flashing, $kg/s\text{-}m^3$
ω	cyclic frequency of forcing signal, Hz
φ	contact angle, degree
ρ	density, kg/m^3
ψ	heat transfer coefficient, W/m^2-K
σ	surface tension, N/m
τ	averaging time, s
ϑ	inhibition factor

Subscripts

b	bubble
c	single-phase convection/condensation/characteristic
crit	critical
e	exit/equilibrium
eV	evaporative
g	gas/vapour
gl	vapour to liquid
htf	heat flux
i	inlet
lg	liquid to vapour
ld	OSV point
m	mixture
q	quenching
sat	saturation
s	steady state
sub	subcooling
w	wall

the associated bubble characteristics of refrigerant R-134a in a horizontal narrow annular duct. They observed aggressive oscillations in the bubble characteristics at higher amplitude of forcing. The forced oscillation caused to dominate the size of the departing bubble and active nucleation site density over the bubble departure frequency. Wang et al. conducted an experimental investigation to see the effect of periodic forcing in the form of a triangular wave on subcooled flow boiling heat transfer and the associated bubble characteristics of refrigerant R-134a in a horizontal narrow annular duct. They noted that the heated surface temperature, bubble departure diameter, bubble frequency and active nucleation site density also oscillated strongly with large amplitudes. Okawa et al. (2010) showed that the periodic oscillation facilitated the axial liquid transport to the film region, which subsequently enhanced CHF and dryout. Chen et al. (2016) experimentally examined the effect of periodic flow on bubble characteristics to show the increase of active nuclear site density, bubble diameter and bubble frequency with forcing amplitude of heat flux. Paruya et al. (2016) studied the effect of the periodic forcing on oscillating boiling flow in low forcing frequencies using numerical simulation and harmonic balance. They showed aggressive oscillations with high amplitude leading to frequency entrainment at a lower frequency depending on inlet subcooling and external heat flux. The high-amplitude oscillations facilitate mixing and heat transfer in boiling.

The above survey indicates that a large number of studies on single-phase heat transfer subjected to oscillating flow have been carried out. However, to the authors' knowledge, the numerical studies and the experimental studies on promoting wall heat flux in boiling flow by the periodic flow perturbation have not matured; the evidence of numerical study in this context, in particular, was not found in literature. The mechanism for the enhancement of heat flux by periodic forcing still remains unclear due to complex bubble dynamics. In this work, we examine the influence of the periodic flow perturbation with low forcing amplitudes on the dynamics of boiling heat transfer from the heated wall of a vertical boiling channel. The high forcing amplitudes would make the channel unstable or would seriously affect the critical heat flux (CHF). This research proposal originated from the study of Paruya et al. (2016) on frequency entrainment during density wave oscillations in the boiling channel, in which the authors claimed the possibility of augmentation of boiling heat transfer at resonance frequencies. We have numerically studied the effect of the sinusoidal variation of the inlet velocity on heat transfer enhancement during subcooled boiling based on a numerical simulation. The parametric variations of the frequency and the amplitude of the forcing on the heat flux augmentation allow us to propose the mechanism of enhancement. The effect of external heat flux also contributes to reinforcing the mechanism.