International Journal of Heat and Mass Transfer 120 (2018) 399–410

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Minimum heat flux and minimum film-boiling temperature on a completely wettable surface: Effect of the Bond number

Jun-young Kang [a,b,1], Tong Kyun Kim [b], Gi Cheol Lee [c], Hyun Sun Park [b], Moo Hwan Kim [b,*]

[a] Thermal-Hydraulic & Severe Accident Nuclear Safety Division, KAERI, Daejeon 34057, Republic of Korea
[b] Division of Advanced Nuclear Engineering, POSTECH, Pohang 790-784, Republic of Korea
[c] Department of Mechanical Engineering, POSTECH, Pohang 790-784, Republic of Korea

A R T I C L E I N F O

Article history:
Received 5 September 2017
Received in revised form 21 November 2017
Accepted 9 December 2017

Keywords:
Bond number
Surface super-hydrophilicity
Completely wettable surface
Vapor bubble releasing dynamics
Film boiling

A B S T R A C T

We investigated the effect of Bond number of sphere Bo_s and surface super-hydrophilicity at minimum film-boiling temperature T_{MFB} and minimum heat flux q''_{min} using quenching experiment at atmospheric pressure and the saturation temperature of water. In particular, we focused on the vapor-releasing dynamics in film boiling and evaluated the main parameters such as vapor-bubble releasing frequency f_b and vapor-bubble departure diameter D_b. We selected two sizes of quench sphere (sphere diameter D_s = 15 mm and 25 mm) based on critical Bond number Bo_C to evaluate the vapor-releasing dynamics depending on the Bo_s. The super-hydrophilic surface was prepared by the anodic oxidation on zirconium (Zr-702) sphere. High speed visualization and inverse heat transfer calculation facilitate a qualitative and quantitative analysis of film boiling heat transfer. The surface super-hydrophilicity of the quench sphere increases T_{MFB} and q''_{min}: 12% and 366% increase for D_s = 15 mm and 20% and 305% increase for D_s = 25 mm, respectively. D_b strongly depends on D_s and exhibits a relatively weak dependency to the surface super-hydrophilicity. f_b is affected by the D_s and the surface super-hydrophilicity. The increase in T_{MFB} is explained by the liquid-solid contact in film boiling. The D25-CWS exhibits the large area fraction of liquid-solid contact versus total heat transfer surface compared to the D15-CWS. The increase in q''_{min} is related to minimum frequency of vapor-bubble releasing to sustain the stable liquid-vapor interface $f_{b,min}$ because the large $f_{b,min}$ indicates the fast destabilization of the liquid-vapor interface in film boiling during quenching.

1. Introduction

Understanding the minimum heat flux q''_{min} and minimum film-boiling temperature T_{MFB} is essential for analyzing the film-boiling heat transfer during quenching. The vapor film with low thermal conductivity ($k_v \sim 0.025$ W/m-K) covers the heat transfer surface, which deteriorates the quench rate in a high-temperature thermal-power system [1]. One of the strategies to increase the quench rate is to increase q''_{min} and T_{MFB} [2,3]. The q''_{min} and T_{MFB} indicate the collapse criteria of vapor film that serves as an insulator, and these film-boiling crisis are, particularly, affected by the system dimension: Bond number $Bo = (\rho_l - \rho_v)gR^2/\sigma_{lv}$ [4].

Classical q''_{min} and T_{MFB} are described by the hydrodynamic and the thermodynamic limits, respectively [5]. The hydrodynamic model to predict q''_{min} is based on the vapor-releasing dynamics suggested by Zuber [6]: $q''_{min} = e_b\, n_b\, f_{b,min}$ where e_b, n_b, and $f_{b,min}$ are the energy per bubble, number of bubbles released per unit area per release cycle, and minimum number of cycles per second to just compensate for the normal collapse rate, respectively. These parameters are represented by *Taylor* instability of the liquid-vapor system (Eq. (1)-(3)), and, are mainly functions of the most dangerous wavelength $\lambda_D = 3^{0.5}\lambda_c = 2\pi\{3\sigma_{lv}/[(\rho_l - \rho_v)g]\}^{0.5}$, which is only determined by the properties of liquid and vapor (0.027 m for the atmospheric pressure P_{atm} and saturation temperature T_{sat} of water). The thermodynamic model to predict T_{MFB} is explained by the superheat limit of the liquid; $T_{MFB} \sim (23/32)T_{cr}$ [7]. However, this model is often substituted by the hydrodynamic model considering λ_D and *Newton's law of cooling*: $T_{MFB} = q''_{min}/h_{film} + T_{sat}$ [8]. Thus, the analysis of the vapor bubble dynamics in film boiling is an intuitive approach to explain the change in T_{MFB} and q''_{min} during quenching.

$$e_b = \left(\frac{4\pi}{3}\right)\left(\frac{\lambda_D}{4}\right)^3 \rho_v h_{lv} \quad (1)$$

* Corresponding author.
E-mail address: mhkim@postech.ac.kr (M.H. Kim).
[1] Dr. Jun-young Kang are applying the postdoctoral researcher in KAERI after Ph.D course in POSTECH, Rep. of Korea.

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.043
0017-9310/

Nomenclature

A	area or length
A_{eq}	heat transfer area to produce one bubble
Bi	Biot number
Bo	Bond number
Bo_s	Bond number for sphere
Bo_c	critical bond number
c_1, c_2	fitting constant
C_p	specific heat
D	diameter
D_v	vapor dome diameter
D_s	sphere diameter
D_b	bubble diameter
D_{tube}	capillary tube diameter
e_b	energy per single bubble
f_b	frequency of releasing bubble
$f_{b,\min}$	minimum number of cycles per second to compensate for the normal collapse rate (or, minimum frequency of releasing bubble)
$f_{b,\min*}$	increase ratio for $f_{b,\min}$
F_σ	surface tension force
F_{buoy}	buoyancy force
g	gravitational acceleration
h_{lv}	latent heat of vaporization
h	heat transfer coefficient
h_{film}	heat transfer coefficient in film boiling
H	immersion depth
k	thermal conductivity
L	length, or height
L_c	characteristic length
n_b	number of bubbles released per unit area per release cycle
P	pressure, or probability
P_{atm}	atmospheric pressure
q''	heat flux
$q''_{\min}$	minimum heat flux
$q''_{\min}{}^*$	increase ratio for $q''_{\min}$
R, r	radius
S	weighting factor
T	temperature
T_{sat}	saturation temperature
T_{cr}	critical temperature
T_w	wall temperature
T_i	initial temperature
T_{leid}	Leidenfrost temperature
T_{MFB}	minimum film boiling temperature
T_c	center temperature
ΔT_{sat}	wall superheat
t	time
t_{cool}	cooling time
V	volume or electric potential
∇V	electric field
x	x-coordinate

Greeks

A	wave number
α^*	critical wave number
β	growth factor (or, the rate of amplification in interfacial disturbance)
β^*	maximum growth factor
ϕ	ϕ- coordinate
$\varepsilon_{\max}$	maximum height of surface roughness
θ	θ - coordinate
θ_c	contact angle
λ	wavelength
λ_c	critical wavelength
λ_D	most dangerous wavelength
ρ	density
σ_{lv}	surface tension of liquid-vapor
ψ	property coefficient

Abbreviation

BZS	bare zirconium surface
CWS	completely wettable surface
PDF	probabilistic density function

$$n_b = 2/(\lambda_D)^2 \tag{2}$$

$$f_{b,\min} = 0.4\left\{\frac{\left[4(\rho_l-\rho_v)^3 g^3\right]}{\left[27(\rho_l+\rho_v)^2\sigma_{lv}\right]}\right\}^{0.25} \tag{3}$$

The vapor bubble dynamics in film boiling varies depending on the Bo_s, which directly affects $q''_{\min}$ and T_{MFB} [4,9,10]. For λ_D, the critical wavelength $\lambda_c = 2\pi\{\sigma_{lv}/[(\rho_l-\rho_v)g]\}^{0.5}$ is a criterion to analyze film boiling on a sphere and determines the releasing dynamics of the vapor bubbles [4]. λ_c is 0.016 m at P_{atm} and T_{sat} of water and corresponds to the critical Bond number for a sphere; $Bo_C = (\rho_l - \rho_v)g(\lambda_c/2)^2/\sigma_{lv} \sim 9.85$. Small spheres ($D_s < \lambda_c$ or $Bo_S < Bo_C$) exhibit the single vapor dome in film boiling, whereas large spheres ($D_s > \lambda_c$ or $Bo_S > Bo_C$) have multiple vapor domes. This classification corresponds well to the interfacial motion in film boiling, which illustrates the growth of a capillary wave at the liquid-vapor interface in accordance with D_s.

Frederking and Daniels [9] analyzed the relationship between D_b and f_b from a sphere during film boiling and compared it to the classical instability theory. The balance between buoyancy force F_{buoy} and surface tension force F_σ is the key to determine the stability of the liquid-vapor interface system. The rate of amplification in interfacial disturbance β, which is approximated by $\{[g(\rho_l-\rho_v)\alpha/\rho_l] - (\sigma_{lv}\alpha^3/\rho_l)\}^{1/2}$, and the wave number $\alpha = 2\pi/\lambda$ are the main variables. Considering the stable liquid-vapor interface (small λ or large α) and the unstable state (large λ or small α), we obtain the critical wave number $\alpha^* = 3^{-0.5}\{\sigma_{lv}/[g(\rho_l-\rho_v)]\}^{-0.25}$ and maximum growth factor $\beta^* = 2^{0.5}3^{0.25}g^{0.75}(\rho_l-\rho_v)^{0.75}/(3\rho_l^{0.5}\sigma_{lv}^{0.25})$ by $\partial\alpha/\partial\beta = 0$. Assuming that $f_b \sim (1/\beta^*)$ and $D_b \sim (1/\alpha^*)$, one can postulate the relationship between f_b and D_b as constant (Eq. (4)), but, this relationship is modified by considering the dependence on T_w and D_s (Eq. (5)) [11].

$$f_b(D_b)^{0.5} \sim \left[\frac{g(\rho_l-\rho_v)}{\rho_l}\right]^{0.5} \tag{4}$$

$$f_b(D_b)^{0.5} \sim \left[\frac{g(\rho_l-\rho_v)}{\rho_l}\right]^{0.5}\left\{1+\frac{2\left\{\frac{\sigma_{lv}}{[g(\rho_l-\rho_v)]}\right\}^{0.5}}{D_c^2}\right\}^{0.5} \tag{5}$$

Gunnerson and Cronenberg [10] suggested the T_{MFB} and $q''_{\min}$ model according to Bo_s. D_b and the minimum frequency of vapor bubble release $f_{b,\min}$ were categorized depending on D_s (Eqs. (6)–(8)),[2] and $q''_{\min}$ was simply described by the energy transport per bubble (Eq. (9)). They defined the four D_s ranges (small,

[2] It corresponds the large sphere suggested by Gunnerson and Cronenberg [10] suggested: $0.013 < D_s < 0.157$ m.