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Statistical features of transition to stable film boiling

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Abstract

The development of transition boiling modes is virtually the formation and spreading process of dry patches induced by applied superheat or heat fluxes. Given that the interactions among multiple dry patches with different sizes, transition boiling can only be described in statistical way. In this paper, dry patches statistical distribution function was obtained and the stochastic feature of transition to stable film boiling was then discussed. The new academic implications on classical MHF (minimal heat flux) model have been revealed. The present investigations tried to make a renewed effort to the understanding of transition boiling. Available experimental results revealed that the present analysis was more reasonable than traditional one in framework.

Keywords: Boiling; Transition boiling; Statistical analysis; Dry patch

1. Introduction

Transition boiling bridges the nucleate boiling and film boiling, which is encountered in a number of applications, including metallurgical quenching processes, and immersion cooling of high temperature components. Although having been studied for decades, transition boiling still holds its place as the least understood of the several boiling mechanisms [1]. Such an occurrence is attributed to the complexity of mechanisms controlling the transition boiling heat transfer, and the difficulty of performing experiments. Since the pioneering work of Berenson [2], researchers noted that the transition boiling process incorporated liquid–solid–vapor triple phases interactions. The heat transfer mechanism was hence regarded as a combined process including transient heat conduction, nucleation boiling, and film boiling heat transfer modes [3]. It is no doubt that dry patches play important roles during whole transition boiling processes, for the dry patches would form at the high-density level and at the great size in transition boiling [4]. The wetting ratio dramatically falls as wall superheat increases. Till stable film boiling has established on the heated surface, the wetting ratio approaches zero [5].

It is not yet unanimous regarding the dynamic features in transition boiling. Witte and Lienhard [6] and Ramilison and Lienhard [7] reported the occurrence of sudden "jumps" between nucleate boiling and film boiling regimes. Large dry patches once emerge, would flush and cover the entire heated surface. However, Bui and Dhir [8] tried, but failed to destabilize the transition-boiling mode by wiping the surface with a brush. Dhuga and Winterton [9] had neither observed any jumps in their transition boiling experiments. We claimed that, although certainly possible, jumps in transition boiling curve were not inevitable [10]. Restated, the occurrence of jumps in transition boiling curve is conditional and statistical. There exists no comprehensive framework to interpret these experimental findings until now [11].

Actually, available literatures on transition boiling mostly encounter a time/surface-averaged procedure in which a stationary boiling process is assumed. While during transition boiling, the wall temperature is extremely non-uniform for the stochastic formation/rewet of dry patches. For the inter-

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Nomenclature

C_p	specific heat at constant pressure
F	fluctuation growth rate
h_{fg}	latent heat
k	drift growth rate
N	dry patch number distribution function
p	pressure
P	dry patch probability function
Pr	Prandtl number
q	dry patch production rate
r	dry patch radius
R	safe probability function
R_a	roughness
s^*	critical radius
t	time
T	temperature

Greek symbols

ξ	dimensionless number
ρ	density
σ	surface tension
λ	thermal conductivity
$\hat{a}$	constants
δ	Dirac delta function
θ	defined parameter
γ	defined parameter

Subscripts

l	liquid
MHF	minimal heat flux
v	vapor
w	wall

actions among multiple dry patches with different sizes, it is becoming apparent that transition boiling can only be described in statistical way. Dry patch dynamic feature could be largely masked by the averaging [12].

From above survey, it may be concluded that a new perspective on transition boiling heat transfer is desired [13]. In this paper, from the view of nonlinear interaction mechanism and inclusion of nonuniform dry patches size distribution, we propose stochastic analysis on dry patches growth in transition boiling system. Dry patches statistical distribution function is obtained and the stochastic feature of transition to stable film boiling is then discussed. The research reported herein is directed in attempt to describe stochastic features in transition boiling process in a new fashion. The new academic implications on classical MHF (minimal heat flux) model have been revealed. Comparisons to our previous experimental results show that present theoretical analysis is not only beneficial to the current understanding of the transition boiling mechanisms, but also potential for the prediction of the transition boiling heat transfer with more accuracy.

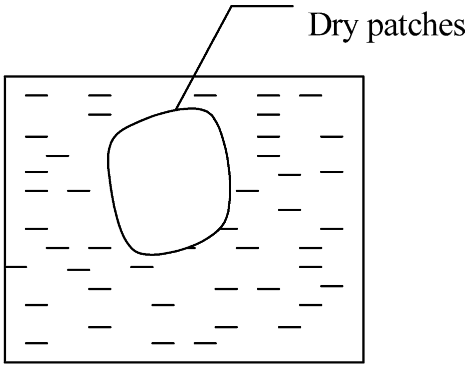

Fig. 1. A single dry patch is surrounded by infinite liquid phase.

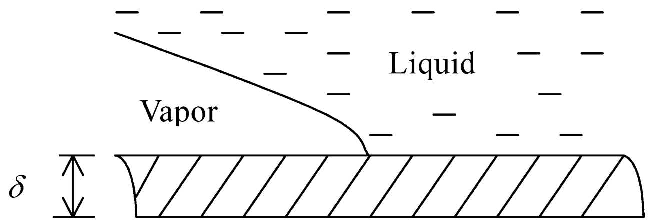

Fig. 2. Analytical model.

2. Physical descriptions

2.1. The case for the existence of single dry patch

If we mainly considered a single dry patch surrounded by an infinite liquid phase, as shown in Fig. 1, the case could be simplified as an illustrative model with lateral heat conduction, as shown in Fig. 2. Physically, when dry patch grows up to a certain size, it cannot be rewetted any longer. This size was often represented as critical radius of dry patch. Typical research could be found in references [14,15]. Let us assume the critical radius of dry patch obtained with method in references [14,15] is s^*. Obviously, as shown in Fig. 2, if the single dry patch is larger than s^* in radius, the vapor front will surely propagate toward the liquid phase till the occurrence of stable film boiling. Propagation is deterministic, not uncertainly [14]. Doubtless, this kind of analyses can only approximately reflects the feature of transition to stable film boiling, for a lot of dry patches with all kinds of sizes often simultaneously exist in real transition boiling.

2.2. The case for the existence of multiple dry patches

Transition boiling system generates highly complicated phenomena. Transition boiling is a dynamic phenomenon with vivid dry patches generation, growth and being rewetted under the action of superheat or heat fluxes. The whole