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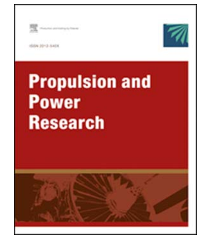

ORIGINAL ARTICLE

Model of formation and roughness calculation of the porous layer on the heated surface during nanofluids boiling

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Abstract The article contains developed by authors model of the porous layer formation. This layer forms on the heated surface during nanofluids boiling. It has a great influence on boiling characteristics, particularly, on critical heat flux value; and it is very important to have clear knowledge about its formation and properties. The main goal of current step of our investigations was to find out correlations: for calculation of porous layer with definite thickness creation time and for its roughness.

1. Introduction

Boiling is one of the most effective ways to remove heat from surfaces with high heat intensity. At the same time the mechanism of boiling and boiling crisis is extremely complicated for describing and modeling; there is interaction between three phases: liquid, vapor and solid. Traditional approaches to these processes describing contains properties of liquid and vapor phases only; properties of the heated surface on which boiling takes place are not contained absolutely or considered with some correction coefficients. These coefficients are usually based on empirical data of boiling characteristics on definite surface types.

With appearance of new type coolants, which affect on the heated surface properties significantly, traditional correlations became less useful. Nanofluids (NFs) are one of these new type coolants. NFs are water-based (or based on other different fluids, usually organic) dispersions of nanoparticles (NPs). NPs are particles with one or more dimensions less than 100 nm.

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Nomenclature

D_0	departure diameter of steam bubble (unit: mm)
c	heat capacity (unit: J/(kg·K))
m	mass (unit: kg)
p	pressure (unit: Pa)
q	density of heat flow rate (unit: W/m^2)
L	work of bubble creation (unit: J)
R_*	vapor germ critical radius (unit: m)
ΔT	surface overheating (unit: K)
F	surface area (unit: m^2)
P	possibility of bubble appearance on covered surface
f_b	steam generation frequency (unit: 1/s)
n_F	steam generation centers density (unit: 1/m^2)
r	specific steam generation heat (unit: J/kg)
T	temperature (unit: K)
d_k	diameter of holes on the surface (unit: m)
g	gravity acceleration (unit: m/s^2)
Y	average depth of holes (unit: m)
$Length$	length of considered surface area (unit: m)
C	nanofluid volume concentration (unit: %)

Greek letters

θ	contact angle (unit:°)
λ	thermal conductivity (unit: W/(m·K))
τ	time duration (unit: s)
γ	coefficient described how many NPs transfer to liquid microlayer under steam bubble during NF boiling
ρ	density (unit: kg/m^3)
ψ	roughness coefficient
φ	volume concentration (unit: %)
β	coefficient described bubble size changing
γ_{SV}	surface tension between solid and vapor
γ_{SL}	surface tension between solid and liquid
σ	surface tension between liquid and vapor
δ_{holes}	distance between holes centers (unit: m)
δ_{layer}	layer thickness (unit: μm)

Subscripts

v	vapor
l	liquid
s	solid
dep	departure
$surf$	surface
$part$	covered by particles
sat	saturation
$rough$	referred to rough surface

One of the most important NFs' properties is capacity for significant (up to two times and more comparatively to the base fluid value) increasing of critical heat flux (CHF) with negligible NPs' concentrations (0.001–0.1 vol%). Experimental results (for example, see Refs. [1–3]) have revealed that the main cause of abovementioned phenomena is nanoparticles porous layer on the heated surface; this layer forms directly during boiling.

The nanolayer influences on boiling heat transfer and boiling crisis in the following ways:

- on the one hand, it causes significant increasing of the surface roughness and wettability;
- porous structure causes additional liquid supply to the heated surface due to capillary forces;
- on the other hand, the layer material usually has low thermal conductivity and causes additional thermal resistance between the heater and the liquid; however, this fact is negligible due to low thickness of the layer (less than 10 μm).

Influence of contact angle θ, which is used for surface wettability describing, on boiling and boiling crisis is in two ways [4,5]. On the one hand, if we speak about work of creation of bubble on the surface L, including creation inside holes with vapor germ critical radius size, we could see: L is smaller when θ is bigger. Therefore, the most possible place for bubble creation is hole with local wettability decreasing. On the other hand, contact angle affects on bubble departure diameter (see Fritz model for smooth surface described in Ref. [5], and model for rough surface in Ref. [14]): with θ increasing heated area under bubbles base increases too; this fact leads to heat transfer deterioration.

Attempts to include surface properties (mainly, wettability) to CHF correlations have been done by a lot of scientists [1,6–10]. Nevertheless, no common theory of nanolayer formation and its influence on boiling and boiling crisis has been done yet; these phenomena investigations are usually experimental and contain only contact angle or surface roughness in empirical correlations which are based on experimental data.

For the further practical applications NFs are not so interesting (because of its low stability: it could not be used in devices and units which work during a long time); but nanostructured surfaces (surfaces with abovementioned nanolayer) are very important. These surfaces production by particles settling from dispersion seems to be one of the most perspective methods.

This article contains an attempt of nanolayer formation on the heated surface during NFs boiling describing. The first variant of correlation for time of formation of nanolayer with definite thickness is represented. For nanolayer surface method of roughness calculation is suggested.

2. Model of nanolayer formation and roughness

Nanolayer formation process on the heated surface during boiling could be divided in 4 main steps, according to our suggestions.

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