Powder Technology 277 (2015) 181–192

Contents lists available at ScienceDirect

Powder Technology

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

Nanofluid pool boiling heat transfer phenomenon

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ARTICLE INFO

Article history:
Received 16 August 2014
Received in revised form 20 February 2015
Accepted 22 February 2015
Available online 28 February 2015

Keywords:
Boiling heat transfer coefficient
Nucleation
Nanoparticles
Roughness
Heat flux
Wettability

ABSTRACT

The purpose of this paper is to explain how concentration of nanofluid, roughness and range of heat flux affect the boiling heat transfer coefficient. The boiling heat transfer coefficient was measured on rough and smooth heated substrates inside water and alumina nanofluid with different concentrations. The heated substrate was observed to be covered by a tiny porous layer of deposited nanoparticles and modified the size of cavities and boiling heat transfer coefficient. In case of smooth heated surface, the roughness, nucleation site density and consequently boiling heat transfer coefficient were enhanced because the size of deposited nanoparticles was bigger than surface roughness. The difference between heat transfer coefficient of alumina nanofluid and water was observed to decrease with heat flux, since big cavities were active to create nucleation in low heat fluxes and the smaller cavities were active only in high heat fluxes. The size of deposited nanoparticles was also observed to increase with concentration of nanofluid and play a significant role on variation of size of cavities in rough surfaces. The roughness of the heated substrate was observed to increase while the size of deposited nanoparticles was bigger than size of cavities. In addition, the effects of suspended nanoparticles on behavior of triple line were investigated, using bubble formation method. The suspended and deposited nanoparticles were observed to have a significant role to modify the dynamics of triple line and bubble growth.

1. Introduction

Heat removal systems are becoming miniaturized and more powerful every day, which require advanced working fluids and cooling systems to raise the capacity of the heat removal. Scientists have been developed a new generation of working fluid, termed as nanofluid, by introducing nanoparticles into a base liquid. Nanoparticles have two major roles on nanofluid boiling heat transfer: a) a bulk effect, associated with suspended nanoparticles, which modifies the effective thermo-physical properties of the fluid including thermal conductivity, viscosity, liquid-gas and solid surface tensions [1–4] and b) a surface effect, associated with deposited nanoparticles which modifies the characteristics of heated surface [5–7] such as homogeneity and roughness [8–12], as well as solid surface tensions and consequently wettability [13–16]. The surface effect is mainly caused by deposited nanoparticles. The evaporation of nanofluid inside the microlayer region, beneath the bubble increases the possibility of collisions, agglomeration and deposition of nanoparticles at the vicinity of triple line [12,13,17–20], forming a tiny porous layer of deposited nanoparticles, covering the heated substrate. Such a layer may well change the solid surface tensions, wettability, surface roughness, active nucleation site density and consequently, affecting boiling heat transfer significantly. Both suspended and deposited nanoparticles have a great potential to change the force balance at the triple line and consequently modify the behaviour of bubble dynamics, such as waiting time, bubble formation time, bubble frequency and departure process. The effects of nanoparticles depend on the concentration and characteristics of nanoparticles such as size, shape, surface coating and material.

The nanoparticles have also been applied for wide range of applications including (a) thermal conductivity enhancement of phase change materials [21] which can be used in thermal storages. (b) Thermal conductivity enhancement of coolant which can be used in automotive industry such as cooling [22], brake [23,24], transmission [25] and combustion systems [23,24].The nanofluids also can be used to modify the thermal management of electronic devices in micro scales, using single [2] and two phase flows [5,6]. (c) Modification of surface wettability [4], 3D printing of electronic circuits and components in micro scales [26], electro-wetting [27] and (d) Biomedical and pharmaceutical industries such as nanodrug delivery [28] and nanomedicine [29]. In general, the nanoparticles have great potentials to modify the physical properties of the nanofluids and consequently improve so many phenomena.

Recently the behavior of nanofluids has investigated under influence of magnetic field from different perspective such as effect of thermal radiation on magnetohydrodynamics nanofluid flow [30], laminar-forced convection nanofluids flow over a stretching surface in a porous medium [31], CuO–water nanofluid flow and heat transfer [32], free convection of ferrofluid in a cavity heated from below [33], nanofluid flow and heat transfer in a rotating system [34] and natural convection around a horizontal circular cylinder [35].

This paper reviews the existing findings related to the nanofluid pool boiling. Part of this paper also is continuation and completion of the

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http://dx.doi.org/10.1016/j.powtec.2015.02.040
0032-5910/

previous paper [7]. The role of suspended and deposited nanoparticles on pool boiling heat transfer coefficient was investigated. Pool boiling heat transfer coefficient was measured on rough and smooth copper heated substrates, with and without the presence of nanoparticles. The nexus between concentration of nanofluid, roughness of heated substrate, heat flux and boiling heat transfer coefficient was investigated. The size of suspended nanoparticles was observed to increase with concentration and modify the size of cavities and nucleation site density of the heated surface. In addition, the bubble formation method was employed to study the dynamics of triple line and bubble growth in presence of suspended nanoparticles. The air was injected into the water, gold, silver, and alumina nanofluids to investigate the effects of suspended nanoparticles on radius of triple line, waiting and bubble formation times as well as bubble frequency which have play key roles on nanofluid boiling heat transfer.

2. Review on nanofluid boiling heat transfer

As surface temperature goes beyond saturated temperature, initiation of nucleation begins from cavities where gas or vapour is trapped. Initiation of nucleation is function of wettability and surface roughness. Introducing nanoparticles, changes the force balance at the triple line, behaviour of triple line, wettability and surface roughness. Nanofluids provide so many opportunities to enhance boiling heat transfer phenomenon. At the same time, they create enormous complexities. Nanoparticles are suspended inside the liquid, vapour and deposited on the heated substrate in nanofluid boiling heat transfer phenomenon.

Nanofluid boiling heat transfer can be affected by many issues including a) physical properties of nanofluids such as liquid-vapour and solid surface tensions, viscosity, thermal conductivity, liquid and vapour densities, vapour and liquid enthalpies, b) characteristics of heated substrate such as roughness, number of cavities per unit area, size of cavities, active nucleation site density, behaviour of triple line, wetting and dewetting, receding and advancing contact angles and c) near surface hydrodynamics such as departure bubble volume, bubble frequency, and hot/dry spot dynamics [36].

Suspended and deposited nanoparticles would change physical properties of working fluid, characteristics of heated substrate and consequently they would change the behaviour of triple line, size of cavities and active nucleation site density as well as heat transfer coefficient. Indeed, nanoparticles have complex effects on boiling heat transfer.

2.1. Deposited nanoparticles

Initiation of nucleation occurs at the cavity sites under the suitable superheating conditions. For heterogeneous boiling, the nucleation would be initiated from trapped vapour or gas inside the cavities. The bubble expansion takes place after initiating of the nucleation by evaporation of surrounded superheated nanofluid at the vapour-liquid interface, microlayer region and triple line region. Fig. 1 shows the main mechanisms of evaporation and consequently bubble volume expansion from an active nucleation site on a heated substrate. As bubble volume expands further, the effect of buoyancy force becomes stronger and starts lifting the whole bubble upward, leading to the bubble departure.

The evaporation of nanofluids inside microlayer beneath the bubble would increase the concentration of nanoparticles in the microlayer region, so the possibility of collisions, agglomeration and deposition of nanoparticles in the region increases. Deposited nanoparticles may form a tiny porous layer of agglomerated nanoparticles on heated surface [12,13,17–19]. The characteristics of heated substrate would be modified continuously [17,19] as the thickness of deposited nanoparticles increases over time during the boiling process.

Similar particle deposition effects were observed in the nanofluid flow boiling phenomenon. Fig. 2 shows the variation of porous layer of deposited nanoparticles on the heated surface in the vicinity of outlet of heating tube (ID = 0.51 mm) after flow boiling test with deionized water and 25 nm alumina nanofluids with 0.1 v%, 0.01 v%, and 0.001 v% concentrations inside the stainless steel microchannels with an internal diameter of 0.51 mm [5,6].

Fig. 2 clearly demonstrates that the thickness and roughness of deposited nanoparticles on the heated substrate increases with concentration of alumina nanofluid. Fig. 3 demonstrates the difference between deposited nanoparticles at the inlet and outlet of the heated surface (ID = 0.51 mm) after flow boiling test with 25 nm alumina nanofluid of 0.1 v%. Temperature of the heated surface and consequently the evaporation rate is higher at the outlet of tube, so the deposited nanoparticles is thicker with larger agglomerations.

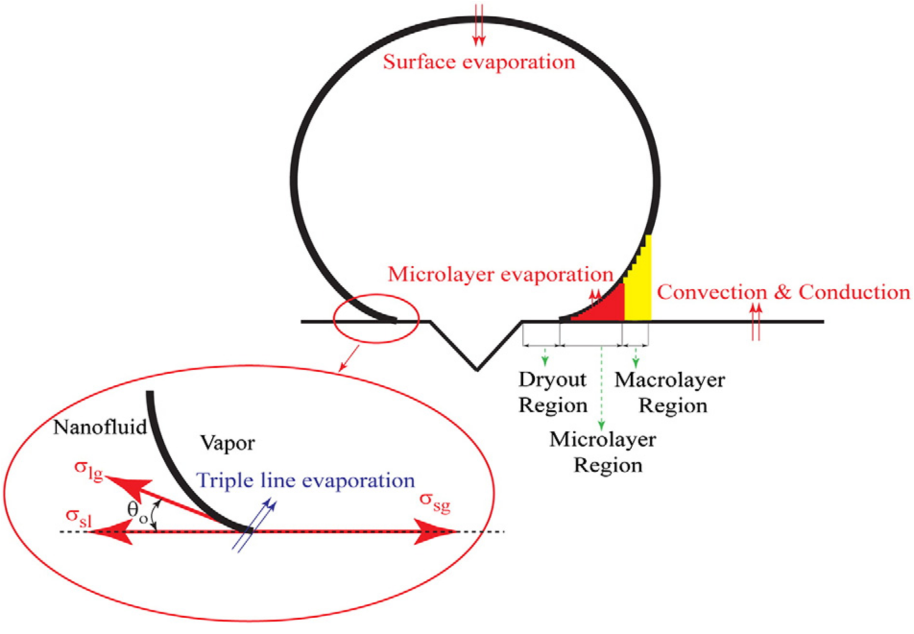

Fig. 1. Schematic of bubble heat transfer and mechanisms of bubble expansion at the active nucleation site on a heated substrate [19].