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Latest developments in boiling critical heat flux using nanofluids: A concise review

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ABSTRACT

The present paper is an overview of the latest developments regarding the application of nanofluids in boiling critical heat flux by means of both pool- and convective-flow boiling. Boiling heat transfer is a significant field in thermal engineering systems, and it is especially used for boiling in power plants as well as the cooling of nuclear reactors and high-tech electronic systems. This concise review contains efforts to show how nanofluids could play an essential role in achieving high heat flux with small temperature differences during the boiling process—which, in turn, improves the critical heat flux (boiling crisis) for such an operation and makes the heat-exchange system's performance safer and more durable. It is also expected that this work could be a helpful new reference guide that will allow investigators to update their knowledge on the topic of boiling critical heat flux using nanofluids. In addition, this work contains concise recommendations for future study directions.

1. Introduction

Nowadays there is an increasing demand for the development of new products with high heat flux and compact space. For these products with high thermal loads, the liquid-cooling systems are more efficient than air-cooling systems [1–3]. Adequate cooling fluids are needed to pass high energy from a solid surface to fluid by applying the smallest temperature difference per unit time and area in the solid surface. On the other hand, the active heat transfer modes-for example, nucleate boiling-will offer a lot of heat transferring per unit area. Therefore, new and functional cooling fluids should be used to overcome the inherently poor thermal properties of conventional liquids such as water, ethylene glycol, and engine oil. During the last decades, considerable research effort has been devoted to finding new thermal fluids with thermal properties that adequately satisfy the cooling requirements of these high-tech products.

One of the essential passive techniques is the use of ultrafine particles, which provide efficient thermal-transport properties, in conventional fluids. The boiling heat transfer has adapted to be one of the most significant heat transfer modes in many industrial applications—such cooling compact heat-exchange systems, power plants, nuclear reactors, and high-tech electronic products. Therefore, the liquid-vapor change phase could provide sufficient cooling for high thermal loads due to the high latent heat of vaporization involved in the boiling process at a relatively low superheat value [4–10]. An issue called critical heat flux (CHF), or dry out—which is the most vital problem related to nucleate boiling—limits the boiling process; controlling this phenomenon will enable the heat-exchange systems to

Abbreviation: CHF, Critical heat flux; DNB, Departure from nucleate boiling; TEM, Transmission electron microscope; SEM, Scanning electron microscope; FESEM, Field emission scanning electron microscopy; XRD, X-ray diffraction; AFM, Atomic force microscopy; DLS, Dynamic light scattering; PSC, Particle size count test; MWCNT, Multi-walled carbon nanotubes; DIW, Deionized water; DW, Distilled water; rGO, Reduced graphene oxide; CS, Chitosan; AG, Arabic gum; EG, Ethylene glycol; AC, Alternating current

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Nomenclature

$\overrightarrow{q_x}$ [kW m^{-2}] Heat flux density
P [KPa] Pressure system
D_h [mm] Hydraulic diameter
∇T [K. m^{-1}] Gradient temperature
$\mathring{m}$ [Kg/ s] Mass flow rate
T_w [K] Wall temperature
T_{sat} [K] Saturation temperature
ρ [Kg/ m^3] Density
K_s [W/ m. K] Thermal conductivity of the solid surface

Greek letters

φ [%] Phi (Volume friction)
μ [Ps.a] Mu (Viscosity)

Subscripts

x x-direction
sat saturation
w wall

sustain their unity.

Advancement in technology has provided us an opportunity to produce ultrafine materials on the nanoscale by using physical- or chemical synthesis methods. Nanofluids are a new class of thermal fluids that contain a dispersing solid particle of materials such as metals, oxide metals, and ceramics that is usually in the size range of 1 to 100nm [11–17]. A nanometer is very tiny and hard to observe with human eyes; it is around 1×10^{-9} of a meter and is used to measure ultrafine things such as the size of atoms, human hair, and blood cells.

It is well recognized that solid materials, especially metals, have higher thermal conductivities than liquids do. In other words, nanofluids were shown to have significantly more-functional thermophysical properties, especially the thermal conductivity, compared to conventional fluids [18–20].

The aim of this work is to review the latest experimental studies associated with CHF's enhancement of boiling heat transfer with nanofluids from 2016 to date. The collected experimental data are summarized and discussed. In addition, this work highlights the most-important reasons behind CHF's improvement through the use of nanofluids. Therefore, this work will be useful for investigators who are interested in the field of boiling heat transfers that involve the use of nanofluids.

2. The mechanism of boiling heat transfer

Boiling heat transfer happens when the temperature of a solid surface, T_w, is sufficiently above the saturation temperature, T_{sat}, of the liquid that contacts the solid surface. It is a phase change from a liquid state to a vapor state in which the vapor bubbles grow and collapse to bulk fluid. Boiling heat transfer is one of the most effective heat transfer modes, and it has been used in a variety of technological and industrial applications related to heat-exchange systems, energy conversion, and the cooling of high-power electronics and nuclear reactors [21–23]. Nukiyama introduced the first attempt at establishing a criterion for boiling heat transfer [24,25]; he was the pioneer who conducted the first experimental investigation of boiling heat transfer in 1934 in Japan. He used a platinum heating wire as a heating element inside a water test chamber at 100 $^{\circ}C$, and the wire's electrical resistance measured the temperature of the surface heater during the run. His results indicated that the heat of the boiling water increased rapidly as the wire was heated above 100 $^{\circ}C$; this increase continued until the temperature of the heating element reached about 149 $^{\circ}C$, which is the point of CHF. Since that experiment, investigators of boiling heat transfer area have carried out intensive efforts to understand this phenomenon [26–29]. Bulk-fluid motion boiling is classified into two main categories: pool boiling and flow boiling (forced convective boiling). In next portion, we will concisely explain them.

As reported above, when the liquid is in contact with the heating surface, boiling will happen at the solid-fluid interface if the temperature of the solid surface is significantly above the saturation temperature of the fluid. Boiling can be divided into two main types. Pool boiling is a type of boiling heat transfer in which the heating surface is submerged in a pool of stationary liquid. The buoyancy effect of the produced vapor plays a vital role in circulating the fluid near the heating surface; thus, bubbles grow and collapse into the bulk fluid. During past decades, many investigators have studied pool boiling heat transfer [30,31] in order to understand this mechanism. Forced convective flow boiling has been used in more industrial applications compared to pool boiling [32,33]. It refers to the boiling of a moving stream of fluid within the heating surface that carries it.

3. Critical heat flux

Heat flux in boiling heat-transfer applications is one of the main parameters for controlling and operating the heat-transfer systems with high flux densities that are used in boilers, evaporators, and the cooling of electronic devices and nuclear reactors. The boiling process has a thermal limit at which the departure from nucleate boiling occurs, depending on boiling conditions. This point called CHF, or dry out, causes overwhelming problems for heat surfaces due to the sudden increase in surface temperature and abrupt decrease in the heat transfer rate [1,34–37,53]. In such circumstances, the most critical issue is that the boiling efficiency is directly interlinked with the failure of the materials of the heating surface. Thus, it is essential to control the CHF to ensure the safety of the heat-exchange systems. Considerable efforts have been made to improve boiling CHF by applying attractive methods, and one of these involves the use of nanofluids as working fluids in the boiling process. In next sections, we will describe the latest enhancement studies of CHF using nanofluids.

4. Recent progress on boiling critical heat flux using nanofluids

Transferring a large heat flux with small-wall superheating is the primary concern of scientists and researchers in the area of boiling heat transfer. Many efforts have been made after 2003 to study the performance of boiling heat transfer using nanofluids due to its potential application in various heat-exchange systems. Gathered data from the Scopus database show the latest experimental investigations on the topic of the CHF of boiling heat transfer using nanofluids in both pool and flow boiling. The most current record is presented in Fig. 1—which clearly shows that more than 30 articles, conference papers, review papers, etc. that are related with studies of the CHF of boiling using nanofluids have been published since 2016. All reviewed studies in the survey explain that the primary reasons for CHF improvement are the porous layers created by nanoparticle deposition as well as the effective thermophysical properties of nanofluids [40–60]. The modification of the geometry and topology of the heating surface during the boiling of nanofluids plays a crucial role in improving the features of a solid surface by changing many parameters such as surface roughness, wettability, and porosity for developed nanolayers. However, it has been shown that it is not difficult to enhance CHF by up to 200% by using low concentrations of nanoparticles [51,57].

Since Choi and his team [18] in 1995 detected the term of nanofluids at Argonne National Laboratory, USA, researchers have