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The effects of nanolubricants on boiling and two phase flow phenomena: A review☆

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ABSTRACT

The study of nanorefrigerant boiling and two-phase flow phenomena is still very much in its infancy. This research field poses many opportunities to study new frontiers but also gives great challenges. This study presents a comprehensive review of nucleate pool boiling, flow boiling, condensation and two-phase flow of nanorefrigerants to summarize the current status of research in this newly developing interdisciplinary field and to identify the future research needs as well. This review has been realized that the physical properties have significant effects on the nanorefrigerant boiling and two-phase flow characteristics but the lack of the accurate knowledge of these physical properties has greatly limited the study in this interdisciplinary field. Therefore, effort should be made to contribute to the physical property database of nanofluids as a first priority. Secondly, systematic accurate experiments and flow regime observations on boiling and two-phase flow phenomena under a wide range of test conditions and nanofluid types should be emphasized to understand the fundamentals. Finally, physical mechanisms and prediction methods for boiling heat transfer and two phase flow characteristics should be targeted and applied research should also be focused on in the future.

Contents

1. Introduction

Boiling and two phase flow phenomena have been used in a variety of industrial applications and processes, such as refrigeration, air-conditioning and heat pumping systems, energy conversion systems, heat exchange systems, chemical thermal processes, cooling of high-power electronics components, cooling of nuclear reactors, micro-fabricated fluidic systems, thermal processes of aerospace station and bioengineering reactors [8]. Boiling and two phase flow heat transfer enhancement may improve energy efficiency and achieve significant energy consumption reduction. One of the methods is to use nanofluids to enhance boiling and two-phase flow heat transfer [9,47]. As a new research frontier, nanofluid two-phase flow and thermal physics have the potential to improve heat transfer and energy efficiency in thermal systems for many applications, such as microelectronics, power electronics, nuclear engineering, heat pipes, refrigeration, and air-conditioning and heat pump systems [19,20,27,28,31].

Furthermore, a new concept described the application of nanoparticles as additives into refrigerants in which the obtained suspension is called "nanorefrigerant." Refrigerant is a material used in heat transfer

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cycles which undergoes a phase change most of the time due to excessive heat transfer rate experienced during the process. Despite most of the fluids finding themselves a place in refrigeration cycles, only fluorocarbons or chlorofluorocarbons are considered as refrigerant according to general opinion. Two methods (single-step method and double-step method) are used for synthesis of nanorefrigerants. Double-step method is generally used to prepare nanorefrigerants. In this method, the nanomaterials are synthesized as dry powders by thermal decomposition and photochemical methods, transition metal salt reduction, ligand reduction and displacement from organometallics, metal vapor synthesis and electrochemical synthesis methods [6]. After production, the nanosized powder is put into the oil to form nanoparticle/oil mixture. Then, this mixture is dispersed by using different types of dispersion techniques such as ultrasonic agitation, magnetic force agitation, homogenizing, and high-shear mixing [50]. In single-step method, vapor nanophase powders are condensed into a liquid having low vapor pressure and dissolved in liquid at the same time. The nanoparticles are produced by applying a physical vapor deposition method or liquid chemical method [43].

To identify the research status of boiling and two phase flow, Cheng et al. [9] presented a review to understand the two-phase flow and boiling heat transfer characteristics of nanofluids and to identify particular areas requiring further study. Most of the available studies deal with water-based nanofluids. Researchers have given much more attention to the thermal conductivity of nanofluids rather than their heat transfer characteristics. Most of the available heat transfer studies are related to single phase flow heat transfer and some are related to nucleate pool boiling. However, the study of flow boiling and two-phase flow of nanofluids is very limited in the literature.

This review paper focuses on the latest advances in the augmentation of heat transfer by using nanorefrigerants. The fundamental and applied research of boiling and two phase flow phenomena with nanorefrigerants with and without lubricants is reviewed. Tables 1–4 provide a summary of the review performed in this paper.

2. Studies on boiling and two-phase flow phenomena of nanorefrigerants

Tables 1–4 present the summaries on the studies of nucleate pool boiling without lubricants, nucleate pool boiling with lubricant, flow boiling and condensation of nanorefrigerants, respectively. The following studies on several related topics such as nucleate pool boiling heat transfer without and with nanolubricants, flow boiling and condensation are respectively reviewed. For nucleate pool boiling, heat flux or superheated temperature degree is normally used as reference. For flow boiling heat transfer and two phase pressure drop, vapor quality, or total mass flux should be used as reference as in the available study.

2.1. Studies on nucleate pool boiling without and with lubricating oil

Some experimental studies on nucleate pool boiling of nanorefrigerants have been presented. The experimental results on nucleate pool boiling are inconsistent with some studies showing a decrease or no change in nucleate boiling heat transfer with the addition of nanoparticles while some show an increase. An overall review on nucleate pool boiling heat transfer including lubricant effect is conducted. Table 1 presents a summary of studies on nucleate pool boiling of nanorefrigerants without lubricants while Table 2 presents a summary of studies on nucleate pool boiling of nanorefrigerants with lubricants or refrigerants with nanolubricants [8].

2.1.1. Studies on nucleate pool boiling without lubricant oil

Park and Jung [29,30] studied the effect of carbon nanotubes (CNTs) on nucleate boiling heat transfer of three halocarbon refrigerants (R123, R134a and R22). In these studies, 1 vol.% of CNTs was added to the refrigerants and they found that CNTs increased nucleate boiling heat transfer coefficients for both refrigerants. Fig. 1 shows their heat transfer coefficients of R134a with and without CNTs. In particular, enhancements up to 36.6% were observed at low heat fluxes. With increasing heat flux, however, the enhancement diminished due to more vigorous bubble generation according to their visual observations. In addition, no deposit of the particles on their heat transfer surface was observed in their study.

Trisaksri and Wongwises [45] studied nucleate pool boiling heat transfer of TiO_2-R141b nanofluid on a cylindrical copper tube surface at different nanoparticle concentrations of 0.01 vol.%, 0.03 vol.% and 0.05 vol.% and pressures of 200, 300, 400 and 500 kPa. Fig. 2 showed their measured nucleate pool boiling heat transfer of TiO_2-R141b nanofluid versus superheated degrees at 300 kPa. Their results indicated that the suspended TiO_2 nanoparticles deteriorated the nucleate boiling heat transfer of refrigerant R141b. However, almost no effect results from adding extremely small amounts of nanoparticles. This was in consistency with the results of Yang and Liu [49] at an extremely low concentration of 0.09 vol.%. However, the boiling heat transfer coefficient decreased with increasing particle volume concentrations, especially at high heat flux. This was contradictory to the results of Yang and Liu

Table 1
Summary of studies on pool boiling of nanorefrigerants without lubricants [8].

Literature	Nanofluid/nanoparticle	Test section	Conclusions
Park and Jung [29]	CNTs-R123 and CNTs-R134a, 1 vol.% of CNTs	Plain stainless steel horizontal circular tube of 19 mm O.D. and length of 152 mm.	CNTs increased boiling heat transfer coefficients, the enhancement was up to 36.6%.
Park and Jung [30]	CNTs-R22, 1 vol.% of CNTs	Plain stainless steel horizontal circular tube of 19 mm O.D. and length of 152 mm.	CNTs increased boiling heat transfer coefficients, the enhancement was up to 36.6%.
Trisaksri and Wongwises [45]	TiO_2-R141b, 0.01%, 0.03% and 0.05 vol.%	Plain copper horizontal cylindrical heater of 28.5 mm O.D. and length of 90 mm.	TiO_2 deteriorated the nucleate boiling heat transfer of refrigerant R141b. No effect from adding small amounts of nanoparticles.
Ding et al. [17]	Cu-R113/B68EP	Boiling vessel of inside diameter of 30 mm and a height of 165 mm	The nanoparticles migrated mass of nanolubricant increased with increasing the mass of nanoparticles and the mass of refrigerant. The migration ratio of nanoparticles decreased with increasing the nanoparticle concentration.
Yang and Liu [49]	Au-R141b, 0.09%, 0.4% and 1%	Plain copper tube with an O.D. of 18 mm and length of 100 mm	Au particles increased boiling heat transfer coefficients. At concentration of 1%, the heat transfer coefficient was more than twice higher than those without nanoparticles.
Peng et al. [33]	CueR113, 0.1 wt.%, 0.5 wt.% and 1 wt.%	Horizontal copper flat surface with a diameter of 20 mm	Surfactants enhanced the nucleate pool boiling heat transfer of Cu-R113 in most cases but deteriorated the heat transfer at high surfactant concentrations.
Peng et al. [34,35]	Cu-R113, Al-R113, Al_2O_3-R113, CuO-R113, CuO-R141b, CuO-n-pentane	Boiling vessel of inside diameter of 50 mm and a height of 95 mm	The migration ratio of nanoparticles increased with decreasing the nanoparticle density, nanoparticle size, and dynamic viscosity of refrigerant, mass fraction of lubricating oil and heat flux, it increased with increasing the liquid-phase density of refrigerant or initial liquid level height.