Nanofluid Pool Boiling: A Review and Experimental Design

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Abstract

Nanofluids consist of nano-scale particles dispersed in a liquid which exhibit the potential for enhanced boiling heat transfer and critical heat flux (CHF). Past experimental results have shown conflicting results and the underlying mechanisms are not fully understood, warranting further study. An experimental program for the study of nanofluid pool boiling is currently under development at McMaster University. Recent literature is briefly reviewed to outline the motivation of the study and a brief description of the future experimental facility is provided.

1. Introduction

Nanofluids are engineered colloidal dispersions of nanoparticles in a liquid. The term "nanoparticle" typically refers to particles 1 – 100 nm in size. Following the pioneering work of Choi et al [1], the field of nanofluids has seen much interest due to reported heat transfer enhancements over their base fluids, even at low particle concentrations.

This paper aims to review several recent studies into boiling heat transfer involving nanofluids with a focus on nucleate boiling heat transfer and CHF. The reported results are reviewed to outline the motivation and design of an ongoing experimental study being undertaken at McMaster University. Additionally, the experimental facility currently being developed is briefly described.

2. Background information

2.1 Nanofluid preparation and stability

The methods used for the synthesis of nanofluids can be classified into three categories: one-step physical, one-step chemical, and two-step. One-step methods involve the simultaneous creation of nanoparticles and colloidal dispersion in situ; two-step methods involve the production of dry powders and dispersion in fluids as two separate steps [2]. The one-step production of nanofluids is beyond the scope of this study. As such a focus is given to two-step production methods.

2.1.1 Two-step (dispersion) method

The dispersion method of nanofluid preparation involves the creation of dry nanoparticles followed by the subsequent dispersion into a fluid [2]. Due to van der Waals forces between the particles, the nanoparticles tend to agglomerate, making the production of a stable dispersion difficult [3]. Techniques such as mechanical mixing and ultrasonic vibration are used to break these agglomerates. Additionally, chemical additives such as surfactants and/or pH modification are used to increase the stability of dispersion method nanofluids [2]. Nanofluids produced in this manner have typically achieved stable dispersions with average particle sizes on the order of 50-200 nm, starting with a dry nanoparticle size on the order of 10-20 nm [4].

2.2 Pool boiling heat transfer and critical heat flux (CHF)

Studies into pool boiling heat transfer of nanofluids have yielded mixed results between researchers. Several researchers have observed enhanced boiling heat transfer while others have observed deteriorated boiling heat transfer or little change at all. In a recent review by Taylor et al, it was noted that there was nearly an even three-way split between experimental results, even when similar heater geometries, base fluids, and nanoparticles were used [4].

2.2.1 Surface modification and wettability

As noted by Taylor et al. in their review, the majority of nanofluid pool boiling studies have noted particle deposition on the heater surface following boiling [4]. It has been widely reported that this layer of particles is a contributing factor in the CHF enhancement and nucleate boiling heat transfer performance observed in nanofluid boiling. The greater the thickness of the deposited surface, the greater the thermal resistance which suggests a decreased heat transfer coefficient would result [5].

In a study of water based nanofluids by Kim et al. [6], nanoparticle fouled surfaces following nanofluid boiling were found to exhibit increased capillary wicking due to the presence of a porous nanoparticle layer. This would allow increased surface re-wettability, delaying the growth of a dry patch during vapour bubble formation contributing to the enhancement of CHF as shown in Figure 1. The group also observed a decreased droplet contact angle following nanoparticle deposition, indicating an increased surface wettability [7].

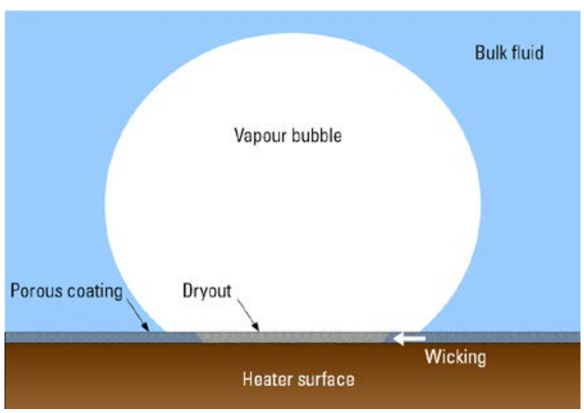

Figure 1: Outline of capillary wicking as a method of surface re-wetting [6]

In a study of surface wettability by Coursey et al. [8], CHF enhancement in poorly wetting systems (such as water on copper) were compared to better wetting systems (such as ethanol on glass). It was observed that water-based nanofluids exhibited CHF enhancement and little change in nucleate boiling performance at low particle concentrations while better wetting systems such as ethanol nanofluids showed no CHF enhancement even at high particle concentrations. Additionally, water nanofluids were observed to exhibit a decreased contact angle only after boiling, indicating that the improved surface wettability resulted from nanoparticle deposition as a result of boiling.

In a continuation of the study by You et al, Kwark et al. explored the effect of nanoparticle concentration on nucleate boiling heat transfer and CHF at atmospheric pressure with water based nanofluids [5]. It was noted that CHF enhancement increased with volumetric concentration until a critical value in concentration is reached. Further increased in concentration did not improve CHF but resulted in deteriorated nucleate boiling heat transfer. It was postulated that CHF enhancement resulted from increased surface wettability due to the formation of a porous nanoparticle coating. As the nanofluid concentration increased, deposition of nanoparticles on the heater surface also increased during boiling. The wettability of the surface was thought to increase up to a critical value where the porosity of the surface could no longer be improved through further deposition. However, continued particle deposition would increase thermal resistance at the heater, impeding boiling heat transfer.

Recent studies of copper-water [9] and carbon nanotube (CNT)-water nanofluids [10] by Kathiravan et al. yielded interesting results. The boiling of copper-water nanofluids was observed to cause decreased boiling heat transfer coefficients with increasing nanoparticle concentrations and enhanced CHF; fouling of the boiling surface with a nanoparticle layer was also observed. These observations are consistent with previously reported results. However, no fouling of the boiling surface was observed during CNT-water nanofluid boiling. In this case, CHF degradation was observed with increasing CNT concentration while the boiling heat transfer coefficient was observed to increase. Kathiravan et al. pointed out that these results were preliminary and suggested that further study was necessary.

3. Experimental design

The objective of the study is to increase understanding of the thermal-hydraulic characteristics of nanofluids. Attention will be paid to how the presence of nanoparticles affects boiling heat transfer and CHF of a nanofluid in comparison to its base fluid. To the knowledge of the author, the majority of the reported data for nanofluid pool boiling has been at atmospheric pressure. Therefore, the impact of boiling at elevated and sub-atmospheric pressures will also be investigated.

3.1 Boiling tank

To ensure maximum compatibility with a wide range of base fluids, a corrosion resistant tank is required. This requirement is further driven by the use of the two-step dispersion method as nanofluids prepared in this manner may require the use of surfactants and pH manipulation. Additionally, a vessel capable of handling elevated temperatures and pressures is desired to allow for future experiments above atmospheric pressure. The vessel size will be minimized to reduce the volume of nanofluids required for experiments.

The vessel body consists of a 12” long section of 4” schedule 40 piping (wall thickness of 0.237”). Standard flanges will be welded to the top and bottom of the tank; this will allow a cooling section and the heater assembly to be fastened to the vessel. Viewing ports constructed of 2.5” pipe will be provided on opposite sides of the tank to allow optical access to the boiling surface.

In the initial experiments to be conducted at atmospheric pressure, the top of the vessel will feature a separate tank to allow the circulation of cooling water. A ½” pipe will extend from the top of the tank to condense vapour and allow for fluid expansion. The heater assembly is attached at the bottom; a description is provided in section 3.2. Both the top and bottom assemblies are self-contained; this modularity will allow for flexibility in the experimental set-up with minimal modifications to the boiling vessel itself.

Thermocouples will be used to measure the temperature of the bulk liquid as well as the liquid near the heated surface. The dynamics of the boiling process will initially be visualized using a high speed camera operating at a resolution of up to 1024x1024 pixels and a frame rate of up to 8000 frames per second.

3.2 Heater assembly

The initial heater assembly used for the experiment will use a heated copper surface assembled into and insulated a standard blind flange. Heat will be provided by a 3/8” cartridge heater embedded in a 5/8” diameter copper rod. Heat is conducted between the cartridge heater and the removable plate through a narrower 1/2” diameter copper rod. To displace fluid below the viewing ports (minimizing the volume of the tank) and to minimize heat loss in the radial direction, the heater assembly is housed in an insulating aluminosilicate sheath.

Thermocouples will be mounted along the copper rod length as well as immediately below the boiling surface. These thermocouples will be used to measure the boiling surface temperature as well as the temperature gradient in the rod in order to determine the heat flux to the surface.

In order to facilitate the surface characterization of the heated surface following boiling, the heated surface will consist of a removable and replaceable copper plate. The copper plate will be bonded to the copper rod using high thermal conductivity cement. This will ensure that a clean surface can be used for each test. This will also facilitate easy removal of the heater surface for further characterization using light microscopy or scanning electron microscopy (SEM).

4. Conclusion

A brief review of the current state of knowledge surrounding the pool boiling of nanofluids was provided, focussing on nanofluid preparation methods, nucleate boiling heat transfer and critical heat flux (CHF). Inconsistencies in the reported results were discussed, highlighting the need for further study. A description of an experimental facility currently under development for the study of nanofluid pool boiling at McMaster University was described, highlighting several of its key features. The facility is currently being commissioned and will be benchmarked in the upcoming months. An improved understanding of the thermal-hydraulic properties of nanofluids is widely applicable. From a nuclear engineering standpoint, use of nanofluids in emergency cooling systems in fission reactors could also allow increased safety margins, or an increased core power level for the same safety margin as a result of the improved heat transfer characteristics [11]. Use of nanofluids in primary and secondary heat transport systems to improve CHF margin may also be possible but further exploration of the chemical and radiological impacts would first be necessary.

5. References

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