J. Energy Conversion

نشریه علمی-تخصصی تبدیل انرژی (JEED)

Volume: 12, Issue:4, 2026: 67-86

دوره ۱۲، شماره ۴، زمستان ۱۴۰۴، ص: ۶۷-۸۶

Experimental Investigation of the Combined Effects of Stable Boiling Surfaces and Porous Structures on Pool Boiling Heat Transfer of Nanofluids

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Extended Abstract

Introduction

Pool boiling is one of the most effective heat transfer mechanisms and is widely employed in thermal and energy systems, including refrigeration and air-conditioning systems, thermal power plants, heat exchangers, chemical processes, and electronic cooling systems. Improving pool boiling heat transfer can increase energy efficiency, reduce the size and weight of thermal equipment, and enhance system reliability and safety. Nevertheless, the performance of boiling systems is limited by thermal instabilities and the occurrence of critical heat flux (CHF), beyond which a substantial increase in surface temperature may occur and potentially lead to thermal failure. In recent years, nanofluids and engineered boiling surfaces have attracted considerable attention as effective approaches for enhancing pool boiling heat transfer. The deposition of nanoparticles on boiling surfaces can modify surface wettability and microstructure, increase the density of active nucleation sites, and consequently improve the CHF. In parallel, porous structures, particularly honeycomb porous structures, can enhance liquid replenishment through capillary action, increase the effective number of nucleation sites, and facilitate vapor removal from the heated surface. Although several studies have investigated the individual or combined effects of nanofluids, nanoparticle deposition, and porous structures, the behavior of a porous structure attached to a boiling surface that has already reached physical and thermal stability through long-term successive boiling-cooling cycles has received limited attention. Therefore, the present study experimentally investigates the combined effect of a stable boiling surface produced by nanoparticle deposition and a ceramic honeycomb porous structure on the pool boiling performance of SiO_2 nanofluids. Two nanoparticle size ranges, namely 20–30 nm and 60–70 nm, are considered. First, the copper boiling surface is subjected to repeated and long-term boiling-cooling cycles to achieve a stable surface condition. Subsequently, a ceramic honeycomb porous structure is attached to the stabilized surface, and its effects on the boiling curve, CHF, onset of nucleate boiling (ONB), and boiling heat transfer coefficient (BHTC) are experimentally evaluated.

2. Materials and Methods

An experimental pool boiling apparatus was developed to investigate the heat transfer characteristics of SiO_2 nanofluids under atmospheric pressure. The system consisted of a stainless-steel boiling chamber, a two-pass copper spiral condenser, a copper test block, cartridge heaters, AC variacs, K-type thermocouples, pressure and temperature data loggers, a vacuum pump, and a cooling system. The boiling chamber was manufactured from stainless steel 304 and equipped with viewing windows to facilitate observation of the boiling process. The test section consisted of a high-purity copper block with a boiling surface diameter of approximately 25.4 mm. Three K-type thermocouples were installed along the copper block at different depths to determine the temperature distribution and calculate the boiling surface temperature and heat flux. The porous structure employed in the experiments was a ceramic honeycomb monolith with an open and regularly distributed channel network. The structure provided a large effective surface area, numerous potential nucleation sites, and efficient pathways for liquid supply and vapor escape. Its ceramic composition mainly consisted of SiO_2, MgO, Al_2O_3, and TiO_2. A porous structure thickness of 1 mm was selected based on previous experimental investigations. To avoid introducing additional thermal contact resistance, the honeycomb structure was mechanically attached to the boiling surface using stainless-steel wires without adhesive or thermal grease. The SiO_2 nanofluids were prepared using a two-step method. SiO_2 nanoparticles with size ranges of 20–30 nm and 60–70 nm were dispersed in deionized water at a mass concentration of 2%. The prepared suspensions were first mixed using a magnetic stirrer and subsequently treated in an ultrasonic bath to improve particle dispersion and stability. The stability of the nanofluids was assessed by visual observation and zeta-potential measurements. No significant sedimentation was observed during two weeks of storage, while the measured zeta potentials indicated satisfactory suspension stability. To simulate realistic operating conditions, the boiling surface was subjected to successive boiling-cooling cycles. Each experiment continued for approximately 10.5 hours, after which the heating process was stopped and the surface was allowed to cool naturally to room temperature. The boiling surface was polished only before the first experiment and was not repolished during subsequent cycles. This procedure was adopted to reproduce the gradual deposition and surface modification that may occur in practical thermal systems during repeated operation. Heat flux was calculated from the temperature gradient in the copper block using Fourier's law, while the boiling heat transfer coefficient was obtained from Newton's law of cooling. The experimental system was validated by comparing the measured boiling data with the Rohsenow correlation and by comparing the measured CHF with the Zuber and Haramura models. The maximum uncertainties associated with heat flux, surface superheat, and boiling heat transfer coefficient were approximately 4.4%, 4%, and 5.5%, respectively. The experimental repeatability was also evaluated. When the boiling surface was repolished before each experiment, noticeable variations were observed; however, when the same surface was retained without repolishing, the maximum deviation among successive experiments was only about 0.57%, demonstrating excellent repeatability.

3. Results and Discussion

The experimental validation demonstrated a very good agreement between the present measurements and established correlations and experimental data. The differences between the measured CHF and the values predicted by the Zuber and Haramura models were only approximately 0.13% and 0.27%, respectively. These results confirm the reliability of the experimental apparatus and the validity of the measurement methodology. The successive boiling-cooling cycles resulted in gradual nanoparticle deposition on the copper surface and the formation of a relatively uniform porous layer. This deposition significantly modified the wettability of the boiling surface. The contact angle of deionized water on the polished copper surface was approximately 67.9°, whereas nanoparticle deposition reduced the contact angle to nearly zero, indicating a substantial transition toward a highly hydrophilic surface. The enhanced wettability and capillary liquid supply helped maintain liquid contact with the heated surface and delayed the development of dry-out regions. After stabilization, the boiling surfaces exhibited consistent thermal behavior over successive cycles. For the 20–30 nm SiO_2 nanoparticles, the stabilized CHF was approximately 1300 kW/m², while the corresponding value for the 60–70 nm nanoparticles was approximately 1250 kW/m². The corresponding surface superheat was approximately 52°C. Compared with deionized water, the stabilized surfaces produced CHF enhancements of approximately 18% and 13% for the 20–30 nm and 60–70 nm nanoparticles, respectively. The relatively lower CHF obtained with the larger nanoparticles was attributed to differences in the morphology of the deposited layer, the density of active nucleation sites, and the effective thermal resistance of the deposited structure. An important consequence of the repeated boiling-cooling cycles was the delay in the onset of nucleate boiling. For the 20–30 nm nanoparticles, the surface superheat at the onset of nucleate boiling increased from approximately 14.1°C in the first cycle to about 25.15°C in the final cycle, corresponding to an increase of approximately 85%. For the 60–70 nm nanoparticles, the corresponding superheat increased from approximately 13.6°C to 23.8°C, representing an increase of approximately 75%. These changes demonstrate the significant influence of nanoparticle deposition and surface evolution on the nucleation characteristics of the boiling surface. The principal contribution of the present study was obtained by combining the stabilized nanoparticle-deposited surface with the ceramic honeycomb porous structure. Attaching the porous structure substantially increased the maximum heat flux. For the 20–30 nm nanofluid, the maximum heat flux reached approximately 1741.9 kW/m², while a value of approximately 1716.2 kW/m² was obtained for the 60–70 nm nanofluid. Relative to the stabilized surfaces without the porous structure, the CHF increased by approximately 34.1% and 37.9% for the 20–30 nm and 60–70 nm nanoparticles, respectively. Compared with deionized water, the corresponding improvements were approximately 57.5% and 55.2%. The honeycomb porous structure also shifted the onset of nucleate boiling toward higher surface superheat values. For the 20–30 nm nanoparticles, the ONB temperature increased from approximately 26.15°C to 28.9°C, corresponding to an increase of about 10.5%. For the 60–70 nm nanoparticles, the ONB temperature increased from approximately 23.8°C to 26.1°C, corresponding to an increase of approximately 9.7%. This behavior indicates that the porous structure modifies the heat and mass transfer processes near the boiling surface and delays the transition to nucleate boiling. Furthermore, the attachment of the honeycomb structure improved the boiling heat transfer coefficient. For the 20–30 nm and 60–70 nm nanoparticles, the BHTC increased by approximately 20.2% and 19.8%, respectively, compared with the corresponding stabilized surfaces without the porous structure. The improvement was attributed to several synergistic mechanisms, including an increased number of active nucleation sites, enhanced surface wettability, improved capillary liquid replenishment, and more effective vapor removal through the interconnected porous channels. The combined approach therefore provides two complementary enhancement mechanisms. Nanoparticle deposition modifies the physicochemical characteristics of the copper surface and promotes hydrophilicity and stable nucleation behavior, while the honeycomb porous structure provides additional pathways for liquid replenishment and vapor escape. The simultaneous action of these mechanisms improves the CHF and BHTC while maintaining relatively repeatable boiling behavior under successive operating cycles. Despite the significant enhancement obtained, the study was conducted at laboratory scale and over boiling-cooling cycles lasting approximately 50–60 hours. During longer-term operation, gradual nanoparticle deposition inside the pores may partially obstruct liquid flow paths and reduce capillary transport. Consequently, the long-term thermal performance of the porous structure may decline under extended operating conditions. Further experiments are therefore required to investigate the long-term stability of the combined surface under substantially longer boiling-cooling cycles and more realistic industrial operating conditions.

4. Conclusions

This experimental study investigated the combined effects of a stabilized nanoparticle-deposited boiling surface and a ceramic honeycomb porous structure on the pool boiling heat transfer characteristics of SiO_2 nanofluids. Two nanoparticle size ranges, 20–30 nm and 60–70 nm, were considered at a mass concentration of 2%. The experimental apparatus was successfully validated against established boiling correlations and CHF models, and the results demonstrated high measurement accuracy and repeatability.

Successive boiling-cooling cycles caused nanoparticle deposition on the copper surface and transformed it into a physically and thermally stabilized boiling surface. The stabilized surfaces increased the CHF by approximately 18% and 13% for the 20–30 nm and 60–70 nm nanoparticles, respectively, compared with deionized water. The subsequent installation of the honeycomb porous structure resulted in a substantial additional enhancement. The CHF increased by approximately 34.1% and 37.9% relative to the corresponding stabilized surfaces without the porous structure, while the improvements relative to deionized water reached approximately 57.5% and 55.2%, respectively. Moreover, the BHTC increased by approximately 20.2% and 19.8% for the two nanoparticle size ranges. The porous structure also shifted the onset of nucleate boiling toward higher surface superheat values by approximately 10.5% and 9.7%.

Overall, the results demonstrate that combining nanoparticle-induced surface stabilization with a honeycomb porous structure can provide a synergistic and effective method for enhancing pool boiling heat transfer. The enhancement is primarily associated with improved wettability, a higher density of active nucleation sites, stronger capillary liquid replenishment, and more efficient vapor removal. Accordingly, the proposed combined surface treatment has considerable potential for advanced high-heat-flux thermal management systems. However, further long-term

experimental investigations are required to evaluate nanoparticle accumulation within the porous structure and to determine the durability of the thermal enhancement under extended industrial operating conditions.

Key words: pool boiling, stable boiling surface, porous structure, critical heat flux, nanofluid

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Cite this article as: Mohammad. Ghorbani, Masoud. Zareh, Cyrus. Aghanajafi, Mohammad Behshad. Shafii, Experimental Investigation of the Combined Effects of Stable Boiling Surfaces and Porous Structures on Pool Boiling Heat Transfer of Nanofluids. **Journal of Energy Conversion, 2026, 12(4), 67-86**.