Critical Heat Flux Amelioration

Subjects: Energy & Fuels
Contributor: Amir Gheitaghy

Critical heat flux (CHF) is the thermal limit of a phase change phenomenon where boiling occurs during heating, which suddenly decreases the efficiency of heat transfer. Ameliorating CHF by altering the boiling surface characteristics can lead to more efficiency, safety, and reliability of the system.

Keywords: critical heat flux ; pool boiling ; metal oxide ; nanoparticle deposition

1. Introduction

Pool boiling is an effective heat transfer process in a wide range of applications related to energy conversion, including power generation, solar collectors, cooling systems, refrigeration, and air conditioning. By considering the broad range of applications, any improvement in higher heat-removal yield can ameliorate the ultimate heat usage and delay or even avoid the occurrence of system failures, thus leading to remarkable economic, environmental, and energy efficiency outcomes. A century of research on ameliorating critical heat flux (CHF) has focused on altering the boiling surface characteristics, such as its nucleation site density, wettability, wickability, and heat transfer area, by many innovative techniques. Due to the remarkable interest of using nanoparticle deposition on boiling surfaces, this review is targeted towards investigating whether or not metal oxide nanoparticles can modify surface characteristics to enhance the CHF.

2. Challenges and Suggestions

Based on the review of available studies, enhanced CHF not only increases heat transfer efficiency but also augments the safety of heat management. A wide diversity of pool boiling experiments have been carried out at various concentrations, preparation methods, and nanofluids stabilities to significantly enhance the CHF. Furthermore, different surface properties, including porosity, capillarity, wettability, and roughness, can increase CHF through a complicated mechanism. CHF can be also elevated through modifying flow channels by either altering its size or incorporating surface modifiers. The application of hybrid or hierarchical structures can substantially improve the CHF for some particular purposes, among which the hydrophilic membrane with micro-channels and a combination of high porosity with the super-hydrophilic nature of the surface can be mentioned. Moreover, CHF is under the substantial influence of surface wettability and capillary wicking. The synergetic impact of the mentioned parameters should be extensively examined for diverse nanoparticle sizes and concentrations to elucidate the mechanism of CHF amelioration. Despite a wide diversity in boiling heat transfer theories to explain the variations in nanofluids' properties and surface wettability, no comprehensive theory has been introduced to mechanistically justify the CHF amelioration for a wide spectrum of nanoparticle size and contents. A lack of such an inclusive framework has limited the nanofluids commercialization in various fields including a nuclear reactor, fossil fuel boiler, spray cooling, and high-power electronics. Resolving the key issues can pave the way for experiments on thermal engineering systems. Researchers have recognized the nanoparticle deposition-induced enhancement in surface wettability and capillarity as the main cause of CHF augmentation. Table 1 summarizes the impacts on nanofluids' CHF.

Table 1. Summary of the parameter variation impacts on CHF.

Parameter Variations	CHF	Reason
Increase in the surface roughness	**Increase**	**The CHF causes a higher superheat.** **Efficient contact area increases.**
Increase in the surface wettability	**Increase**	**The liquid traps in the porous structure and the vapor layer formation is prevented.** **The number of active nucleation sites decreases because of the low contact angle and the vapor layer formation is prevented.**
Increase in the capillarity	**Increase**	**The dry regions under the vapor bubbles are wetted by the fresh liquid.**

So far, several questions have remained unanswered. Thus, highly creative and practical investigations are required to establish the advanced approaches for CHF amelioration. The following recommendations can be considered for further understanding of the fundamental mechanisms of CHF amelioration:

(1) Despite the relative maturity of nanofluid-related studies, issues such as long-period stability, probable erosion, and required maintenance measures as well as cleaning procedures have remained obstacles to nanofluid commercialization. In this context, studies to extend the available predictive correlations or numerical simulation tools for CHF prediction are highly encouraged. Furthermore, the next generation of nanofluids, including shell-core nanofluids, microfluidics, and hybrids of more than two nanofluids, are interesting topics owing to their phase-change characteristics and optimized thermo-physical properties, which may result in higher heat transfer efficiency and outstanding stability.

(2) Regarding the depositing tendency of nanofluids during boiling, texture fabrications and coating particles on the surface have been intensively explored to improve CHF. The probable micro/nanostructure detachment or failure during the boiling process needs to be further addressed experimentally. Moreover, in the case of applying nanotubes or nanowires as the coating substance, the choking issue must be avoided by the systematic optimization of their diameter and length. Besides, the complexity of the surface properties' relationships should be addressed to further clarify the fundamental mechanisms of CHF amelioration.

(3) In spite of huge improvements to surface modifications for flow boiling, a considerable gap still remains between the studies and engineering applications, particularly considering the size of the system. Large engineering scales with different shapes were explored by micro-channels, making the coating process an obstacle in practical engineering scales.

(4) The literature review showed that the integration of hybrid and hierarchical structures can significantly enhance CHF. It is, however, accompanied by difficulties for separately investigating the impact of surface features on CHF amelioration. Putting the safe CHF enhancement as the major objective, the integration of advanced approaches, such as acoustic methods, magnetic fields, and other creative techniques through novel preparation methods and materials are highly recommended.

(5) Nanofluid stability has remained one of the major challenges. Instead of experimental studies with varying mass fractions, various approaches have been tested (i.e., pH control, surfactants, and surface functionalization) to prevent from nanoparticles' agglomeration and sedimentation, which are, albeit, at a research-level. In this regard, the industrial application of nanofluids will be realized only when their long-term physical and chemical stabilities are guaranteed at the mass production level.

(6) Nanoparticle size is another important factor in the heat transfer field. The use of smaller nanoparticles is recommended. Thus, cost-effective synthesis methods should be established to prepare relatively small nanoparticles.

(7) The relative size effect of nanoparticles in the liquid phase requires further examination to prevent particle clustering.

(8) To the best of our knowledge, a limited number of studies have attributed the CHF amelioration to alternations in nanofluids' thermal transport properties. Therefore, a database including the thermal transport characteristics along with the detailed specification of nanoparticle sizes and dispersion stability with/without surfactant is recommended, in which the promising nanofluids are prioritized.

(9) Regarding the key role of the deposited layer on the heating surface in CHF amelioration, the thickness should be optimized to induce the maximum latency in the CHF occurrence. Moreover, the stability of the deposited layer should be experimentally checked in several replications.

(10) The synergetic impact of surface wettability and capillary wicking should be addressed to mechanistically elucidate the CHF enhancement for various particle sizes and concentrations.

(11) The application of nano-coats on the heating surface by the physical/chemical vapor deposition method is a promising approach compared to nanofluids. This technique, however, demands extensive investigations regarding its stability and optimal thickness to examine the delay in the CHF occurrence.

(12) The bubble dynamics should be empirically and numerically examined to determine the exact share of the deposited layer and nanoparticle in the CHF amelioration.

(13) Regarding the significance of pressure, the irreversible growth of dry patches should be explored at various pressure levels to elucidate the CHF enhancement in nanoparticles deposited layer.

3. Concluding remarks

The present study is an overview of the CHF amelioration of pool boiling surfaces through the use of metal oxide nanoparticles deposition. The impact of metal oxide nanoparticles and their thermo-physical properties, concentration, shape, and size were addressed and the inconsistencies or conflicts in the available literature were highlighted. In addition, nanoparticle deposition techniques were reviewed to find an efficient substitution for deposition rather than nanofluid boiling. Moreover, possible mechanisms and models were discussed to explore the enhancement findings. This review study had the following observations:

(1) Besides the innovative dimensional analysis-based Kutateladze's CHF formulation, five different CHF mechanisms have been widely employed: bubble interference, hydrodynamic instability, macrolayer dry-out, hot/dry spot, and interfacial lift-off, among which the Zuber's hydrodynamic instability theory has gained the highest popularity owing to its mechanistic formulation and theoretical attractiveness. Lately, the theoretical-based interfacial lift-off mechanism has been widely confirmed by experimental results that can deal with various surface orientations.

(2) The impacts of thermo-physical properties, concentration, shape, and size on CHF have been extensively addressed in the heat transfer field. Accordingly, CHF rises with wall thickness enhancement but reaches an asymptotic value beyond a thickness threshold. Thus, the data corresponding to wall thicknesses beyond this threshold is highly essential. Altogether, a limited amount of data covers the entire relevant parameters of the fluids with various thermal features. A severe shortage is also felt regarding the horizontal, downward-facing surface orientations reflecting the need for more advanced strategies to plan future studies including the micro-photographic analysis of near-wall interfacial phenomena to confirm or reject the introduced CHF mechanism.

(3) Considering the complexity of the CHF phenomenon and its dependence on a diverse range of factors, the available data should be combined in a comprehensive database to assess diverse models and correlations. Such a database will be expanded by the inclusion of new data to fill the vacancies regarding the relevant parameters.

(4) Nanofluids can undoubtedly improve the CHF, which can be attributed to the enhanced surface wettability upon nanoparticle deposition. The data regarding the impact of nanofluids on nucleate boiling HTC are, however, contradictory, which may be due to involvement of numerous complex factors, such as the type of liquid, initial surface roughness, and heat flux in addition to nanoparticle type, size, concentration, preparation, and functionalization procedure, which can substantially affect the thermophysical characteristics of the nanofluid and surface characteristics (i.e., surface finish, active nucleation site density, wettability and changes in the triple line). Such complexities can definitely restrict the theoretical attempts to model the nanofluid boiling.

(5) Bath quenching the metal portion of a nanofluid is related to the cooling rates similar to, or even weaker than, those of the base liquid. The cooling rate can be accelerated by successive quenching as it will thicken the nanoparticle layer on the surface. At elevated surface temperatures, this layer will further destabilize the vapor film, leading to the premature disruption of the film boiling pattern.

(6) The nanofluid-induced nucleate boiling enhancement can be attributed to nanoparticle deposition on the surface, resulting in capillary wicking in the porous layer and enhancement in surface wettability and bubble dynamics. These impacts are competing with each other depending on the size of nanoparticles relative to the surface roughness.

(7) Although the nanofluids have shown high potentials in improving the boiling performance, some practical issues should be closely considered prior to the utilization of nanofluids in practical cooling purposes, among which the clustering, sedimentation, and precipitation of nanoparticles, the clogging of intricate features, the heating surface erosion of the temporal variation of cooling performance, and the cost of quality can be mentioned.

(8) Despite the improving impacts of nanofluids on the thermal conductivity of the boiling fluid, the majority of their usefulness is rooted in their surface modification. Other approaches of surface modifications (such as micro/nano studs, nanotube/nanowire arrays, microporous structure, and nanoparticle pre-deposition) are capable of offering comparable or even better heat transfer enhancements with no practical problems relevant to use of nanofluid boiling.
