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Pool boiling heat transfer driven by an acoustic standing wave in terrestrial gravity and microgravity

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ABSTRACT

Terrestrial and microgravity pool boiling generated from a platinum wire heater in the presence of an acoustic standing wave were performed using degassed FC-72 Fluorinert liquid. The sound wave was created by driving a half wavelength resonator at a frequency of 10.15 kHz. Microgravity conditions were created using the 2.1 second drop tower on the campus of Washington State University. Burnout of the heater wire, often encountered with heat flux controlled systems, was avoided by using a constant temperature controller to regulate the heater wire temperature. The amplitude of the acoustic standing wave was increased from 28 kPa to over 70 kPa and these pressure measurements were made using a hydrophone fabricated with a small piezoelectric ceramic. Cavitation incurred during experiments at higher acoustic amplitudes contributed to the vapor bubble dynamics and heat transfer. The heater wire was positioned at three different locations within the acoustic field: the acoustic node, antinode, and halfway between these locations. Complete boiling curves are presented to show how the applied acoustic field enhanced boiling heat transfer and increased critical heat flux in the terrestrial environment, while in microgravity the acoustic field was found to be capable of filling the role of terrestrial gravity in maintaining nucleate boiling. Video images provide information on the interaction between the vapor bubbles and the acoustic field.

1. Introduction

For traditional terrestrial applications, boiling has been recognized as one of the most efficient heat transfer mechanisms. Terrestrial nucleate boiling relies on the buoyancy force to remove vapor bubbles from the heater surface. The absence of gravity in space eliminates the buoyancy forces and limits the ability for vapor removal. Without any alternate force present, vapor bubbles will grow and tend to remain on or near the heater surface commonly causing a vapor blanket to form over the heater that causes severe deterioration in boiling heat transfer. Efficient nucleate boiling stops and the heat must now be conducted through the vapor layer which is called the film boiling. The inefficiency of film boiling often quickly elevates heater surface temperatures leading to a possible burnout of the surface. The ability to sustain nucleate boiling in a space microgravity environment could lead to more effective and efficient means of transferring heat. Acoustic forces could provide the gravity replacement force to sustain stable nucleate boiling. However, the fluid dynamics and thermal transport of a boiling two-phase flow interacting with an acoustic force without the presence of gravity have not been given the attention it deserves. In this paper, the main objective is to provide some fundamental understanding on the dynamic interaction between a boiling two-phase flow and an acoustic standing wave in terrestrial gravity and microgravity.

1.1. Pool boiling in microgravity

Among the early work, Keshock and Siegel [1] and Siegel and Keshock [2] discovered that in microgravity bubbles grow larger and stay longer on the heater surface, which results in merger of bubbles. Weinzierl and Straub [3] found that for pool boiling at low heat fluxes the heat transfer coefficient is equal or higher in microgravity than in terrestrial gravity. They thought that it is because the inception of boiling occurs at lower heat fluxes in microgravity. Straub et al. [4] gave a review on microgravity boiling heat transfer and pointed out published results do not show general consistency. From their own experiments they suggested that the evaporation and surface tension are the basic mechanisms

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in microgravity pool boiling and the inertia force in bubble departure governs the qualitative behavior of boiling heat transfer coefficient.

Ervin et al. [5] and Merte et al. [6] reported transient microgravity pool boiling results from their 5-second drop tower experiments. Their main objective was to investigate the boiling inception in R-113 under microgravity. They found the boiling inception in microgravity is much more explosive than that under normal gravity and they attributed the pure conduction without natural convection and an instability at the wrinkled vapor-liquid interface (Lee and Merte, [7]) as the key factors. Microgravity experiment on board an aircraft was performed by Oka et al. [8] to study the pool boiling mechanisms. They found that coalescence of bubbles and bubble oscillatory motion are the basic flow pattern on the heater surface. Under low heat fluxes and high subcooling, they mentioned that partial nucleate boiling was observed during the 25 s of microgravity. Based on their sounding rocket experiment, Abe and Akira [9] concluded that stable and effective nucleate boiling can be maintained under sufficiently subcooled conditions. For lower subcooling, coalesced bubbles eventually covered the entire heater surface causing film boiling. Based on space shuttle experiments, Merte [10] reported that partial dryout and rewetting periods take place in subcooled nucleate boiling which makes the process unstable, but the average heat transfer coefficients during dryout and rewetting were about the same. A series of papers were published by Professor Merte and his co-workers (Lee and Merte [11,12]; Merte and Lee [13]; Lee and Merte [7]) on bubble nucleation, growth, and dynamics in microgravity. No work has been reported in the open literature concerning the interaction between an alternate force field and a boiling system in microgravity. This article reports the research findings on the fluid mechanics and heat transfer characteristics of a boiling system that is imposed with an acoustic standing wave in the presence and absence of gravity.

1.2. Effects of acoustics on gas bubbles in an isothermal system

Crum and Eller [14] performed experiments to study the motion of air bubbles smaller than the resonance size through a standing acoustic wave in water and isopropyl alcohol. The bubbles could be trapped at a position slightly above the uppermost pressure antinode where the buoyancy of a bubble was balanced by the acoustic force. It was found that translational velocities of small air bubbles created by the acoustic force were relatively large compared to the rise velocity of the bubble in the absence of a sound field. Further results indicated erratic bubble movement when the pressure amplitude exceeds a threshold value.

A glovebox experiment aboard the space shuttle on USML-1 showed the agglomeration of air bubbles larger than the resonant size (1–15 mm) at the acoustic pressure node (Marston et al. [15]). Observations showed that the bubbles did not coalesce until a surfactant was injected through a hypodermic needle at the surface of a large bubble. Coalescence initiated a wave that dispersed and traveled around the bubble. The acoustic levitation device used by Marston et al. [15] was similar to the one used for the study of bubble shape oscillations in 1 g where bubbles up to 12 mm in diameter were levitated (Asaki et al. [16]). The levitator consisted of a 3″ diameter piezoelectric ceramic transducer mounted to the bottom of a water filled Plexiglas chamber. The driving frequency for the glovebox experiment and the study of shape oscillations was 63 and 22.5 kHz, respectively.

The presence of a bubble in an acoustic standing wave has further complications. The non-uniform distribution of the radiation pressure (average force) over the surface of a bubble induces a non-spherical bubble shape (Asaki and Marston [17]). Bubble rotation and induced shape oscillations can occur. The presence of the bubbles may also affect the acoustic field. Resonance size bubbles can significantly detune a resonator through a monopole response of the bubbles. However, it has been observed by the above authors that detuning of the levitator is significantly reduced by bubbles much larger than the resonance size with radii less than approximately 3 mm.

1.3. Acoustic effects on boiling heat transfer

The effects of acoustics on pool boiling have been conflicting in quantitative terms. Qualitatively it has been shown numerous times that heat transfer increases in an acoustic sound field. The following summarizes the terrestrial boiling in an acoustic field. Wong and Chon [18] found that only above a certain pressure, the acoustic vibrations will effect heat transfer. This pressure they call the "Critical Sound Pressure". Increases in the heat transfer coefficient were well pronounced in the natural convection region, but negligible in the nucleate bubble region. They note that cavitation and intense turbulence were the main reasons for the increases in heat transfer. Park and Bergles [19] note that acoustics slightly increased burnout heat fluxes from a horizontal cylinder. Heat transfer at low heat fluxes increased when the fluid was subcooled and decreased when the fluid was saturated. Iida and Tsutsui [20] found that the minimum and maximum heat fluxes were raised in an acoustic sound field. Natural convection and film boiling were increased while no noticeable change was found in the nucleate boiling region. They noted that the sound pressure profile within the fluid body effects the heat transfer coefficient profile.

Sitter et al. [21] demonstrated the feasibility of an applied acoustic field to remove bubbles in microgravity boiling. The primary objective of this research is to extend the previous preliminary work of Sitter et al. [21] and to develop complete boiling curves through the use of a constant temperature heater for a physical understanding of the acoustics interaction with the terrestrial and microgravity boiling flows. Critical heat flux is often an important design parameter for boiling heat transfer equipment and an extensive study on this phenomenon is desirable. It is also important to know how the applied acoustic standing wave removes and transports vapor bubbles. Studying the effects of heater location within the sound field is one way to develop a better feel for the acoustic interaction with the boiling heat transfer process.

2. Theoretical background

2.1. Physics of bubble–acoustics interaction

Boiling heat transfer is a complicated process and the balance of many forces which act on vapor bubbles contributes to the complexity. These forces include surface tension, drag force, pressure force, buoyancy force, Inertia Force, thermocapillary force, thermophoretic force, and molecular momentum force.

It has long been known that bubbles can be trapped in a liquid by an acoustic standing wave. This provides a visual understanding of the fact that a standing wave exerts a net force on the bubble. A standing wave is produced when the acoustic chamber, fluid and acoustic resonator are properly coupled. In other words, the dimensions of the chamber, resonator driving frequency, and speed of sound in the fluid must be such that they satisfy the wave equation. Further details are explained later in the description of the acoustic chamber.

If a bubble is small as compared to the wavelength of sound, then at any instant the translational force exerted on the bubble by the sound field is equal to the bubble volume times the negative