Experimental Thermal and Fluid Science 61 (2015) 96–104

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental study on the attenuation of pressure waves in a cavity induced by flow boiling

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ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form 3 October 2014
Accepted 26 October 2014
Available online 1 November 2014

Keywords:
Pressure wave attenuation
Cavity
Boiling
Bubbly flow

ABSTRACT

The experimental work presented in this article deals with the study of low-frequency high-amplitude pressure wave attenuation in a cavity when boiling takes place on the inside. The working fluid was HFE7100. Regarding the flow regime, the study considered two different situations: pool boiling and flow boiling in the low to moderate Reynolds number regime. Regarding the operating parameters, the study considered: (a) the type of evaporator, (b) the temperature of the evaporator, and (c) the frequency of the pressure waves. Three different types of evaporators were manufactured and tested: a flat one and another two based on a micro pin fin structure. Pin fin sizes for these two evaporators were 500 μm × 500 μm × 500 μm and 1000 μm × 1000 μm × 1000 μm respectively. The temperature of the evaporators was varied between 40 °C and 80 °C. Frequency of the pressure waves changed between 35 Hz and 75 Hz. An additional isothermal reference case (no boiling) was used for comparison purposes. The typical order of magnitude of the peak-to-peak applied pressure amplitudes was 0.2 bar. Regarding the results, it was found that boiling causes a significant attenuation of the peak-to-peak amplitude of the pressure waves in the cavity. The main parameter acting on this attenuation was the temperature of the evaporator (related to the input electrical power), while the actual micro-structure of the evaporator played a nearly negligible role. Also, it was found that while a small electrical power input of about 5 W achieves an attenuation factor of about 0.5, four times as much power (20 W) is needed to halve again the attenuation factor to 0.25. This suggests a scaling law relating attenuation and power which could be used for engineering design purposes.

1. Introduction

The interaction of pressure waves and bubbly flow is a subject that has been studied for a long time. In fact, one of the earliest studies on the subject was published by Mallock [1] more than a century ago. Other theoretical studies related to modelization of this phenomenon have been published by Carstensen and Foldy [2], Wijngaarden [3], Caflisch et al. [4], and Commander and Prosperetti [5] that, in addition, performed a systematic comparison between theoretical models and experimental results. On the side of practical applications, the interaction of pressure waves and bubbly flows has been directed, mainly, to the problems of sound propagation/attenuation and heat transfer enhancement. More recently, micro-bubble injection has been proposed as a mean to mitigate damage caused by strong pressure waves in some types of nuclear technologies.

Regarding sound propagation and attenuation in bubbly flows, it is relevant to mention the works of Silberman [6], Prosperetti [7], D'Agostino and Brennen [8] and Nomura and Nakagawa [9]. In these references, the authors studied the interaction between sound and ultrasound fields and bubble flows using different means to gather both qualitative and quantitative information propagation and attenuation characteristics. A similar study using pressure waves of moderate amplitude instead has been reported by Dontsov and Nakoryakov [10]. In this study, average bubble diameter was 0.5 mm and pressure increments were of the order of 0.1 MPa. Typical pressure attenuations were of the order of 0.1 and it was found that non-uniform bubble distribution enhanced this attenuation. Strong pressure oscillations of the order of 50% of the ambient pressure past a bubbly flow have been studied numerically by Raju et al. [11] although, in this case, the focus was more on the development and validation of a hybrid Lagrangian–Eulerian flow solver than on the specific physics aspects of the problem itself. Regarding applications for heat transfer enhancement, the use of ultra sound fields was proposed long time ago,

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http://dx.doi.org/10.1016/j.expthermflusci.2014.10.023
0894-1777/

Nomenclature

f	frequency (Hz)
P	pressure (bar)
Q_{flow}	volume flow rate (cm^3/min)
Re	Reynolds number
T	temperature (°C)
$T_{evaporator}$	evaporator surface temperature (°C)
t	time (s)
$K_{\Delta Pcavity}$	pressure attenuation factor in the cavity
ΔP	peak-to-peak pressure amplitude (bar)
ΔP_{cavity}	peak-to-peak pressure amplitude in the cavity (bar)
$\Delta P_{reference}$	peak-to-peak reference pressure amplitude (bar)

Fand [12] and Lee and Parker [13]. The specific influence of ultra sound fields on boiling has been reported, among others, by Park and Bergles [14], Iida and Tsutsui [15], Yamashiro et al. [16], Kim et al. [17] and Baffigi and Bartoli [18]. In the last case, that is the most recent, Baffigi and Bartoli [18] used 40 kHz ultra sonic waves and reported increases on the heat transfer coefficient of the order of 18–25%. Finally, it is important to mention the work of Futakawa et al. [19] which have proposed bubbly flow as a mitigation methodology for the erosion caused by strong pressure waves in a high-power pulsed spallation neutron facility. In their experimental work, the authors injected helium micro bubbles (average diameter 100 μm) into flowing mercury. Then, a low frequency (1 Hz) high amplitude (0.4 MPa) pressure wave was applied to the flow and its time evolution was measured and analyzed for a variety of different conditions. In their conclusions, the authors stated the potential of this technology for damage mitigation purposes and suggested a further approach to control it by acting on the spatial distribution of bubbles.

The work described in this article deals with an experimental study aiming to characterize low-frequency high-amplitude pressure wave attenuation in a fluid inside a cavity using heat transfer to a flat/micro-pin fin evaporator as the control parameter. The heat transfer causes the flow to boil and a continuous supply of bubbles is generated at the evaporator that interacts with the pressure waves. The study was performed under both pool boiling and flow boiling conditions, and scaling laws relating pressure wave mitigation to thermal power were generated. Regarding the organization of the article, the problem and the experimental setup are described first; then, results are presented and discussed and, finally, conclusions are given.

2. Description of the problem and experimental setup

The problem considered was that of low-frequency high-amplitude pressure wave attenuation inside a cavity in which boiling took place under controlled conditions. The cloud of bubbles generated at the evaporator modified the overall character of the carrier fluid from purely incompressible to semi-compressible and this fact changed wave behavior significantly. Different types of evaporators and different levels of supplied heat per unit time (power) were considered. The working fluid was HFE7100 and the experiments were performed under both pool and flow boiling conditions. Specifically, pressure attenuation in the cavity and in the inlet channel was measured as a function of the governing parameters of the problem.

To carry out the study, a dedicated experimental facility was designed, manufactured and assembled. The facility had primary and a secondary circuits, see Fig. 1 (flow motion is clockwise). The primary circuit contained: (a) a pulsating (reciprocating) pump controlled via a frequency variator, (b) the cavity where boiling took place, and (c) a reservoir. A flow meter was inserted in the line connecting the cavity to the reservoir. A junction was placed in the line connecting the pump to the cavity. The line issuing from this junction (the secondary circuit) ended up in the reservoir. This line had an insert with a valve, so acting on this valve allowed the flow to be diverted from the primary to the secondary circuits and vice versa. The practical effect was that the flow rate entering the cavity could be controlled. In the case of pool boiling, only a very small amount of fluid per unit time was allowed to enter the cavity to compensate for the fluid that was evaporating. The cavity was transparent to allow monitoring of the liquid surface level. In the case of flow boiling, different flow rates were allowed to enter the cavity which meant that different flow Reynolds numbers were considered. Since properties of the working fluid HFE7100 are temperature dependent, the reservoir was kept refrigerated so that the fluid temperature was constant in the line going from the reservoir to the pump. The cavity was instrumented with five thermocouples (TC1 to TC5 in Fig. 1) that measured fluid temperature, evaporator temperature, and external temperature of the cavity itself (needed to evaluate heat losses associated to natural convection). Another thermocouple was located inside the reservoir (TC7) and yet another one (TC6) in the line leading to the cavity. In addition to the continuous reading of the thermocouples, a contact surface Amprobe TPP2C thermometer was also used throughout the experiments to cross-check the temperature measurement of the external walls of the cavity and to ensure that no hot spots were present. Regarding pressure measurements, one pressure sensor was inserted in the cavity (PS in Fig. 1) and another one (PS) in the line leading to it (and after the junction that separated the primary and secondary circuits).

The cavity was manufactured out of methacrylate. Its dimensions (in mm) and front view are shown in Fig. 2. Depth of the cavity was 20 mm. Wall thickness was 15 mm. When full, it contained 46 cm^3 of HFE7100. Internal diameters of inlet and outlet lines were 4 mm and 12 mm respectively.

Three different evaporators were manufactured and tested in the cavity. Overall dimensions of the square-shaped evaporators, manufactured on Aluminum alloy, were 1 cm × 1 cm. The first evaporator was flat. The second one contained an array of 25 pin fins of cubic shape and individual size of 1000 μm × 1000 μm × 1000 μm.

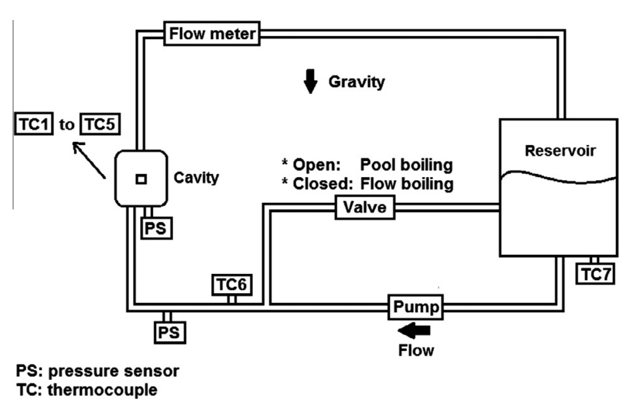

Fig. 1. Sketch of the experimental facility.