Pergamon

Int. Comm. Heat Mass Transfer, Vol. 23, No. 1, pp. 35–44, 1996

0735-1933/96 $12.00 + .00

0735-1933(95)00082-8

STATISTICS OF BOILING IN A CAPILLARY U-TUBE

Daniel R. Kabele, Mihir Sen and Patrick F. Dunn
Department of Aerospace and Mechanical Engineering
University of Notre Dame
Notre Dame, IN 46556

(Communicated by J.P. Hartnett and W.J. Minkowycz)

ABSTRACT

This is an experimental study of boiling in a capillary U-tube immersed in water with heating through an electrical wire at the center of the tube. Visual observation and study of video recordings formed the raw data for analysis. Average frequencies and power spectral densities of bubble emission were determined for different heat fluxes. The average frequency of bubble emission without regard to U-tube branch was found to increase with heat flux. However, the distribution of emission between the two branches was more complicated. At low heat fluxes one of the branches predominated and bubble emission from there was periodic; at intermediate heat fluxes both branches emitted at similar frequencies, largely in an alternate manner; at large fluxes the two branches seemed decoupled and the probability of emission from one branch being followed by the other was about one-half.

Introduction

Boiling is a heat transfer phenomenon that is very common to many thermal engineering systems and devices. In nucleate boiling, vaporization of the liquid occurs at a nucleation site on the boiling surface, from which the bubble detaches itself and ascends. Though nucleate boiling has been studied by many researchers and much is known about the process, many of its intricacies have yet to be understood. Part of the reason for this is the fluid mechanical complexity which accompanies bubble generation, making the boiling phenomenon hard to model. With better understanding of bubble generation, it is possible that more efficient boiling surfaces can be designed and incorporated into practical devices.

Nucleate boiling is an excellent example of random behavior in a heat transfer processes, as is obvious from watching a pot of water boil. What is less clear is whether the randomness is due to turbulence in the fluid bath provoked by the passage of bubbles, or whether bubble emission itself is random. On the one hand there appears to be experimental evidence that bubble emission could indeed be random in nature, while on the other mathematical and physical models developed as explanations of the process are on the basis of a periodic cycle of events. It is possible that this difference can be reconciled within the context of deterministic chaos [1], as other physical problems have been. In such a case randomness would be a manifestation of chaos in a low-dimensional dynamical system representative of the process.

Studies of periodicity and frequency of bubble emission have been carried out by Paul and Abdel-Khalik [2]. They found that nucleation site density along a platinum wire increases linearly as the heat flux increases. The average bubble departure frequency per nucleation site as a function of boiling heat flux minus the onset of boiling heat flux for water boiling on a platinum wire increases linearly. Nishikawa and Fujita [3] also did a study on nucleate boiling in narrow spaces by observing the boiling behavior within a vertical narrow annulus between an inner copper heater and an outer glass wall.

Initial inspiration for the present series of experiments was provided by the work of Shaw [4] and Martien et al. [5], who observed the dripping patterns of a leaky water faucet and found evidence of deterministic chaos. A periodic dripping pattern gave way to more complicated behavior as the flow rate was increased, ultimately reaching a chaotic state. With this in mind, one can also wonder if bubble emission during boiling from a single nucleation site behaves similarly, even though there are considerable differences in the physics of the two problems. Experiments related to this were carried out by Acharya and Sen [6] for a vertical capillary tube open at the top and closed at the bottom. Bifurcations corresponding to changes from periodic emission of constant size bubbles to cyclic emission of bubbles of different sizes were observed as the heat flux was increased. Transitions from periodic to a two- and then three-period state were observed by using one-dimensional return maps of the time interval between successive bubble emission events. It was also found that the average frequency of bubble emission increased with applied heat flux, including a linear relation in the initial stages. Those experiments, however, were with a single nucleation site and did not address the question of interaction between adjacent nucleation sites, something which occurs naturally in most practical cases of nucleate boiling. It is important to understand the problem of interaction, but in a well-controlled geometry.

Some experiments with capillary U-tubes were performed by Adams et al. [7]. They found evidence of strong interaction between boiling from each branch. There was considerable fluid motion within the U-tube, often oscillating back and forth between the two branches of the tube.

The experiments reported here were carried out with a capillary U-tube, each branch of which served as a nucleation site. While the ultimate goal is to obtain better understanding of nucleate boiling, the present mission was devoted to periodicity and randomness of bubble emission in isolation from the fluid mechanics of the boiling pool. Another aspect of interest was the nature of boiling in a confined space, something that is also common in applications in which only a few nucleation sites exist with considerable interaction between them. Through the study of bubble emission patterns, it is hoped that a basic understanding of the stochastic nature of boiling will be achieved.

Experimental Set-Up

A schematic of the test apparatus is shown in Fig. 1. The capillary U-tube was of glass with inside and outside diameters of 1.52 mm and 2.79 mm respectively. The U-tube had a height of 38.1 mm and the centers of the openings were separated by 9.53 mm. It was totally immersed in a distilled hot water bath kept at approximately 98°C. All experiments were run only after degassing the water by boiling it for 45 minutes. There was an electrical heating wire of nichrome through the center of the tube. Current was supplied to the wire by a variable DC power source and measured by a Beckman Tech 360 ammeter. The resistance of the wire was known from which the power supplied to the wire, Q, could be determined.

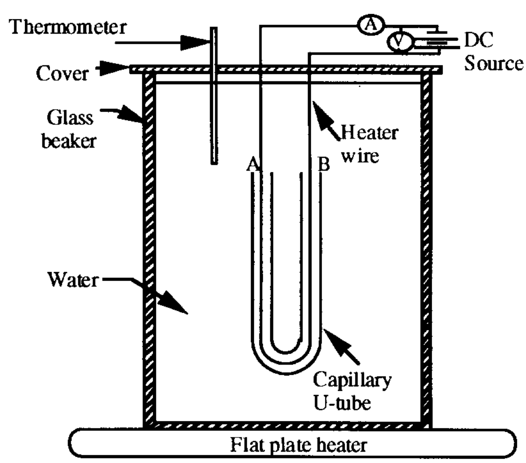

FIG. 1
Schematic of Set-Up

The set-up was similar to that used by Adams et al. [7]. They were, however, unable to distinguish between emission from the two branches of their U-tube due to the fact that the openings were too close together (3.75 mm). The openings in the present experiment were farther apart.

Observations were made at six different heat fluxes to the electrical wire: Q = 2.51, 3.05, 3.75, 4.12, 5.54, and 7.06 W. For each heat flux, approximately 2 minutes of videotape at 30 frames a second were shot of bubble emission. Using a video-editor, each frame of the videotape was analyzed and the instants at which a bubble was released from either the left or the right branch of the tube was recorded.

Results

Figure 2 are typical data for three heat fluxes, where the small circles are positioned at the frame number at which a bubble was observed to leave one of the branches. At 2.51 W only the right branch is bubbling, while both branches exhibit activity for the higher values of heat flux. At 3.75 W the events can be seen to roughly alternate between the two branches. At 5.5 W bubble emission is randomly distributed, with perhaps somewhat more activity in the left branch. These observation can be quantified more precisely.

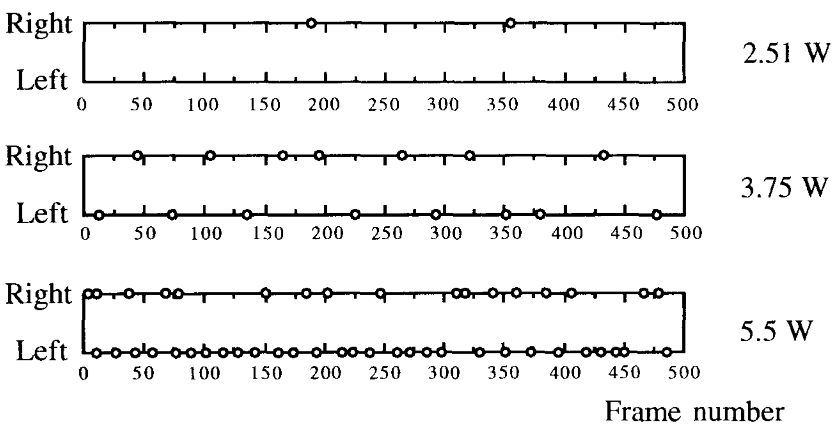

FIG. 2
Bubble Emission Observed on Videotape

Figure 3 shows the average frequency of bubble emission calculated by counting events over a period of time. The curves marked L and R correspond to boiling from the left and right branches respectively, while L+R refers to that from any branch. The L+R frequency is the sum of the L and the R frequencies. Initial boiling at low heat fluxes is only from the right branch so that the frequency of L is indicated as zero. In the intermediate range both L and R frequencies are similar. At higher heat fluxes there is no apparent pattern in the L and R curves.

There is a certain probability associated with the emission of a bubble from a given branch which depends to some extent on the history of events. With the given U-tube, each time boiling occurred within it, the vapor was forced to 'choose' to escape the tube by going out either the left branch, or the right branch. By observing hundreds of frames of videotape, some statistics were accumulated to form a type of "probabilistic map." In other words, if during the last emission, the bubble left through one branch, how likely was it that it would exit by the same branch the next time? How likely would it be for it to exit via the other branch? How does heat flux and rate of emission affect this behavior? Answers to these questions would help us understand to what extent the distribution of bubble emission between the two branches is random.

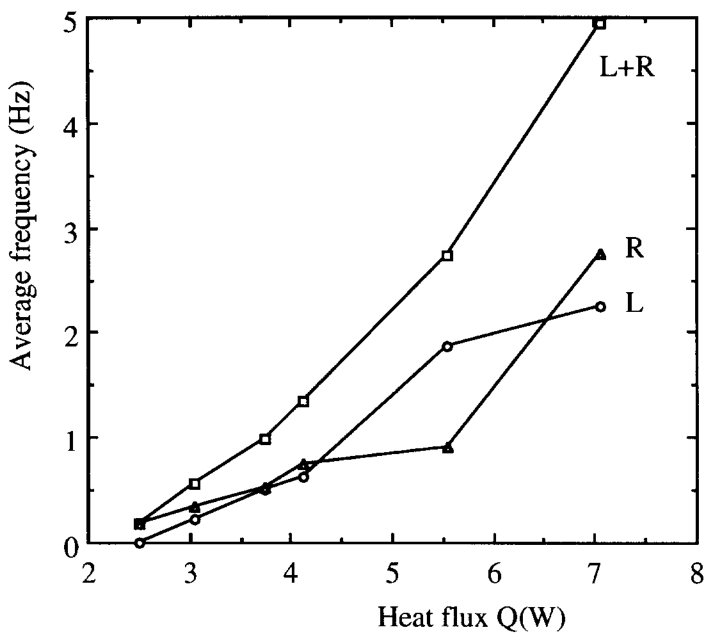

FIG. 3
Average Frequency

The results of such an analysis are shown in Fig. 4. This graph was constructed such that at any given heat flux, the percentage of bubbles which exited the right branch after the left (LR), the left branch after the right (RL), the right branch after the right (RR), and the left branch after the left (LL) can be seen. Starting at low heat flux, bubble emission took place entirely out the right branch, as indicated by RR spanning the entire height of the graph. But as the heat flux was increased to moderate levels, the alternating pattern became dominant; over 80% of the bubbles emitted exited the side opposite to which they last exited (RL and LR). This is why the L and R frequencies in the corresponding part of Fig. 2 are similar. For a high heat flux the four patterns had roughly the same probability. At this stage we have a random behavior of bubble emission in terms of its distribution between the two branches.

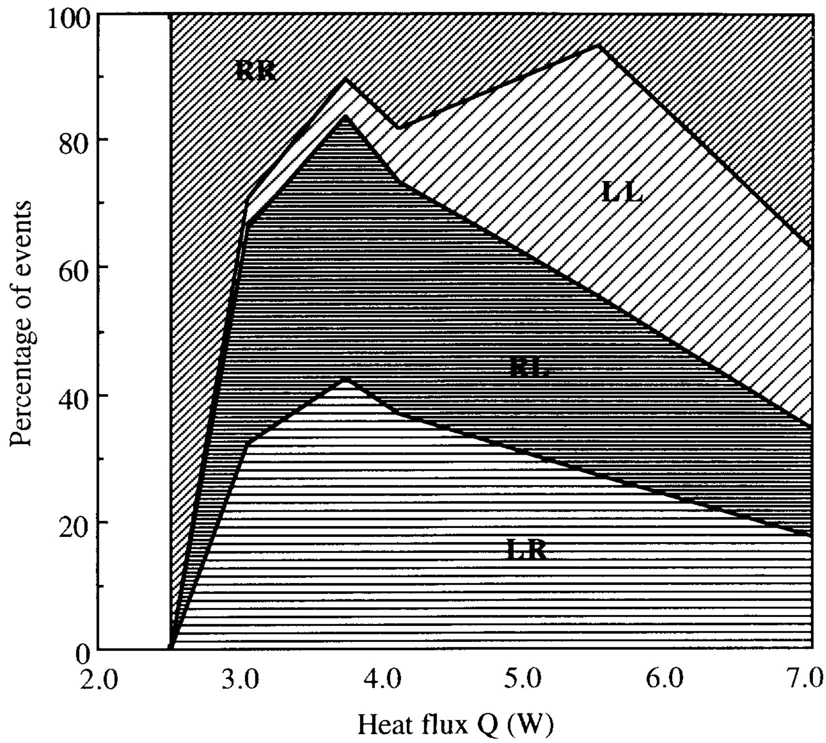

FIG. 4
Probability of Bubble Emission

Power Spectral Densities

From the video data two signals, $x_L(t)$ and $x_R(t)$, were created corresponding to the left and right branches, each with a series of pulses of width equal to the time interval between frames (1/30 s), and centered at the instants of bubble emission. Another composite signal $x_{L+R}(t)$ was also constructed in which there was a pulse for every emission of a bubble, regardless of which branch it came from.

A Fourier transform defined as

$$F_j(f) = \int_{-\infty}^{\infty} x_j(t) e^{-i2\pi ft} dt$$

where j = L, R, and L+R, was calculated for each one of the signals. The power spectral density is then simply

$$PSD = |F_j(f)|^2$$

The PSD is normalized by its maximum so that its numerical value is not as significant as the frequency distribution.

At a low heat flux bubble emission is only from one side, but is very periodic. The PSD for such a case is shown in Fig. 5. The peaks are harmonics of the fundamental resulting from the square wave nature of the pulses. Each peak is quite narrow. At intermediate heat fluxes, both branches come into play, mostly in an alternating manner. Bubbling from each branch is more or less periodic with similar periods, as shown for a representative heat flux in Figs. 6(a) and 6(b). The overall effect of bubbling from both branches, indicated in Fig. 6(c), is also one of periodicity, though at double the frequency of each branch. The harmonics are again multiples of the fundamental, the average frequency corresponding to Fig. 6(c) being 0.988 Hz. The width of each peak in the spectrum is an indication of some aperiodicity present. Figures 7(a),(b) and (c) show the spectra of bubbling from the left, right, and both branches, respectively, for a higher heat flux. The average frequency for both branches is 2.725 Hz; that of the left and right branches are considerably different, being 0.901 and 1.869 Hz respectively. The spectrum is much broader indicating that bubble emission is less periodic and much more random.

Discussion and Conclusions

It appears that boiling is dominated by natural convection at low heat fluxes. There is flow of cooler water down one branch, boiling taking place in the lower end of the U-tube, and the hot vapor being pushed out the other branch. This pattern, however, begins to change for intermediate heat fluxes when bubble emission begins to alternate. By visual observation, it seemed as if there were a certain volume of very hot water at the bottom of the tube which swung back and forth, allowing cooler water to reach the bottom of the tube from one side while boiling out the other, then swinging the other way and releasing a bubble out the opposite side. Finally, as the heat flux became high, bubble emission was very frequent. As one bubble was formed at the bottom of the tube, it was pushed both by the pressure of the bubble already exiting out of one of the branches, and by the pressure of the incoming water through the other branch, causing a more random and unpredictable bubble emission pattern.

Thus, overall bubble emission frequency is quite predictable in its behavior. Its distribution, however, between the two branches is not; it is absent at low heat fluxes, regular at intermediate values, and irregular at high fluxes.

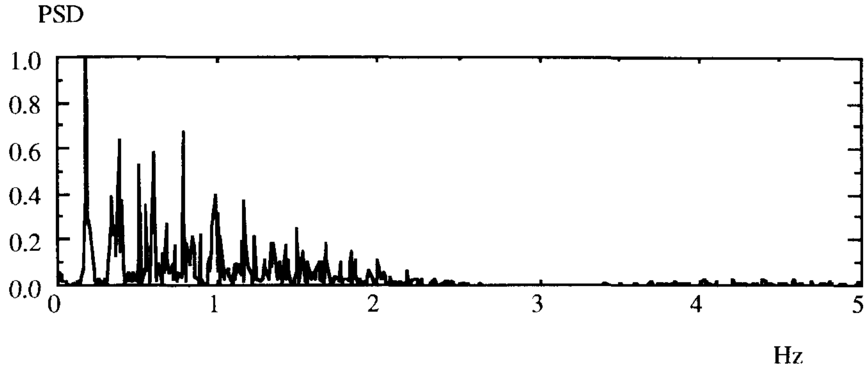

FIG. 5
Power Spectral Density for Bubble Emission in Right Branch at Q = 2.51 W

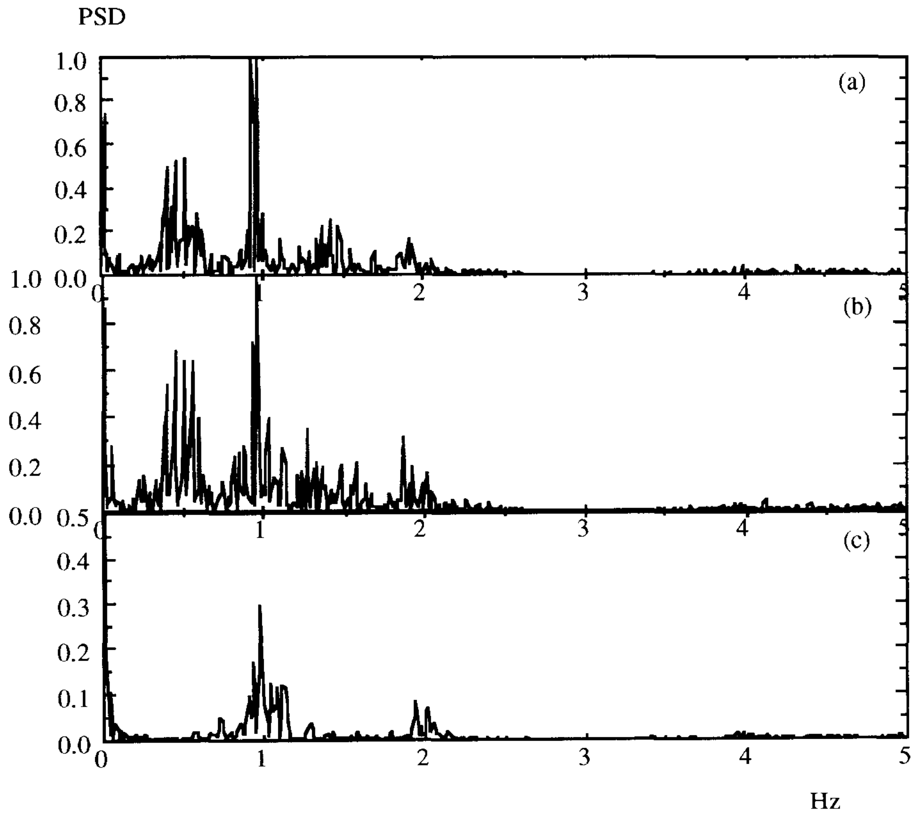

FIG. 6
Power Spectral Density for Bubble Emission at Q = 3.75 in
(a) left branch, (b) right branch, and (c) both branches

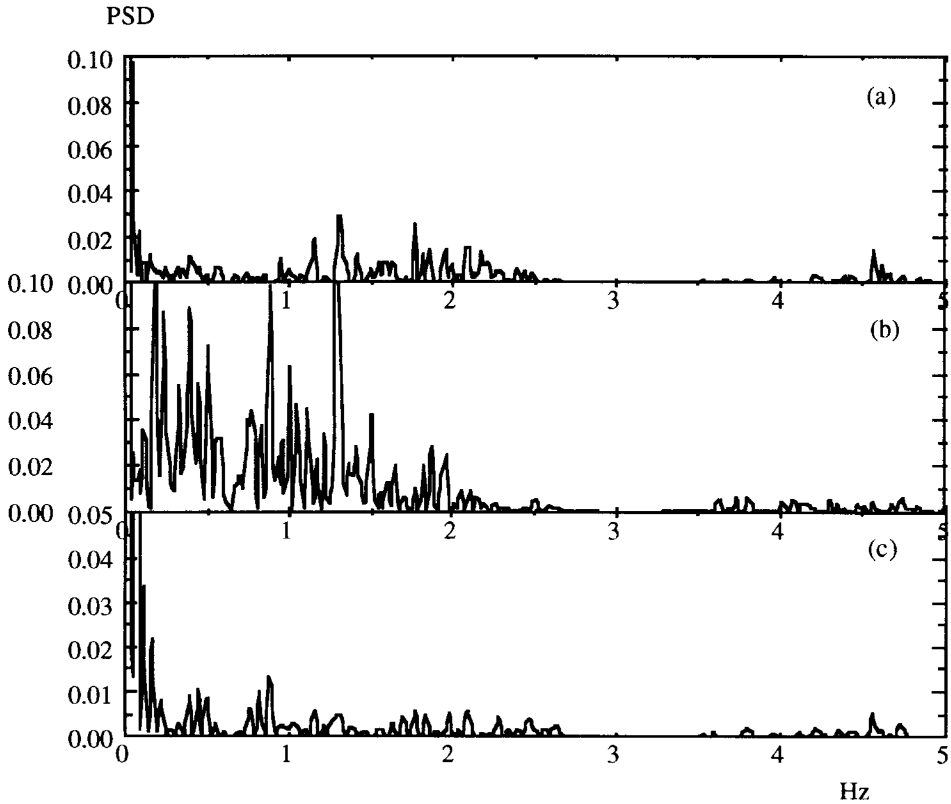

FIG. 7
Power Spectral Density for Bubble Emission at Q = 5.5 W in
(a) left branch, (b) right branch, and (c) both branches

Acknowledgment

The authors acknowledge partial support from NSF through Grants 1420-14795 and INT 90-01983 for this project.

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Received June 12, 1995