Study of the Vapor Bubble on an Inkjet Printhead Heater Surface

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Abstract

The optical reflectance of an open pool inkjet printhead heater surface has been determined to provide unique information on the evolution of the bubble. This transient reflectance probing technique can produce accurately nucleation energy threshold, bubble lifetime, collapse time and others. With suitable calibrations, it can also produce the time-dependent temperature at the heater liquid interface up to the onset of nucleation.

Introduction

The nucleation of ink to form a vapor bubble is of fundamental importance in thermal inkjet technology. For effective and repetitive ejection of ink, the nucleation must result in a stable, dominant bubble. Important considerations of the thermodynamics of ink and its nucleation have been discussed by Allen, et al.[1] and Asai[2]. Parameters which are key to bubble formation for the ejection of a thermal inkjet are degrees of superheat, heating rate, surface roughness, liquid properties, etc. Superheating a liquid can convert it into high pressure vapor phase. A high heating rate maintains the reproducibility of nucleation. A smooth heater surface minimizes the number of nucleation sites which can cause early nucleation and therefore reduce superheat. Finally, fluid properties dictate nucleation. Thus these parameters jointly affect the performance of the inkjet. It is known that the superheat limit for a typical water-based ink is about 330°C. The degree of superheat for ink should be as close to this limit as possible in order to assure good ejection.

Two techniques are commonly used in the study of the evolution of the bubble in thermal inkjet printing technology. The first makes use of a piezoelectric transducer to capture the signals caused by bubble nucleation and collapse. The second takes advantage of a stroboscope for high speed bubble visualization. Bubble parameters such as formation, collapse, morphology, etc. can be determined. However, there are other parameters very much time dependent and important to bubble thermodynamics which may not be readily quantified with these techniques. An example is the onset of nucleation. At the heater-ink interface, the rate of temperature increase during superheating is of the order of 100°C per microsecond. If the resolution of the experiment is 0.1 μs, errors can be as high as 10°C which is more than 1.0 MN/m^2 in the initial vapor pressure. Such a high amount of energy density can be important to the performance of the inkjet.

In a recent study by Yavas, et al.[3] of the nucleation of a liquid at a pulsed-laser-heated solid interface, the optical reflectance transients were used for the determination of the threshold fluence for a variety of liquids. With a 16 ns wider laser pulse, they were able to deduce the initial formation of a layer of submicron sized bubbles, their growth and collapse. The thermal conditions at the heater-ink interface are different from a pulsed laser heated surface since the heating rate of the former is much slower. However, their probing technique is particularly useful for the study of nucleation on a smooth opaque surface such as the inkjet heater.

This paper reports some results in the nucleation of a liquid on a thermal inkjet printhead heater from measurements of the reflectance of the heater surface in an open pool arrangement. It will show that the evolution of the bubble can be captured with high temporal resolution. The experiment also included the effect of liquid temperature on nucleation. The optics of a multifilm structure such as in a thermal inkjet heater is discussed to explore the potentiality of extending the technique for the determination of the thermal nucleation threshold.

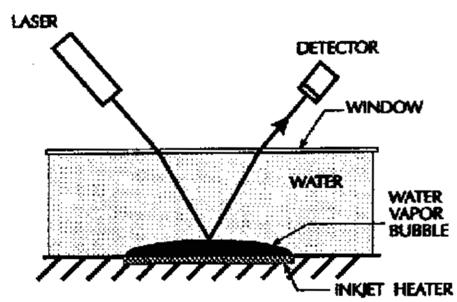

Figure 1. Schematic of the printhead heater reflectance probe.

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Experiment

The experiment consists of measuring the reflectance of a heater structure of an open pool thermal inkjet printhead. Water was used as the medium. A prototype printhead, specially fabricated without the nozzle plate, was mounted inside a small chamber fitted with a glass window. The thick film ink barrier was left intact around the heater. The principal dimension of the heater was about 50 µm. A HeNe laser (0.633 µm wavelength) and associated optics provided an angle of incidence of 10° and a 20 µm diameter waist at the heater surface. The optical arrangement is as shown in Figure 1. The intensity of the reflected beam was measured with a silicon PIN diode and recorded with a 500 MHz digital oscilloscope as a 2 µs wide electrical pulse was supplied to the heater. The entire printhead except for the electrical connection was immersed in water. Measurements were taken at nominal liquid temperatures of 22°C, 32°C and 42°C. Higher liquid temperatures caused damage to the printhead and therefore data are not available. The water was recirculated with a peristaltic pump through a heat exchanger maintained at constant temperature. Whenever measurements were taken, the pump was turned off momentarily to stop large bubbles from traversing the optical beams. Since each measurement took only a few seconds, there was not enough time for appreciable thermal stratification of the water near the heater surface. The walls of the chamber were insulated to minimize thermal losses.

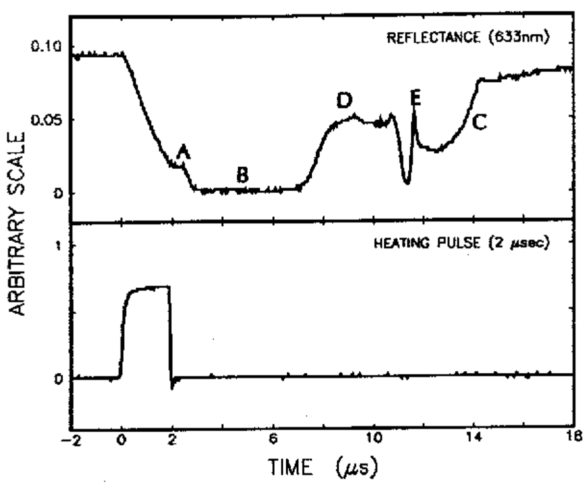


Figure 2. Typical transient reflectance signal from a printhead heater as it undergoes the nucleation cycle

Results and Discussion

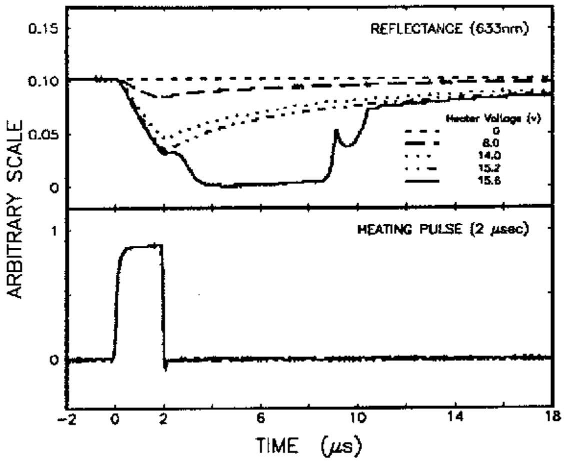
The transient reflectance from a single firing of the heater produces a very well defined scenario of nucleation. An example is shown in Figure 2. At time zero when the 2 µs electrical pulse arrives, the reflectance decreases monotonically as the solid surface is heated. The effect of temperature-dependent reflectance change will be discussed later. Near the negative edge of the pulse, labeled A in the figure, the reflectance decreases at a faster rate as nucleation begins. The reflectance is generally zero when the laser illuminated surface is covered by bubbles, denoted at B in the figure. Two effects cause this to happen. The first is that the reflectance at the bubble surface is only 2%. However, the nonplanar bubble surface also defocuses the reflected beam so that the effective reflectance is reduced. The second is that rays reemerging from the bubble are also defocused.

The reflectance signal recovers from a small value as the bubble collapses. This occurs at C in the figure. At this point the bubble size is rapidly decreasing until the entire surface is free of nucleation. There are occasions in which the reflectance does not remain zero between the conditions B and C. This appears at D in the figure. It is believed to be due to an unstable bubble which oscillates on the heater surface and momentarily allows more light to be reflected back to the photodetector. Another event that can occur is the presence of a reflectance peak such as at E in the figure shortly before bubble collapse. This is due to the formation of a secondary bubble immediately following bubble collapse. Presence of undissolved gases can be a cause.[1] The occurrence of this secondary bubble can also produce a spurious ejection of low velocity ink which degrades print quality. This secondary bubble eventually collapses as the reflectance gradually returns to its initial value before heating.

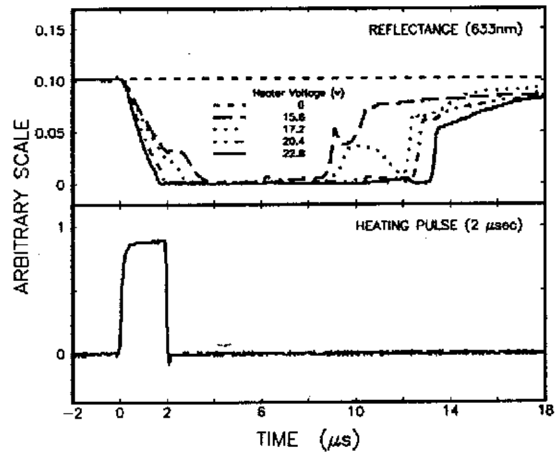
The reflectance measurements provide several key parameters for the interpretation of the performance of the printhead. They are discussed as follows.

Onset of Nucleation

The reflectance transients at several heater voltages are shown in Figure 3. At low voltages at which nucleation is absent, reflectance decreases as the heater is heated. As soon as the heating pulse is terminated, cooling begins and the reflectance increases until it reaches the initial unheated value. As the voltage is increased to above a certain value, nucleation appears. This is shown in Figure 3a at 15.6 v. This is the minimum voltage for a 2 µs wide pulse to sustain repetitive nucleation for this printhead. At these conditions, the reflectance is seen to bulge at the end of the heating pulse and increase slightly before decreasing to zero when the probe area is bubble filled. The reflectance increase suggests that cooling has taken place and the heater is not fully covered by nuclei. Thus nucleation is very much localized near threshold conditions. These nucleation regions expand rapidly, perhaps from homogeneous nucleation of the superheated liquid, until nucleation is complete on the entire surface. As the voltage increases, the bulge due to reflectance increase disappears as shown is Figure 3b. At the edge of the reflectance profile where it decreases during heating, the reflectance decrease shows two distinct slopes. The more moderate negative slope corresponds to the initial heating without nucleation and the steeper negative slope when nucleation takes place. The point where the two reflectance slopes merge, i.e., Point A in Figure 2, is the onset of nucleation. This onset advances to earlier time as the

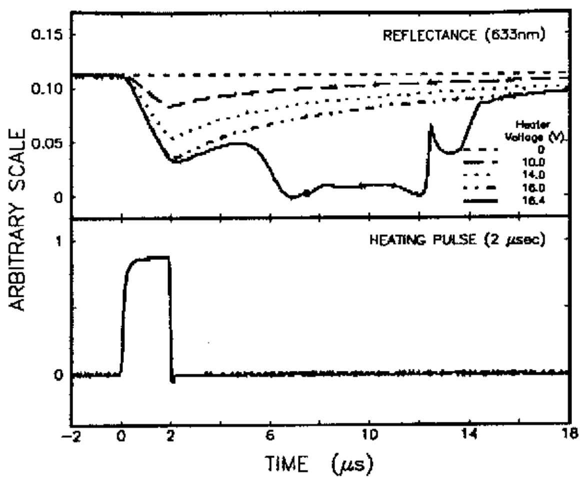


(a) 22°C water

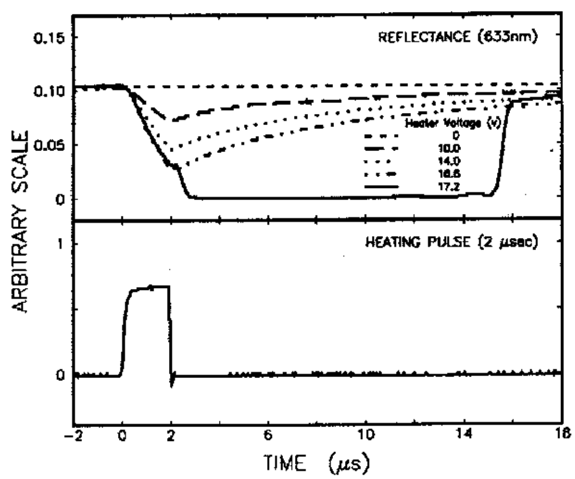


(b) 22°C water

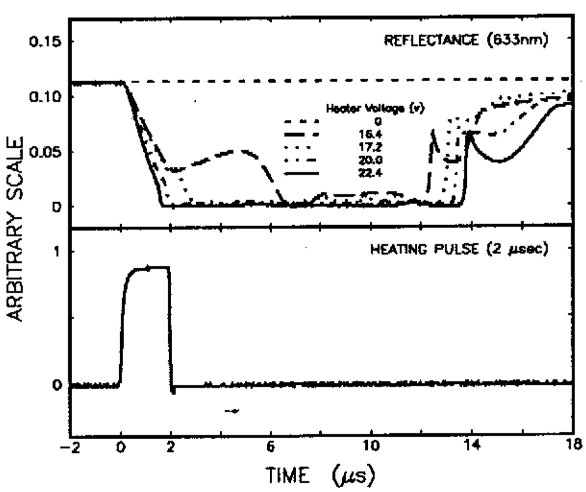
Figure 3. Reflectance of the printhead heater



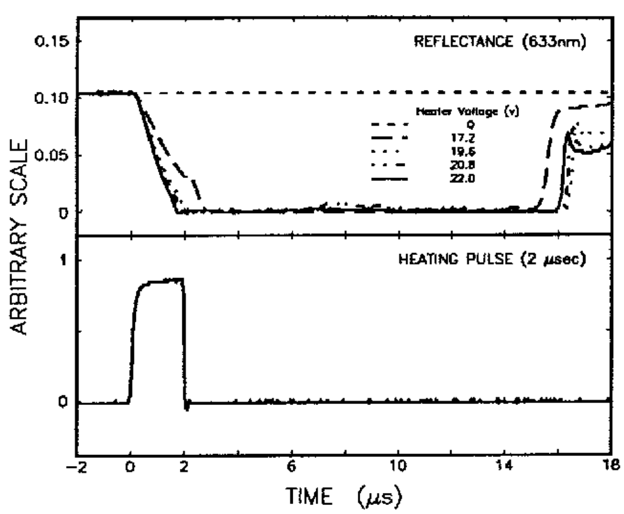
(a) 32°C water



(c) 42°C water



(b) 32°C water



(d) 42°C water

Figure 4. Reflectance of the printhead heater at different water temperatures

voltage increases. This is interesting because it shows that as the heating rate increases, the onset of nucleation can occur before the termination of the heating pulse. When nucleation is complete on the heater surface, a vapor layer appearing on the heater impedes heat transfer. Further heating beyond this point is dissipated mainly by conduction through the solid components in the printhead. Thus electrical energy arriving after nucleation is complete will increase the temperature of the printhead. The reflectance probe therefore can be used to interpret the relationship between heating pulse height, width and nucleation onset.

Bubble Lifetime

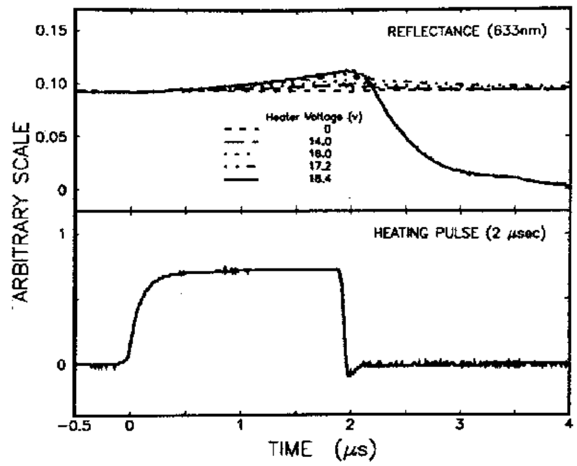
The bubble lifetime can be determined from the reflectance measurements. If the bubble collapse is considered complete when the reflectance recovers to 0.75 of its initial value, then the typical lifetime for this printhead is about 11 μs, depending on the voltage applied to the heater. A higher voltage tends to lengthen the bubble lifetime as seen in Figure 3b. The reflectance does not assume its initial value quickly until the heater cools to its steady state temperature.

Heated Water

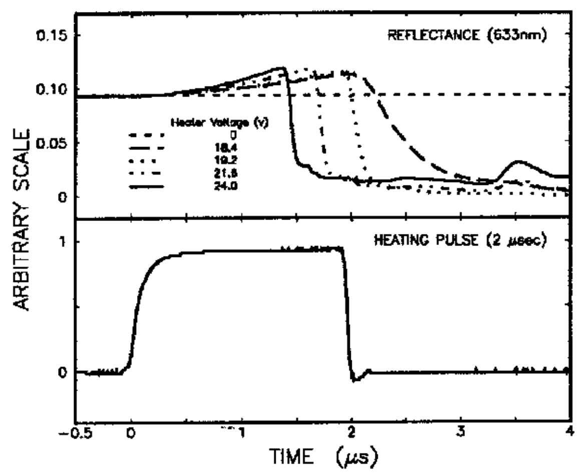
The reflectance measurements at elevated water temperatures are shown in Figure 4. They appear similar to the reflectance in Figure 3 taken at 22°C. However, there are three main differences. First, as water temperature increases, bubble collapse is delayed. Taking as the reference condition when the onset of nucleation occurs at the end of the heating pulse, bubble collapse appears at 10.5 μs, 12.2 μs and 14.0 μs for water temperatures 22°C, 32°C and 42°C respectively, as shown in Figures 3b, 4b and 4d. Thus as the water temperature is increased, it takes longer for the liquid to cool down to the point that the vapor can begin to condense. Second, the secondary bubble, while remaining conspicuous at 22°C and 32°C, was not observed at or near the threshold conditions at 42°C except at high voltages, though these conditions are not shown in Figure 4d. The reason is unclear. However, this can be a benefit in minimizing the effects of the secondary bubble in printhead design. Third, the nucleation thresholds can be seen in Figures 3a, 4a and 4c to be 15.6v, 16.4v and 17.2v at 22°C, 32°C and 42°C respectively. Intuitively, the voltage threshold should decrease with water temperature since less energy is required to produce the superheat. The present observation is opposite to this. It may be due to the decrease of gaseous nuclei in the water as its temperature goes up (the solubility of gases in water increases as temperature rises). However, additional study is required to confirm this speculation.

Temperature Threshold for Nucleation

A potentially important application of the reflectance probing technique is in the determination of the temperature threshold for nucleation. Since the degree of superheat is important for ejection of ink, it would be very useful to measure such a quantity. However, there has been no publication on the measurements of the time-dependent temperature at the heater/ink interface. This parameter is usually obtained from empirical values or computational techniques. It can be seen from the above data that the reflectance of the heater is related to its temperature. In particular, when the heating pulse is active, reflectance decreases up to the termination of the pulse if there is no nucleation and increases thereafter. When there is nucleation, the reflectance increases towards its unheated value only after the bubble has collapsed.



(a)



(b)

Figure 5. Reflectance of a printhead heater which shows increasing temperature produces increasing reflectance

The reflectance changes when the heating pulse is present depend on the heater material and the multifilm structure. Thus these changes are very much device dependent. This is shown in Figure 5 with the reflectance measurements from another printhead of similar heater design which show that the reflectance actually increases as the heater temperature increases. This effect is completely opposite to previous data but can be easily understood from the optical properties of multiple thin films. A simple example can explain this effect. Figure 6 shows the computed reflectance of a silicon substrate coated with a SiC film, a material commonly found in an inkjet heater. A temperature increase is simulated with an increase in the extinction coefficient of the SiC layer. It can be seen that the reflectance of the surface can increase, stay constant or decrease as the extinction coefficient increases, i.e., temperature increases, depending on the SiC thickness. In reality, the actual reflectance changes depend on all the films in the heater structure, their thermal properties and thicknesses. Nevertheless, this example serves to illustrate the variations on reflectance with temperature-dependent changes on the extinction coefficient of a thin film. In the present study with several printheads, all three types of reflectance changes with temperature have been observed. Small changes in the thickness of the SiC layer appear to affect the heater reflectance properties the most. The above discussion assumes that the probe wavelength is 0.633 μm. It should be noted that the reflectance properties are also very much wavelength dependent.

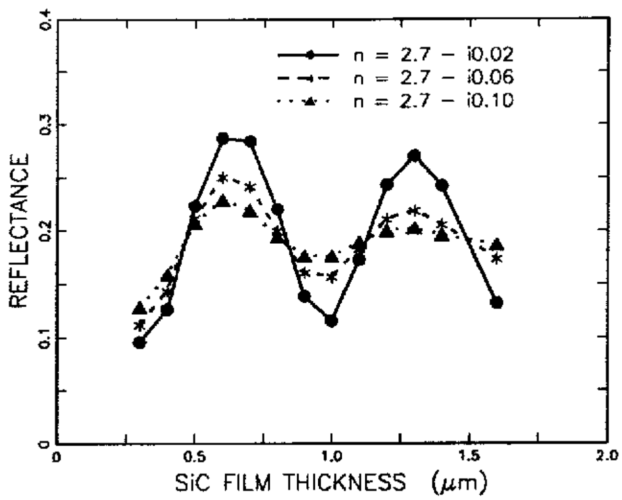


Figure 6. Computed reflectance of silicon coated with a SiC film at 0.633 μm wavelength, n is the refractive index of SiC

The application of a thin film for transient temperature determination during the nucleation of a liquid film has been reported by Leung, et al.[4] from the transmission properties of the thin film. The nucleation surface has to be specially treated for their carefully controlled experiment. The present probing technique requires no such surface modifications although the test printhead may have to be specially selected for the most favorable properties between temperature and reflectance.

For the determination of the temperature threshold, it is advantageous to select a printhead which has increasing reflectance with increasing temperature. As shown in Figure 5, the onset of nucleation is much easier to identify for such a case. For example, the threshold can be defined as the point of zero reflectance gradient with time. In this respect, the present probing technique can determine its occurrence to 0.1 μs or less. Beyond this point the reflectance decreases abruptly as bubbles grow on the heater surface. This reflectance decrease also can be seen to become steeper as the heating rate increases, suggesting that the nucleation rate also increases with heating rate. Although the actual demonstration of the determination of the temperature threshold is not included here, it is not difficult to visualize that it can be done, albeit in a destructive way. This requires the heater structure heated to a steady state temperature, usually in excess of the softening temperature of most plastic parts in the printhead.

Conclusions

The optical reflectance of the heater in an inkjet printhead has been used for the determination of the energy threshold for nucleation, bubble lifetime, bubble collapse and secondary bubble generation. These parameters are useful for the design of the printhead. The technique can be extended for the determination of the temperature threshold for nucleation, a parameter which remains difficult to quantify in thermal inkjet technology.

Acknowledgments

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