Drop Generation Processes in TIJ Printheads

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Abstract

Transparent channel printheads have been used to study the process physics and channel fluid dynamics of thermal ink jet drop generation. All phases of drop generation have been observed and recorded on video tape. The spatial and temporal parameters of the various drop generation phases have been measured and have been found to be in good quantitative agreement with 3D fluid flow calculations. This study has produced a number of insights into the process physics of vapor bubble nucleation and drop ejection. In addition, mechanisms responsible for the disruption of channel refill and the drop ejection process have been identified.

Background

Thermal ink jet operates by the application of a short electrical pulse to a heater which heats a thin layer of ink at the heater surface. During heating, the ink in contact with the heater surface superheats and a vapor bubble is nucleated. The nucleation of the vapor bubble is dependent on the heater surface, the ink composition, as well as on the form of the thermal input. As the vapor bubble grows it transmits momentum to the surrounding fluid and ejects ink out the channel nozzle in the form of well defined drops. After the completion of the heating pulse the vapor bubble collapses and ink refills the channel from the ink reservoir.

TIJ channel ingestion has been defined as a situation in which air penetrates into the channel to cover all, or a portion of, the heater, and consequently prevents full vapor bubble generation and effective drop ejection. Channel ingestion results in erratic drop behavior (channel dropout). Two variants of ingestion have been assumed to be the source of most channel dropout, particularly at higher temperature and frequencies. The first involves the generation of a vapor bubble large enough to fill the front channel and break to the outside air. The second type of ingestion involves the retracting meniscus penetrating into the heater pit, resulting in trapped outside air. If the trapped air becomes large enough to fill the pit it would then cause dropout.

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The Xerox thermal ink jet printhead utilizes a print element fabricated via VLSI technology, while the channels and ink inlet are formed in silicon by oriented-dependent etching (ODE).[1] The heater substrate is covered by a polyimide layer in which etched pits are provided for the heater and structures in the channel plate[2] as shown in Figures 1 and 2. In order to study the process physics of vapor bubble formation and drop ejection, thermal jet printheads were fabricated in which the silicon channel plate was replaced with a quartz channel plate having thick polyimide film channels and a by-pass plug imaged on the plate. The channel dimensions of this structure are comparable to those of the regular 300 spi Xerox thermal ink jet printhead and were designed to give the same drop characteristics as the regular TIJ printhead.

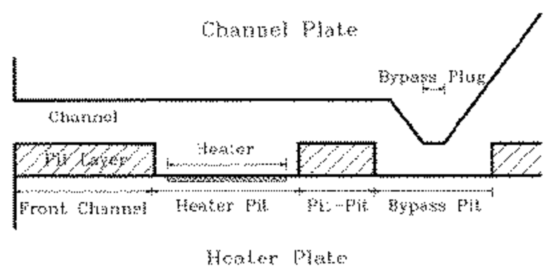

Figure 1. Cross Section of Channel

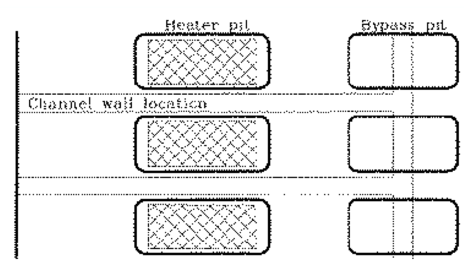

Figure 2. Top View of Pit Layer

Experimental

The transparent channel printheads were operated using an in-house test unit that provided the drive signals for the printheads, and controlled an x-y positioning system. The computer-controlled test unit has a sensor that detects the drops at a known distance from the nozzle and collects all the drop characterization data. The temperature of the printhead is controlled at a constant value in the range from 15 to 70°C. Observations of drop generation dynamics in and around the channels were made with flash lamp or LED strobe illumination. The various phases of vapor bubble growth/collapse, drop ejection, meniscus movement, and channel refill were measured and the process recorded on video. These processes were studied as a function of pulse width, pulse voltage, frequency, and temperature. A dyeless water-based ink containing 20% 1,2-ethanediol and 3.5% 2-propanol was used for all the tests. The frequency range was 0.1 to 6 kHz, the firing pulse widths used were 2 and 3 µsec and the firing voltage was 10% above the threshold voltage.

Experimental work on the thermal ink jet technology was complemented with numerical modeling studies. The fluid flow calculations are carried out using a commercially available code called FLOW3D from Flow Science, Los Alamos, New Mexico. The 3D fluid flow analysis code is coupled with a 1D thermal code to describe the nucleation and bubble dynamics process. It is assumed that the nucleation takes place when the ink-heater interface reaches a temperature of 280°C. The temperature inside the bubble is assumed to be uniform and the gas pressure is calculated from the Clasius-Clapeyron equation. The fluid flow calculations were based on the geometry of the transparent channel printhead described above with a heater pulse of 3 msec and an ambient temperature of 25°C.

Results and Discussion

Channel Fluid Dynamics

A series of transparent channel printhead tests was run in order to measure the spatial and temporal parameters of the vapor bubble formation and drop ejection process. The results of these measurements were compared to those of the 3D fluid code modeling. The initial stages of nucleation occur with the formation of localized micro-bubbles, occurring in less than <50 ns, on the heater surface. Observation and measurement of the initial stages of vapor bubble nucleation using a high speed (nanosecond) stroboscopic system will be the subject of a future paper. Uniform vapor bubble nucleation began at 2 µsec after the start of the 3 µsec firing pulse. As the vapor bubble grows with time, a drop emerges from the nozzle of the channel and a meniscus (air and ink interface) is observed to form in the channels shown in Figure 3. Full vapor bubble extension occurred at 15 µsec and the vapor bubble was observed to extend slightly out of the heater pit in the nozzle direction. Final vapor bubble collapse occurred at 39 µsec toward the rear of the heater. At this point the meniscus has reached and entered the heater pit. Due to the meniscus penetration in the pit, some small air bubbles are trapped in the pit, however they are ejected with the ink drop on the next heating pulse without any observable effects on drop characteristics. At 3 to 4 µsec after the vapor bubble collapse, a secondary fluid streamer drop is found to emerge from the nozzle along with the main drop. The fluid streamer drop can be explained to be the result of the interaction of the retreating meniscus with a shock wave generated by the collapsing vapor bubble. Finally the channel refills completely to the nozzle opening in 200 µsec for the 3 µsec pulse.

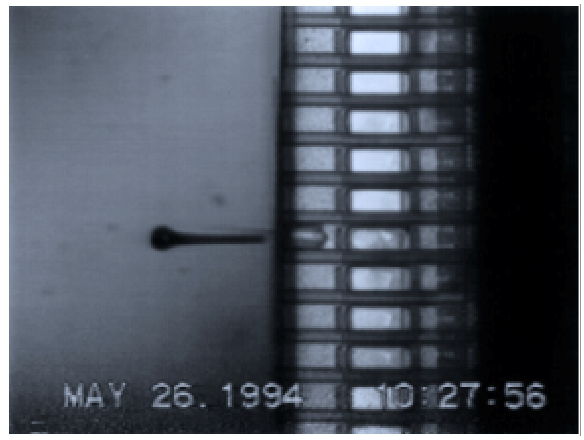

Figure 3. Micrograph of Emerging Main Drop and Streamer Drop

These drop generation processes observed in the transparent channel printhead are in very good agreement with 3D fluid flow calculations based on similar channel geometry. The cross section through the center of the channel (Figure 4), shows the shape of the vapor bubble 5 µsec after nucleation and the emergence of the drop. Figure 5 shows the fully grown vapor bubble at 15 µsec with the vapor bubble out of the pit on the nozzle side of the pit. Figure 6 shows the meniscus position after the vapor bubble has collapsed at 50 µsec. Figure 7 shows the cross sectional view as seen from the top of the transparent channel plate. At 6 µsec after the final vapor bubble collapse, a secondary fluid stream drop emerged from the meniscus as a result of a shock wave generated by the collapsing vapor bubble. As discussed above all of the calculated features are clearly seen in the transparent channel printhead setup. The calculated drop volume, drop velocity, and timing of various events are in close agreement with the experimental observations.

Ingestion and Channel Dropout

At higher temperatures (65°C) and frequencies (4.5 kHz), the vapor bubble extended 90-95% of the front channel, while the meniscus retracted to the middle of the heater pit without outside air entrapment, channel dropout, or degradation of drop properties. It is assumed that at high enough temperatures the vapor bubble will be large enough to break to the outside air, but this has not been observed yet. Again at these high temperatures the retraction of the meniscus into the pit does result in the entrapment of some small air bubbles. These are ejected with the ink drop with the next heating pulse without any discernible effects on drop quality. If a particular channel shows refill difficulties then the meniscus retraction becomes larger and can result in a very

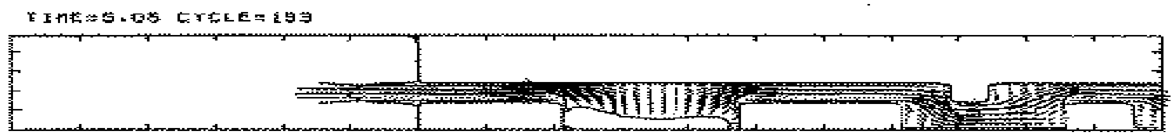

Figure 4. Channel Cross Section Showing Vapor bubble Expansion

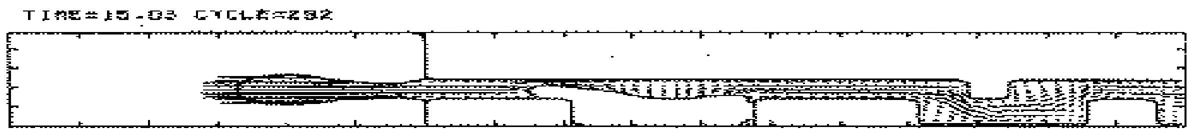

Figure 5. Channel Cross Section Showing Full Vapor Bubble Expansion

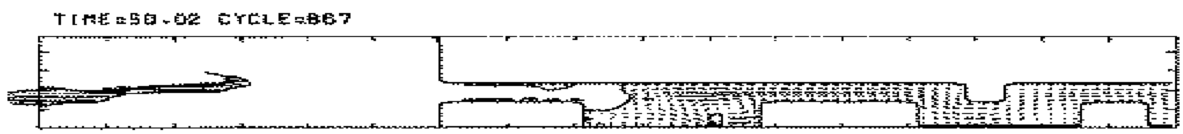

Figure 6. Channel Cross Section Showing Meniscus Position at Vapor Bubble Collapse

Figure 7. Top Channel View Showing Fluid Streamer Generation at Meniscus

large trapped air bubble. Channel refill obstructions at the rear region of the channel (rear entrance or bypass pit), such as debris or a large air bubble, have been observed to result in a vapor bubble-meniscus interaction. Both of these channel obstructions have been seen to result in channel dropout. Ingestion dropout is usually self-regenerating requiring 10-100 pulses to recover, although large trapped air bubbles can cause permanent channel dropout. Some rear channel restrictions of refill cause a series of slow, sputtering, severely misdirected drops but no actual dropout.

Under regular operating conditions the transparent channel printhead drop ejection is very robust relative to ingestion channel dropout. The presence of the meniscus in the pit does not necessarily result in ingestion channel dropout. The main cause of channel dropout is the interaction of the retracting meniscus and the collapsing vapor bubble, which normally results from channel refill restrictions.

It has also been found that channels can be run up to 9 kHz (3 µsec) without ingestion or channel dropout. At the higher frequencies drop ejection occurs before refill is complete, however the drops ejected are stable and discrete up to 10 kHz. Above the F_{max} of 5 kHz the drops are faster and smaller having a “streamer” form. At 10 kHz, the directionality of the drop becomes unstable, showing oscillatory behavior although dropout does not necessarily result.

Acknowledgments

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