

Split Pulse Timings and Their Effect on Bubble Momentum and the Superheated Boundary Layer of a Thermal Ink Jet Device

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Abstract

This paper quantitatively examines the underlying thermodynamics behind split fire pulse timings. It is shown that there is a direct relationship between the properties of the superheated boundary layer at the onset of bubble nucleation and the experimental data. An application specific - finite element program is shown to predict the jetting response curves with a 0.92 correlation coefficient. The theoretical analysis is robust enough to accurately predict the jetting response for varying pulse trains on two vastly different print head designs. Finally, it is shown that the maxima of the jetting response curves versus time are fundamentally related to the thermal diffusivity of the thin films.

Introduction

When current passes through the thin film resistor of a thermal ink jet device, heating rates on the order of several hundred million degrees per second are experienced. When ink at the heater surface reaches its superheat limit, it explodes into vapor. Since film boiling at the superheat limit produces vapor pressure on the order of 100 atmospheres, the bubble grows rapidly. The phase change pressure pulse is positive for about one microsecond. During this time, the liquid in the bubble chamber is accelerated. Typically, during the period when the pressure pulse is positive, the magnitude of acceleration at the bubble wall is on the order of one million g's. Because the accelerating wall rapidly moves the liquid away from the heater surface, and the vapor filling the void has much lower thermal conductivity than liquid, most of the energy required for the phase change process must be transferred into the ink prior to bubble nucleation. Since rapid bubble growth interrupts thermal energy transport into the ink, it is important to accurately predict when the boiling process is likely to begin - prior to computing any phase change bubble dynamics. It will be quantitatively shown that the properties of the thermal boundary layer in the ink at the onset of nucleation dictate the jetting response of the device. However, before that issue can be addressed, it is required to provide some background information to build upon.

Bubble Reliability

While ink is a complex mixture of humectants, colorants, surfactants and other chemicals - water is the primary ingredient on a molecular basis. For typical inks, the mole fraction of water is about 0.9. Given that most of the ink molecules are H_2O, it is reasonable to assume the molecular kinetics of water and ink should behave similarly. Even with this simplifying assumption, there is a great deal of ambiguity in the literature concerning the superheat limit of water based ink. It is possible to find references indicating a variable superheat limit as low as 230C,[1] and some publications present experimental data that's in excess of the 374 C critical point.[2]

Since the phase change pressure pulse is an exponential function of temperature, a crisp definition of nucleation criteria is required. To that end, a paper was presented at IS&T-NIP12[3] that combined the nucleation rate equation, reliability statistics and 2D transient heat transfer to predict the probability of bubble nucleation as a function of time and heater position [$R(x,y,t)$].

The numerical model was tested against water and isopropyl alcohol. The lab verification included various inks, heater sizes and pulsing conditions. The results, shown in Figure 1, indicate the bubble reliability calculations correlate strongly with the lab data.

Computing the time to nucleation dictates the temperature field at the start of bubble growth, and it's the first step in the process of quantifying the relationship between jetting performance and the thermal boundary layer in the ink.

Bubble Momentum

While Figure 1 validated the bubble reliability model, it did not indicate whether there was any advantage, or disadvantage, of driving heaters with any particular power density. In fact, it may be wrongly assumed that low power density drive conditions would be superior because they allow more time to transport energy into the thermal boundary layer. This subject was addressed in a paper presented at IS&T-NIP14.[4] Figure 2 is a compilation of data taken at varying power densities. This experiment included several different inks, and heater area varied by more than an order of magnitude. Yet all of the data could be placed on a single, normalized plot – indicating a fundamental process at work.

Details of the thermodynamics behind Figure 2 can be found in reference,[4] but they may be summarized as follows. In the low power density regime to the left of the maxima, the advancing bubble wall outruns the advancing temperature field. Ideally, the entire heater would reach the superheat limit at the same instant; however, this is not possible due to thermal diffusion into the aluminum electrodes on the heater edge. Once homogeneous nucleation begins at the heater center there is a race between the advancing bubble wall and nucleation probability in the colder regions of the heater. For high quality nucleation, the bubble wall must lose this race. Slowly propagating temperature fields due to low power density pulses cause a situation where the advancing bubble wall grows into a region too cold to sustain nucleation, so it begins to decelerate. But a fraction of a microsecond later in the fire pulse, this region may reach the superheat limit, causing re-acceleration of the bubble wall. A slowly propagating temperature field, characteristic of the low power density regime, causes an alternating expand-collapse activity at the bubble wall. Bubble reliability calculations show this effect. As explained earlier, bubble reliability is the probability of nucleating a bubble, and it can be computed as a function of time and heater position. A typical bubble reliability result is shown in Figure 3. This plot provides a snapshot of nucleation probability over the entire heater surface during the fire pulse.

This hypothesis was qualitatively verified with open pool bubble experiments. Vapor bubbles produced with low power density drive pulses had a ragged shape and were very erratic. This supported the hypothesis that intermittent nucleation and the alternating expand-collapse dynamics at the bubble wall during the fire pulse were responsible for degraded jetting in the low power density region. Conversely, vapor bubbles generated with a high power density pulse had a smooth shape and were repeatable.

Bubble shape adjectives like smooth or ragged are visually descriptive, yet they lack the precision of a number. To quantify the nucleation characteristics responsible for velocity variations in the low power density regime, a term was derived. Knowing the transient temperature field and the probability of nucleation across the heater surface led to a dimensionless term called nucleation quality (Q^*). The derivation of Q^* was presented at IS&T-NIP14.[4] It was shown that nucleation quality dropped off rapidly in the low power density region and was constant in the high power density region, mimicking the velocity variation seen in the data.

Continuing the examination of the velocity response data of Figure 2, the high power density conditions to the right of the maxima in Figure 2 create high quality nucleation and very stable droplets, but jetting response declines in this regime as well. The underlying cause is straightforward - high heating rates associated with power density pulses exceeding 2 GW/m^2 cause the superheat limit to be reached very quickly, allowing little time for thermal energy transport into the ink. As expected, this results in a shorter duration pressure spike, as shown in Figure 4.

Multiplying the phase change - pressure impulse (i.e. the shaded region of Figure 4) by heater area produces a term with units of momentum. The growing bubble, acting as a virtual piston, imparts momentum to the liquid, so it is logical that this term should show a similar response to power density as droplet momentum lab data does. However, as discussed earlier, low power density reduces the jetting response, and this must be factored into the equation as well. Since nucleation quality is dimensionless, multiplying by Q^* leaves the momentum units intact.

Normalizing the experimental data and simulation results permits them to be placed on a single plot. Figure 5 shows the correlation between measured droplet momentum and computed bubble momentum across a range of print head designs. While there is some scatter in the data, the overall trend is repeatable, and predictable.

The bubble reliability and momentum calculations were performed with an application specific program package developed at Lexmark to simulate heat transfer, phase change and bubble dynamics.

Split Fire Pulsing

It was shown that high power density drive pulses are required to achieve stable droplet velocity. The low power density regime is not an option because intermittent nucleation, characteristic of this regime, causes unstable jets. In the high power density regime, droplet velocity is very stable, yet Figure 5 shows that linearly decreasing droplet momentum is an unwanted byproduct.

To eliminate velocity degradation in the high power density regime, it can be shown that splitting the pulse into two segments improves jetting performance greatly. Typical lab results are shown in Figure 6. Each data point in Figure 6 has exactly the same input energy at the heater, yet the jetting response varies up to approximately 35%.

Split fire pulsing is well known as a means of varying droplet mass.[5] Qualitative and empirical explanations for this phenomenon abound. Since it is the goal of this paper to quantitatively examine the underlying thermodynamics, let's consider several alternative hypothesis's as a means of predicting the jetting response data of Figure 6.

One viable hypothesis is; the prefire pulse effects a reduction of ink viscosity. However, for the print head of Figure 6, the fluid column height between the heater and the nozzle exit was 41 microns. Yet the thermal boundary layer due to the entire pulse train was only 2.5 microns thick, and the contribution of the prefire pulse to the boundary layer was just a fraction of that. With that in mind, it is highly unlikely that reducing viscosity in the first 5% of the ink layer could cause a 35% increase in jetting response. That said, it is safe to conclude - viscosity reduction due to the prefire pulse was not responsible for the jetting response data shown in Figure 6.

Another hypothesis is that the prefire pulse heats the ink in the nozzle. This is also an unlikely hypothesis to explain the data in Figure 6 since the nozzle entrance was more than 25 microns away from the heater and the entire thermal boundary layer was just a couple microns thick. Another hypothesis is, the prefire pulse combined with the delay time causes a uniform temperature distribution in the ink inside the bubble chamber. Again this explanation has no bearing on the data of Figure 6 because the fact that a boundary layer exists at all negates the hypothesis, at least in this experiment. Finally, an obvious hypothesis attributes the split fire pulsing effects to thermal energy. While the thermal energy hypothesis is the most obvious one for explaining the data in this experiment, it will be shown that thermal energy by itself is insufficient, on a quantitative basis, to describe the jetting response shown in Figure 6.

Bubble Momentum

It was shown earlier, the bubble momentum term could be used to explain jetting response as a function of power density. Let's examine that hypothesis, as applied to the split fire data of this experiment. The Lexmark heat transfer - phase change - bubble dynamics model was used to simulate all conditions of the split fire experiment. These results are shown in Figure 7. Judging from the likeness of the response curves in Figures 6 and 7, it appears that the bubble momentum simulations and the experimental data have similar characteristics.

While this may provide a satisfactory link between theoretical and experimental results, it begs for a more fundamental explanation.

Thermal Energy

Since thermal energy is the fuel for the phase change process, it is reasonable to assume the most fundamental variable to explain the data of Figure 6 would be the energy in the ink's thermal boundary layer. There's nothing wrong with the bubble momentum explanation, but thermal energy is more fundamental.

Using the Lexmark model, it is possible to compute bubble reliability $R(x,y,t)$ as a function of time and temperature field. Once $R(x,y,t)$ is computed, it is a straightforward calculation to determine the thermal boundary layer in the ink at the film boiling onset. Figure 8 shows the results of a typical thermal boundary layer calculation when a split fire pulse is used. It is easy to see that the thermal boundary layer is just a few microns thick and not isothermal.

Once the boundary layer has been determined, thermal energy is easily calculated. Figure 9 shows a reasonable correlation between thermal energy and the experimental data for delay times less than one microsecond, but the correlation diverges greatly beyond this point. It may be tempting to disregard the deviation in the long delay time region because it is beyond the area of interest, but the joy of discovery lies in investigating the underlying causes when experimental data does not behave as expected.

Superheated Boundary Layer

As delay time increases, more energy diffuses into the thermal boundary layer of the ink. Yet it was shown in Figure 9, this doesn't necessarily translate into improved jetting performance. The reason for that is; not all of the thermal energy in the ink is available for phase change. Only the energy in the superheated region of the boundary layer can participate in the phase change process. Thermal energy in the subcooled region of the boundary layer cannot be used for phase change because it is below the saturated vapor temperature.

With this in mind, thermal energy was recomputed, but this time it was limited to just the superheated region. Typical superheated and subcooled regions were identified in Figure 8. The heat transfer simulations verified that bubble momentum as well as the lab data response curves were a function of the superheated portion of the boundary layer. However, something was still missing because the correlation coefficient still wasn't high enough to stop the investigation. It may be argued - the missing parameter might be related to thermal diffusion path length because the phase change process occurs over a finite period of time. With this in mind, it was hypothesized that perhaps the missing parameter was related to the thickness of the superheated boundary layer. The following equation was posed to describe the split fire jetting response.

$$\Delta Jet = 100 \times [(wf)(E / E0) + (1-wf)(d / d0) - 1] \qquad (1)$$

ΔJet = Increase in jet performance over a single fire pulse (percent)
$E = E(t)$ = thermal energy in the superheated boundary layer for a split pulse (Joules)
$E0$ = thermal energy in superheated boundary layer for an equal energy single pulse (Joules)
$d = d(t)$ = thickness of the superheated boundary layer for a split pulse (microns)
$d0$ = thickness of the superheated boundary layer for an equal energy single pulse (microns)
t = delay time
wf = weighting factor ($0 < wf < 1$)

It was found that a weighting factor of 0.5 provided the highest correlation. The simulation results are shown along with the lab data in Figure 10.

A weighted combination of energy in the superheated portion of the boundary layer and the thickness of that region appears to be the correct hypothesis to explain the spit fire data in this experiment.

To validate this hypothesis, another experiment was run on a print head that had a similar thermal barrier layer, but was different in every other way: ink, heater size, overcoat thin film stack, bulk silicon temperature, power density, flow features, etc. Lab data, along with the associated simulation results, are shown in Figure 11. It appears that the hypothesis still holds. From a statistical viewpoint, the hypothesis presented above has a correlation coefficient of 0.92. In other words the hypothesis explains 92% of the variability associated with the experimental data of Figures 10 and 11.

Discussion

The correlation shown in Figures 10 and 11 provides a strong signal that the correct hypothesis to explain the split fire lab data is a weighted combination of: energy in just the superheated portion of the boundary layer at bubble nucleation and the thickness of that region. In these experiments, the superheated boundary layer was always less than one micron thick, so any alternate hypothesis based on viscosity reductions due to the prefire pulse was rejected because the superheated region was less than 2% of the fluid column, yet a 30-40% increase in performance was effected. Also, the total thermal energy hypothesis was rejected for this experiment on the basis of the poor correlation shown in Figure 9. This lack of correlation was due to a fundamental fact; only the superheated portion of the ink may participate in the liquid-vapor phase change. While ink in the subcooled region had been heated above ambient, it had no effect on phase change at the bubble wall.

Optimal Delay Time

All of the lab data and simulations had several general characteristics. First of all, as more energy was put into the prefire pulse, jetting response increased. This trait held until the prefire pulse was long enough to cause nucleation by itself. When that happened, performance actually degraded because the thermal boundary layer started behaving like the single pulse - high power density condition discussed earlier.

The other obvious characteristic shown in Figures 10 and 11 is that there appears to be an optimal delay time region. The optimal time between the prefire and fire pulse appears to be around 2 microseconds. Since the optimal delay time appears to be relatively constant and independent of the other variables in this study, it suggests a fundamental property is responsible. Arguably, the only fundamental properties linking the data sets of Figures 10 and 11 are the thermal diffusivities of ink and the thin films of the device. An indirect proof of this hypothesis exists in the 92% correlation shown in Figures 10 and 11, but nothing is a satisfying as a closed form proof. In this case, it would quite difficult to show a closed form proof because with split fire pulsing, the heat transfer into the ink is not steady state and the surface condition is neither constant temperature, nor constant heat flux. A closed form proof relating optimal delay time to thermal diffusivity is not presented here. The numerical and experimental results speak for themselves.

While it is not a closed form proof, an order of magnitude analysis of the optimal delay time can be obtained by estimating the time during which the primary diffusion path favors the ink side of the device. This time is limited because once the temperature field has propagated through the thermal barrier layer and into the silicon, the transport path for energy begins to favor the substrate side (the thermal diffusivity of silicon is about 600 times greater than water). With that in mind, it is possible to estimate the heat propagation time by looking at the units of thermal diffusivity. Thermal diffusivity is expressed in units of (m^2/s). Then it follows that an estimate of the propagation time would have the following form:

$$t = h^2 / a \qquad (2)$$

t = (estimate) time for heat flux to propagate through the thermal barrier (s)
h = thickness of the thermal barrier (m)
a = diffusivity of the thermal barrier (m^2/s)

For the experiment of Figure 6, the thermal barrier layer was 1.8 microns thick, and the diffusivity of this thin film was approximately, 1x 10^{-6} m^2/s. Then by the above formula, an order of magnitude estimate for the propagation time through the insulator is 3.3 microseconds. Since the thermal barrier must provide an insulation path during the prefire pulse and the delay, the optimal delay time is then estimated as 3.3 microseconds minus the 0.7 microsecond prefire pulse. Perhaps it's no coincidence that this estimate of 2.6 microseconds is very close to the maxima of the lab data. So it may be argued that after several microseconds the primary path for heat conduction starts to shift towards the silicon side, resulting in a declining jetting response for delay times exceeding this. This is exactly how the experimental and numerical results behave. Admittedly, the thermal diffusivity - barrier thickness formula above ignores the effects of temperature gradients, boundary conditions, other diffusion paths, etc. It is not intended to be anything other than an order of magnitude estimate to show why exceedingly long delay times cause the competing heat conduction paths to favor the substrate side of the device.

Conclusion

To achieve high quality bubble nucleation, a high power density drive pulse must be used. High power density pulses cause the superheat limit to be reached before the optimal amount of thermal energy is transferred into the ink. Split fire pulsing has been demonstrated to improve the jetting response when high power density is used. Several alternate explanations were investigated to explain this phenomenon, but none of them provided a robust match for the data in this experiment. It was shown that the most likely hypothesis to explain the experimental data was a weighted combination of thermal energy in the ink's superheated boundary layer and the thickness of that region at the onset of film boiling. It is logical that this hypothesis fits the experimental results because only the superheated region of the ink participates in the phase change process. It was shown that this hypothesis explains 92% of the variability in the experimental data. It was also shown numerically and experimentally that the optimal delay time was about 2 microseconds. An order of magnitude analysis also indicated that the optimal delay time was fundamentally related to the thickness and diffusivity of the thermal barrier layer between the silicon and the heater.

References

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Biography

Robert Cornell is a Senior Technical Staff Member in the Lexmark Ink Jet R&D organization. Since 1989, he has been focused primarily on heat transfer and bubble dynamics from both experimental and numerical viewpoints. For the last 23 years he has been involved in a wide range of printer programs at Lexmark and IBM. He received his formal training as a Mechanical Engineer at the University of Pittsburgh.

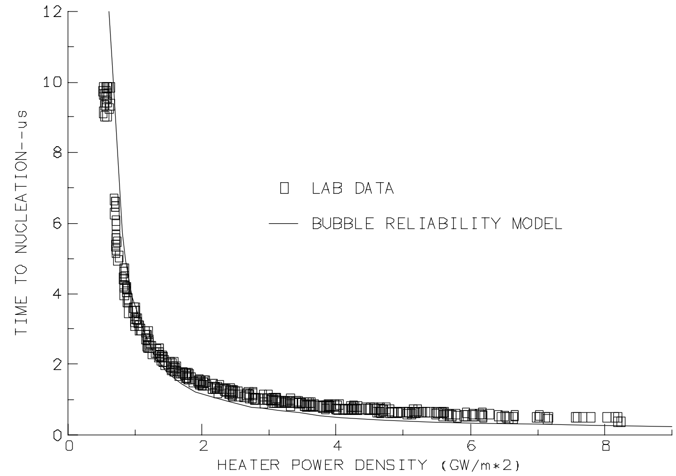

Figure 1: Time to Nucleation Vs Heater Power Density

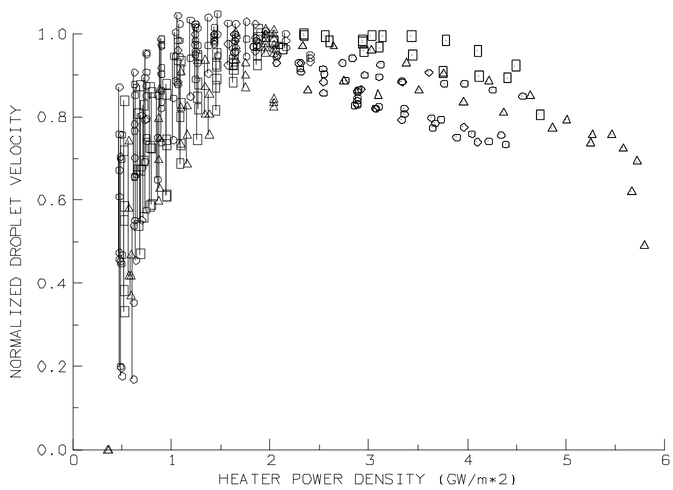

Figure 2: Velocity Response Vs Heater Power Density

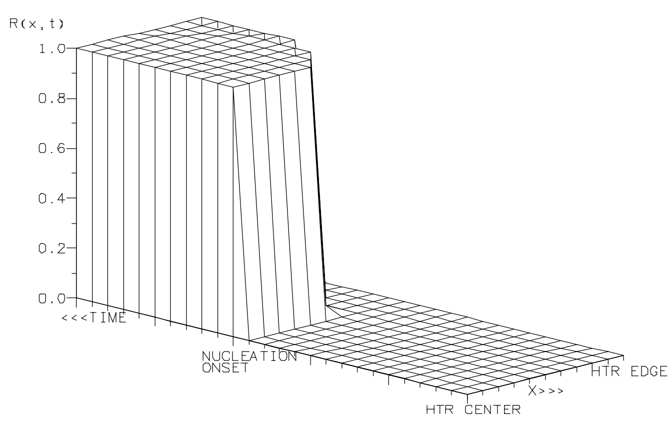

Figure 3: Bubble Reliability Vs Time and Position

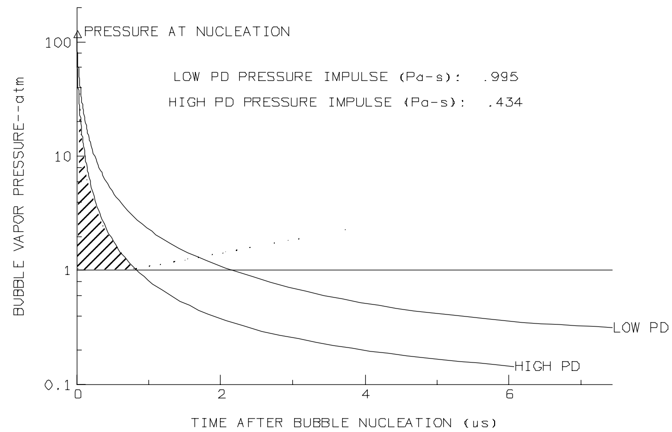

Figure 4: Phase Change Pressure and Power Density

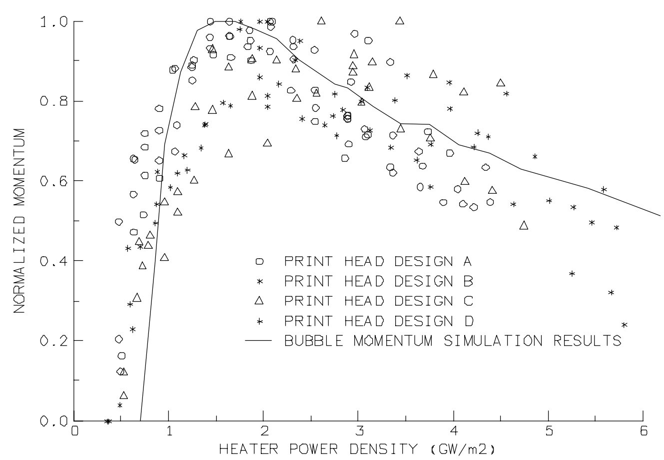

Figure 5: Momentum Vs Heater Power Density

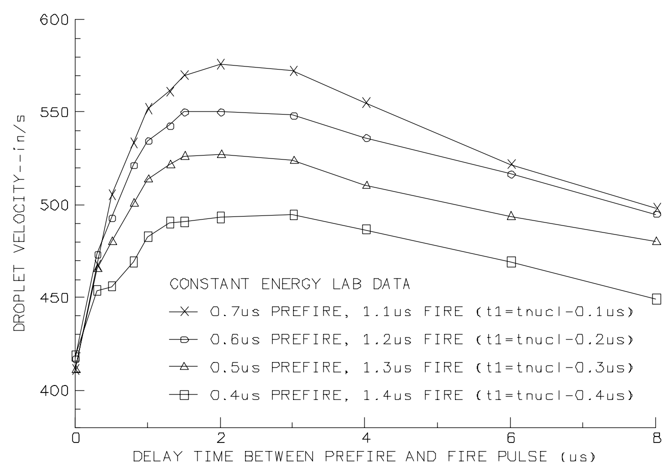

Figure 6: Jet Velocity for Various Split Fire Pulse Trains

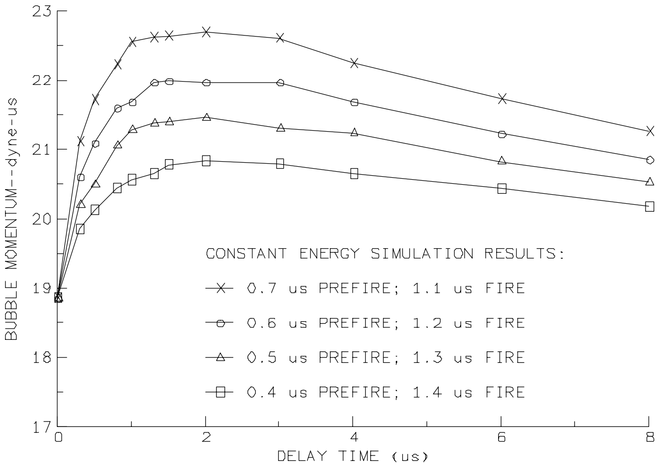

Figure 7: Bubble Momentum and Split Fire Pulsing

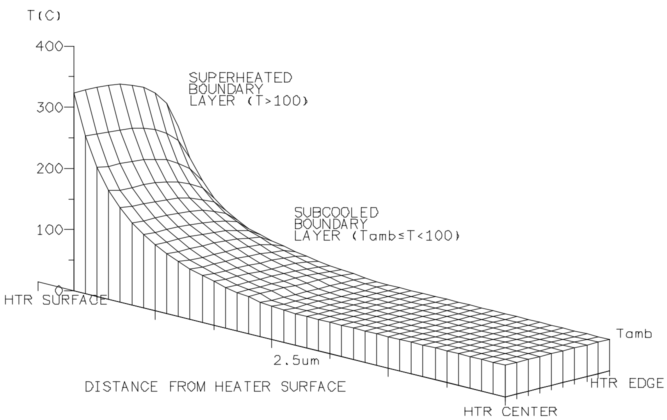

Figure 8: Thermal Boundary Layer in the Ink

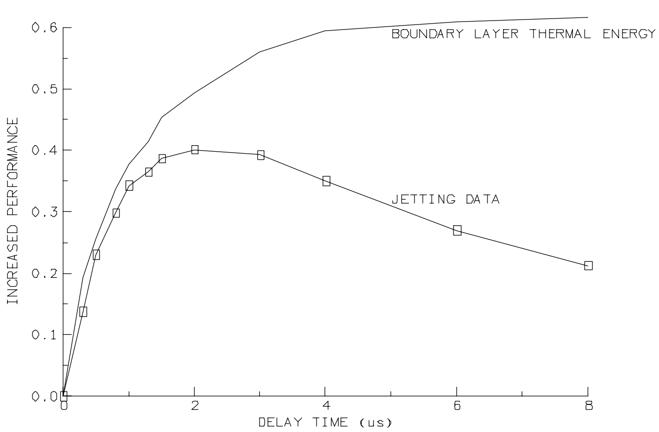

Figure 9: Thermal Energy and Split Fire Data

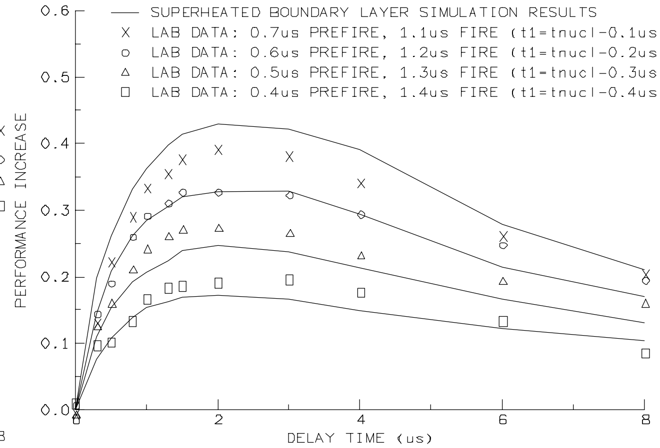

Figure 10: Split Fire Data and Simulations

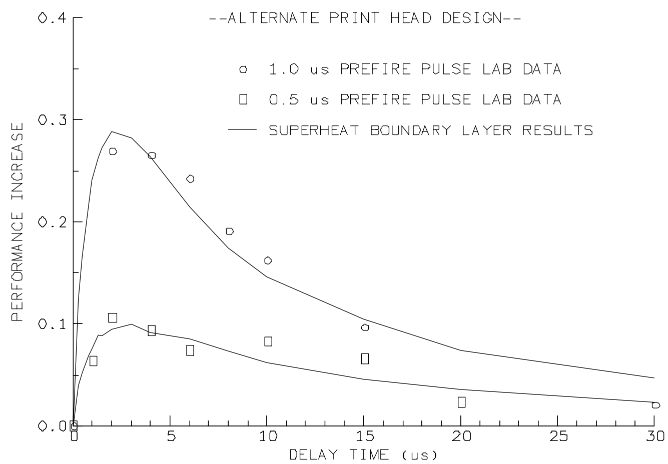

Figure 11: Validation of Hypothesis – Alternate Head Design