Heat Transfer Issues in Print-heads: Control and Applications

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Abstract

Thermal Control in MEMs is becoming a major subject. As the manufacturing capabilities increase and help design and build more complex structures, driving more power in smaller scale dimensions it becomes a must to harness the heat flows within the device. Sometimes, to enable a concrete function that precise, accurate heat transfer, other times just to ensure device and operation reliability. We will review the subject of heat transfer in MEMs in general and print/heads specifically.

MEMs in general and thermal inkjet print-heads in particular have different functional layers and structures designed for its intended function. When considering control over the MEMs desired operation this puts a series of constraints on the dimensions and material properties of this layers that are discussed. Equally important is the degree of "intelligence" build up on the device itself has an impact on the capability for Thermal and Energy Control. Having more capability is an enabler of several features such as speed of operation but many times needs to be traded by cost. Discussion of current solutions such as sensors in the print-heads, firing pulse schemes, pulse width modulation and others are discussed in the paper.

Last but not least it is increasingly important to take a global system perspective when designing for Thermal Control in MEMs since many of the times MEMs are meant to work within a system where other components act as important heat sources.

Introduction

Where, almost, everything is about heat transfer. Inkjet print-heads must be nowadays more widespread MEMs devices, but further applications for MEMs are coming on the way that will make a difference in fields very different than printing. For current Microscale and soon to be Nanoscale devices with higher power demands heat dissipation is a major issue. Thermal print-heads in the pursue of higher nozzle density and higher printing frequencies coupled with the drop weight reduction (with a lower thermal effciency in terms of ng/uj) can operate at 40W, other more demanding applications knock on the 100W, over the 100W/cm2 for power density.

Aside from the purely component centered issue there is also the global system issue. Specific to Wide Format printing we encounter new applications that not only push further in the width and speed vectors but also on the ink technology, and new solvent based or UV based inks require post heating/curing post-treatments that really pose a challenge to the overall system since print-heads no longer deal with self-heating alone but with more important heat sources from the curing modules.

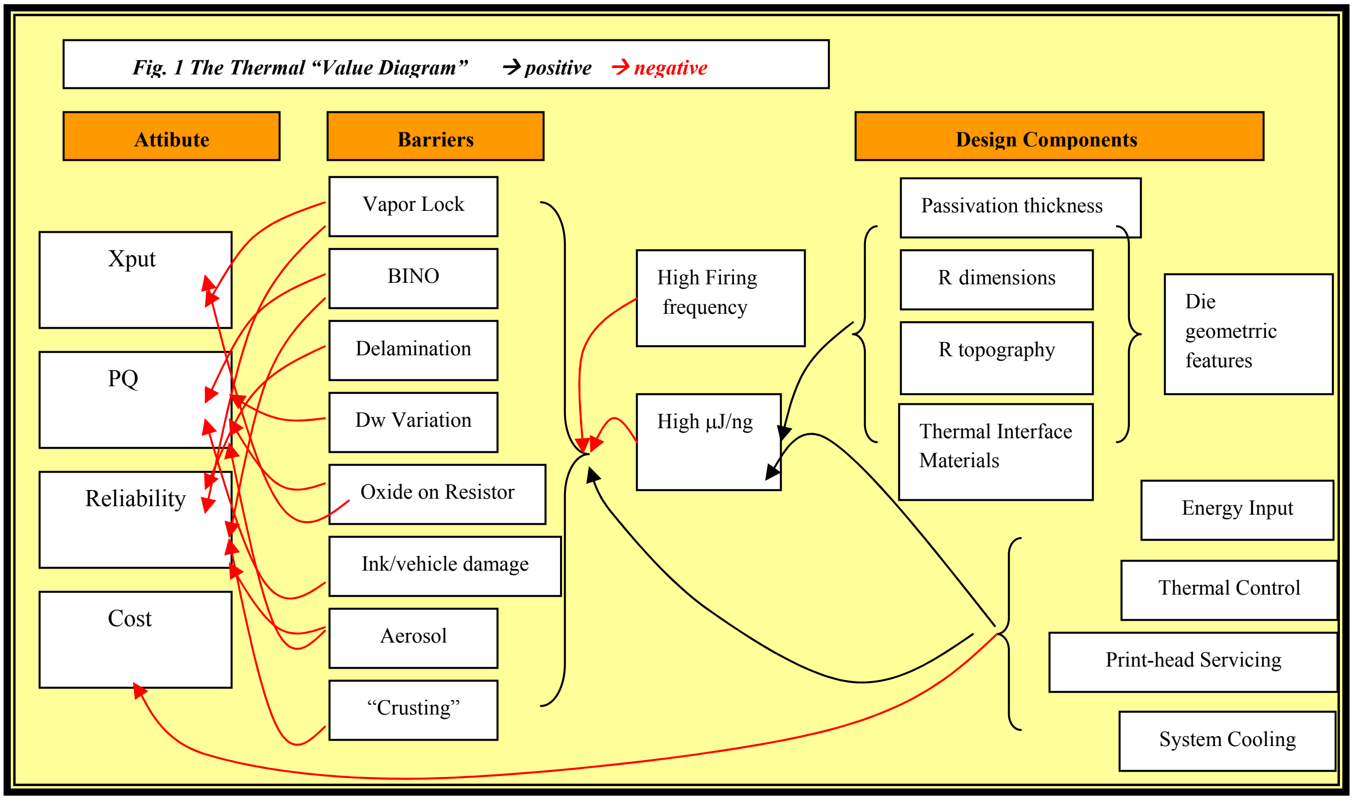
Applications

Other new applications beyond printing target thermal inkjet technology increasingly, the precise dosing of chemicals or fuel injection are good examples and despite they use the same principles there are significant differences in the operating temperature due to the very different nature of the fluids. Chip on Lab applications rely on the precise fluid pathways and heaters that provides thermal inkjet technology to redesign processes that before demanded a long cycle time and a significant cost. One good example of that is the Polymerase Chain Reaction process (PCR) by means of which DNA segments in a sample are multiplied. The process involves several (tenths) heating cycles to precise temperature setpoints , heating and cooling alternativelly, first heating it over 90°C for around 30 seconds to achieve DNA ***denaturation*** or breaking the double helix in two single , strands , this is followed by the ***primer annealing*** step which requires "cooling" down to 50-60°C for over a minute to allow primers anneal to complimentary regions in the DNA "template" strands. Finally comes the ***primer extension*** process that targets a temperature around 70°C. The key point is that changes from one step to another must be accomplished as fast as possible to achieve a good throughput. With heating rates in excess of 30°C/sec and cooling rates of 20°C/sec lab on chips can deliver the throughput required , the step changes are matter of fractions of a second. As important as the heating rates it is the temperature control which is provided by keeping a feedback loop using a sensor in the chamber. Also temperature uniformity must be kept, however although Silicon makes a perfect thermal chamber, its high thermal conductivity (λ of157 W /m K) makes it somewhat challenging to keep uniformity over time which can be achieved isolating the chamber with micromachining.

A different option over the thermal cyclic chamber is to etch a fluid pathway with differentiate zones. The fluid containing the DNA samples will meander through the different zones , each corresponding to one of the 3 steps required for the PCR process. Movement of the fluid is achieved through the micropumping that uses thermally created bubbles to push the liquid.

There is currently plenty of MEMs applications that use thermal as a drive for the targeted function, such as differential microcalorimeters for biomolecular recognition, thermal micropumps that make use of thermally generated micro-bubbles to move fluids along with rates ranging from under a nanoliter per minute to several milliliters and microvalves or electrothermal actuators based on thermally activated bimetallic membranes or Ti-Ni alloys that can undergo plastic deformations and later recover its original shape by means of heat application .

All of such applications rely while being wide different have one thing in common, they rely on accurate heat transfer mechanisms for its application.



Active Thermal Control

There are plenty of reasons for thermal control on MEMs. Ranging from proper operation to reliability of materials the execution at spec temperatures is a key component of MEMs and their function. For Thermal Inkjet print-heads we could draw a summary scheme outlining the basic effects vs. design knobs (Fig 1).

Thermal control has several components to it, from input energy, energy efficiency, heat transfer profile, to thermal sensing and cooling mechanisms if required among others.

Proper energy input is required and a dynamic management is a must for most applications due to varying duty cycle demands during execution and heat accumulation during operation. In an inkjet print-head, variables such as the firing frequency or the amount of nozzles fired at once are clear examples of scenarios that require different energy delivered.

For such control on the amount of energy to be delivered, a thermal based feedback loop must be implemented. Thermal sensors have to be designed with the right technology and located in the right place. In print-heads it is specially useful to have average temperature measurements across the die attained by means of the thermal coefficient of resistance (TCR) of an ad hoc circuit that meanders across the die:

$$R = R_0 e^{[TCR*(T-T_0)]}$$

By measuring the resistance change we have a good estimate of the die temperature.

Proper operation in the printhead translates clearly on proper ink ejection and thus printed quality. Physical properties such as ink viscosity, do change with temperature, also does the drive bubble size, raising the drop weight, which translates to color unaccuracies and other defects on the printed page.

But there are also Reliability and Safety reasons to monitor and control the device temperature. High temperatures affect materials, particularly adhesives used in the layer interfaces on many MEMs can undergo glass transitions through repeated thermal cycling above certain peak temperatures and cause delamination. Resistors suffer from oxidation that increases with temperature changing its surface properties and heat transfer characteristics, which ends up raising the required turn on energy for the firings. Different microstructures can suffer from stresses derived from local uneven thermal expansions. For inkjet particularly, temperatures higher than desirable affect nozzle health by means of ink damaging (excessive vehicle evaporation, dry burnt residues on nozzle plate or on top of resistors) or in the case that fluid temperature in the chamber is above 100°C (not just the superheated layer above the resistor) we can trigger a "vapor lock" event when, as a consequence of the high temperature, a vapor bubble is generated that won't collapse preventing any ink exit. Since ink is the major heat carrier, subsequent firing quickly accumulates heat on the die to the failure point (Fig 2).

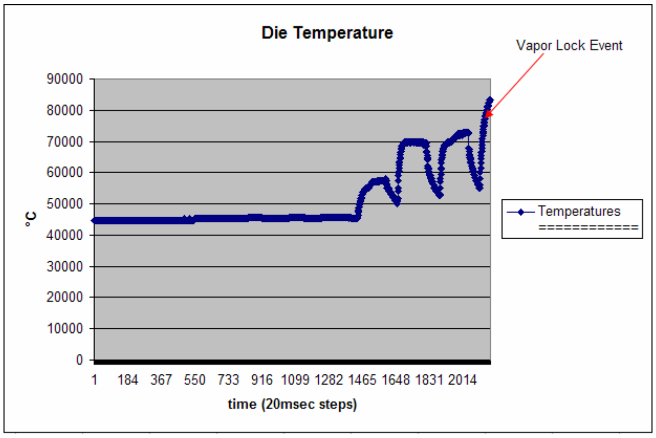


Figure 2

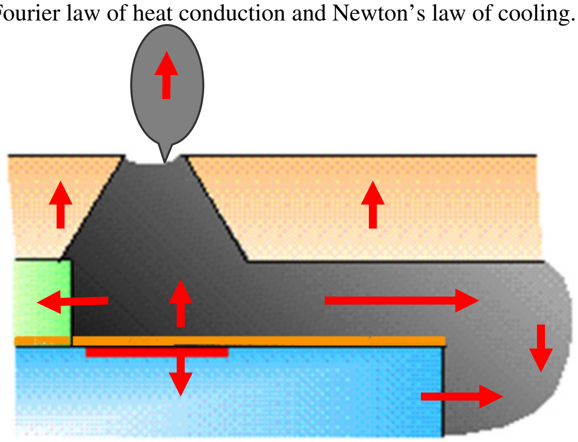
In Fig 2 you can see that actual reported temperature is below 100 °C, this is due to the fact that actual reported temperature is not ink but die temperature.

Another side effect of working at higher temperatures is the undesired creation of bubbles that stand in the fluidic pipes and can block ink pathways, this is a defect known as BINO or bubble induced nozzle outs.

When designing for thermal control it all starts with the proper dimensions so to configure an adequate heat transfer in the device, it is therefore critical to have a model of the Heat Transfer flows in the device.

Heat Pathways in an inkjet print-head

Physics used for description are the energy balance equation, Fourier law of heat conduction and Newton's law of cooling.



In a simplified model view, the heat is generated in the resistor in silicon, conducted through the passivation layer into the chamber and then, transferred by convection to the ink which at the ejection takes most of the energy as both: kinetic energy for the ejected drop and as a temperature raise for the ink in the chamber. Heat transfers from silicon back to the ceramic carrier through the thin film by conduction and there is convection interchange between inner ink channels and silicon and ceramic, also between the two latter and air through the surfaces in contact.

Taking a look at the different coefficients for a particular case:

	Volume of ink in (m^3)	Area in contact with ink (m^2)	h on ink side (W/m^2/K) (natural convection)	h on ink side (W/m^2/K) (forced convection)	Area in contact with air (m^2)	U=$h_{Si\text{-}air}$= $h_{C\text{-}air}$ on air side (measured- W/m^2/K)
Ceramic	6 x 1.64E-8	6 x 6.43E-5	~8000	6-10,000	7.0e-4	35
Silicon	6 x 3. 65E-9	6 x 2.05E-5	~5000	10-17,000	1.6E-4	

Fig 3. [1]

We can see clearly that forced convection is the main mechanism for the system heat removal.

For this reason liquid cooling strategies are specially suitable for high heat removal. One of the big trends in microchip cooling is the ***microchannel technique***, for which a series of microchannels are etched in the backside of the chips and cooling fluid is circulated to remove the heat generated by the electronic components. At these small µm dimensions there is an advantage to convection because of the small Nusselt Numbers that compares convection heat transfer from a surface to conduction heat transfer.

Nu =h L / k

Where:
h=convection transfer coefficient
L= characteristic legth
K=thermal conductivity

Assuming thus constant Nu, as L decreases h must proportionally increase.

A concrete explored application for inkjet is that of ink recirculation through the print-head ink manifold from the ink reservoir located outside.

Apart from the main forced convection mechanism it is clear that since heat is conducted from the resistor up through the so called passivation layer (providing shelter to resistor from direct exposure to ink and bubble collapse), the thicker the layer the bigger the amount of energy required (Turn On Energy) and so the less efficiency measured in µj/ng. Ideally, thus, it is desirable to have the thinnest possible layers between where heat is generated and where it has to be transported. In the case of the inkject print-heads this is to the ink chamber and the channels, but this comes at the cost of resistor reliability since cavitation damage is present in thermal firing chambers and thinning the protection is no good. The design option is about the ***Thermal Interface Materials*** of choice that can help draw a particular heat transfer profile, among other characteristics. Effectively, these materials can help improve heat transfer across a given interface or alternatively, increase the resistance and block heat transfer for the desired areas. Among the materials already in use for a variety of applications we can find greases, phase change materials , filler polymer matrices and carbon based materials. The most recent trend is the use of ***carbon nanotube coatings***. Using chemical vapor deposition, arrays of multi wall carbon nanotubes of different densities and sizes can be grown over Silicon and other surfaces increasing the contact points at the interface between two solids with subsequently increased thermal conductivity. [2]

Particularly, for our inkjet print-heads, we can go back to our model to envision how heat transfer happens between the different layers, what are the temperatures attained in the steady state and where is the energy stored in the system.

The model uses the basic equations for energy balance, conduction and convection:

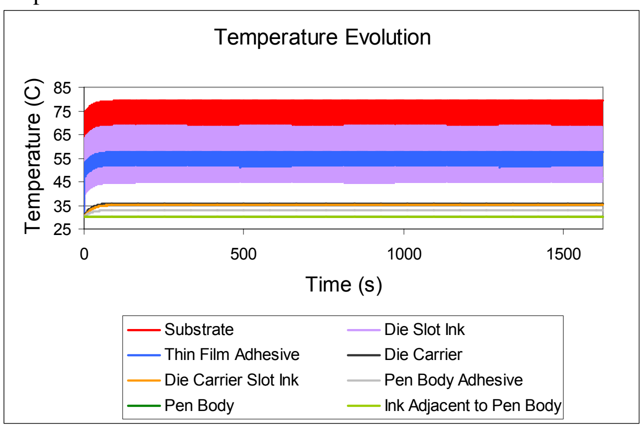
$\nabla * q = q_{gen} + \rho c\ dT/dt \quad (q_{gen} = \text{q generated within})$

$q = -k\ \nabla T(r,t)$ Fourier

$q = hA\ \Delta T(r,t)$ Newton Cooling Law

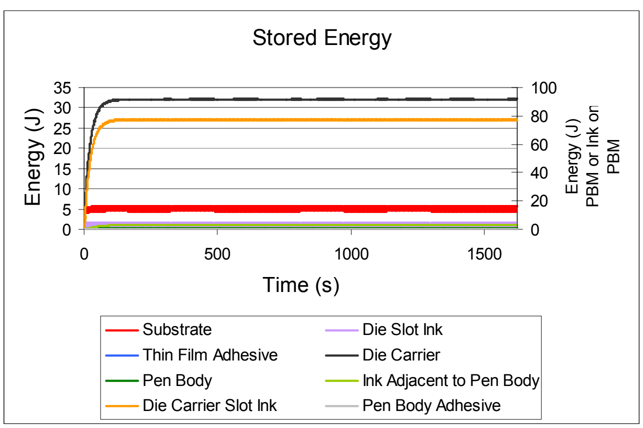
The model is well correlated to empirical measures.

In terms of steady state temperatures we get from this simplified model:



Corresponding to an input power of 20W.

In terms of the energy storage.



Which clearly outlines Die carrier (ceramic in this case) and its fluidic manifold as the biggest energy reservoirs.

Actually, thinking of short intense swaths an strategy can be applied by overdimesioning the heat storage adding more thermal mass to the printhead.

In the case of Large Format applications embedded in system with multiple heat sources above ambient temperature, apart from energy optimization and layer heat transfer enhancement, we might need to consider additional resources such as **conditioning of the printzone** or usage of ***solid-state thermoelectric refrigerators***. Using Peltier cells, heat can be pumped out of the system to a heat sink. Some applications remove the heat directly from hot spots like particular CPU chip locations , attaching them directly to the cold side of the Peltier , others combine with heat diffusing mechanisms prior to collection by the Peltier for a more general heat removal. Thermoelectric cooling can pump a good deal of heat flux ranging in the best cases around 100-300 W/cm2, and can be embedded in thin film, though a lot of limitations arise depending on the device purpose and characteristics. One fundamental limitation of Peltier is that the cells work over an specified and limited temperature difference. Some implementation in inkjet systems is feasible as long as Peltier components stay out of the print-heads thin film, mostly for cost reasons.

Resistor design in itself is another hot spot, dimensions, aspect ratio conform the way that resistor delivers the energy, its topography can account for lateral losses if too pronounced.

Scale Issues

Speaking of the resistor diimensions difficulties arise as resistor size decreases, bubble instability, capacity issues, among others. There is also an apparent increase in the turn on energy per unit area. Ideally, having a rule to keep the firing performance would be a big want when going small. How to fire such nozzles in a reliable form?

By looking at the simplified 1-D heat equation we can make some quick assumptions:

$$\frac{\partial T}{\partial t} - \alpha \frac{\partial^2 T}{\partial x^2} = 0$$

Where $\alpha = \kappa/\rho c$ is the thermal diffussivity.

In non-dimensional form we have:

$$\frac{\partial T}{\partial \theta} - \left(\alpha\tau / l^2\right)\frac{\partial^2 T}{\partial \varphi^2} = 0$$

Where τ is actually interpreted as the firing pulse width and l the resistor length. The term in parentheses happens to be the ***Fourier number***, the ratio of heat conduction rate to heat storage.

By considering a concrete material selection it is assumable that α is constant. Then, as we want the solutions of the equation to have the same form as we scale the resistor down, pulse width τ has to change with R^2 (l^2 in this case). [3]

As we scale down MEMs to the ***nanometer range*** all the heat transfer mechanisms that hold for macroscopic scale and even into the microscale hit an important limit at the nanometer range because of the mechanism heat transport mechanism within solids. Within solids, heat is transferred through the vibration of the atom bonds, each of this energy packs is known as a *phonon* travelling through the lattice. Phonons do crash into each other as they travel, also they interact with electrons, as a result of this interactions they get scattered from the original direction. For this reason, their path from A to B is not an straight line. How do phonons get from A to B?, some parameters help us understand, Mean Free Path defined as the distance (average) phonons can travel before colliding with another phonon, also the time it takes to go from A to B is longer and it is defined as Mean Free Time or the mean time phonons travel without collision to other phonons. These magnitudes are different for different materials and they vary according to:

- Material Temperature
- Molecular structure
- Grain Geometry
- Congregation Molecules

So, in nanoscale solids these magnitudes become really important and they account for the heat transfer properties while at larger scales the colision effects are "averaged out" and thus the traditional heat transfer mechanisms apply.

For this reason, solids at nanoscale suffer a delay in heat conduction and are thus, worse heat conductor that they are at the microscale. This poses a clear challenge when going for nanoscale structures in MEMS devices wherever heat transfer is a must.

One left knob is **Energy** and **Thermal Control**.

Proper energy input needs to adapt to all the varying circumstances, this is, putting intelligence in the system. By being able to modulate the energy waveform: pulse width and /or voltage as a function of:

- Power density required
- Thermal Energy stored in the system
- Device caracterization

All driven by adequate sensor inputs. This way we are able to improve the thermal efficiency by substantial amounts.

Other strategies might include smart distribution of the printing adapting to the environmental circumstances.

All of these systems are actually working on many printers in the market.

Summarizing

In the pursuit of thermal control in MEMs there are clear vectors for improvement such as increase heat removal and reduce heat input. However the path to achieve those is not always straight forward as many of the solutions collide among them, or with the intended application or the intended cost. As main trends, we envision thermal interface material and layer geometry always looking for higher efficiency design coupled with enhanced cooling structures within MEMS (most significant among them being Microchannel and Solid State thermoelectric cooling) and intelligent adaptive algorithms that respond to system evolution. One key point to keep in mind is the scale at target (specially on the path from MEMs to NEMs) since different rules apply as we go from the micron to the nanometer.

Acknowledgements

The author wishes to thank Ozgur Yildirim, Satya Prakash, Manish Giri, Erik Torniainen, Niels Nielsen, Bill Knight and many other colleges in Hewlett Packard since many of the information in this article comes from work done by researchers a the Inkjet Printing Divisions.

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Author Biography

Pere Cantí studied Physics in Barcelona Universitat Autonoma de Bellaterra and an MBA from UPF . He became engineering Director for Centre of Applied Technology in Barcelona from 1987 to 1993 and joined HP with a grant in 1994. He was hired by HP in Barcelona in 1997. In 2000 he joined the print/head development team. He is currently focused on the interaction between the print-head control and writing systems.