A Customer-Oriented Productivity Model For Thermal Ink-Jet Printers (Parts 1&2)

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Abstract

This paper describes a model that can be used to assess the productivity of an ink-jet printer from the customer's viewpoint based on specific systems-level design choices. Many considerations go into the design of an ink-jet printer. Foremost among these is the speed of the printer, or the time it takes to print a page. Simplistically, the time to print a page is determined by the number of jets of each color in the printhead, the firing frequency of the jets, and the number of passes the printhead must make over the paper to complete a page. In reality, however, the actual time to print a page is strongly dependent on a number of design parameters and systems-level trade-offs. For example, the nature of the document itself may make it possible to quickly skip white spaces due to either large margins or breaks in the document content. Additionally, many ink-jet printers offer a variety of printing modes to suit the type of document being printed. This may include single-pass or draft modes for text, or different levels of multi-pass printing for graphics or pictorials.

Mechanical efficiency of TIJ printheads is very poor. The printhead temperature depends on the operating environment of the printer and the area coverage of the images within a particular job mix. Thermal bursts, idle times and temperature-dependent changes in operating conditions are all parts of the thermal equation. Excessive temperature swings can lead to print quality degradation by changing the drop volume, by interfering with the nucleation process, etc. For a reliable operation, the printhead temperature must be maintained within a certain operating window. This could require a reduction in printing speed: a direct hit on productivity. Therefore, a successful printhead design must address thermal management and image processing issues in an integral framework. The development of such a systems-level approach is discussed in this paper.

Overview

A systems-level heat management model has been developed to simulate customer-like use of an ink jet printer. The model is used to prevent over-engineering of thermal systems and to reduce their cost. The approach starts with the selection of an image portfolio to represent customer applications. Each image is then processed before it goes into the re-shuffling stage where the pixels are counted based on the print mode and the printhead architecture. The output is a spatial map of area coverage for each color. This data is next transformed into time domain (duty cycle) by mixing in the printer idle times. Finally, this information is fed to a thermal model, which simulates the transient response of the printheads.

Viewed as a black-box, the user specifies any sequence and number of documents, and the systems model "runs" this print job as fast as possible without exceeding the thermal limits that would cause printing failure or quality degradation. To achieve this, the model slows down or speeds up the operation based on the printhead temperature. The end result is printing speed versus number of pages printed.

Background

The thermal ink-jet marking process is based on super-heating a small amount of liquid until a vapor bubble is formed which subsequently ejects a drop of ink from a jet or channel. Although some of the generated heat is ejected along with the drops, about half of it remains behind in the printhead. This excess heat will lead to a rise in temperature of the printhead. As the temperature of the printhead increases, the volume of the ejected drop (and thus the diameter of the printed spot) increases. In addition, operation at elevated temperatures can lead to outgassing of air from the flowing ink, which can subsequently choke off the flow of fresh ink to the nozzles. At still higher temperatures, ingestion may occur, and no drops will be fired from the jets. Thus, in order to continue producing good print quality and prevent failures, it is essential to maintain the temperature of the printhead between certain operating limits.

The design/architectural specifications of the drop ejectors and printer will ultimately determine the operating bounds of the printer, and the temperatures generated inside the printhead. The degree to which these operating bounds and temperature conditions are stressed will then be determined by the nature of the images to be printed, as well as the mix of print jobs sent to the printer. Thus the design of an effective heat management strategy must take into account not only factors such as the efficiency of the drop ejectors, design of the heat sink or other heat dissipating mechanism, firing frequency and number of jets in the printhead, volume of the ejected drops, temperature of the incoming ink, etc., but also the duty cycle determined by the image data, provisions for white space skipping over the printed area, and the time-dependent printing history of the printer. In fact, this paper illustrates the crucial role that the images and job mix can play on the customer's perception of printing speed and throughput.

There are several approaches to dealing with the build-up of excess heat in printheads. These include:

1. Use of heat sinks - A heat sink in direct contact with the printhead can be used to absorb excess heat from the printhead. The surface area of the heat sink can also be designed to dissipate energy to the ambient environment. This approach is used in current Xerox products.
2. No heat sink - With this concept, the thermal mass of the printhead is made to be small, and almost all of the heat generated during the ejection process is dissipated to the ink and expelled with the ejected drops. In order for this to work, a good thermal contact between the ink and the printhead is required.
3. Hybrid approaches - These approaches use a good thermal contact between the ink and the printhead in order to expel as much of the heat with the ejected drop as possible, but also use a heat sink to cope with residual heat at higher duty cycles.
4. Slow down - The printer may be made to slow down or even stop printing for a time if heat cannot be dissipated away from the printhead quickly enough and the temperature of the printhead becomes excessive.

Thus, there are a variety of ways to deal with heat build up in the printhead. This paper describes a general purpose systems-level model that was developed to ascertain how well a particular design meets the customer requirements in terms of throughput and operating latitudes for the expected mix of images.

The unique feature of this model is that it takes into account the print mode of the printer (i.e., single pass, two-pass, etc.) along with the real image data that might be sent by a customer's application. The final outputs of the model are print time for a particular document (based on the print mode and arrangement of jets), and the throughput as a function of page number printed (i.e., in a long job run). This data makes it possible to assess the throughput of the printer as seen from the customer's viewpoint under various printing conditions. In this way, the design and operating trade-off decisions can be realistically assessed for their acceptance in the marketplace.

Systems-Level Model

The aim of the systems-level heat management model is to simulate the working of a Thermal Ink-Jet printer from the user's perspective. There are two major components to the model. The first component simulates the image path, and the second component models the time-dependent temperature distribution within the system. The two components of the model are tied together by an interface that passes the number of pixels to be printed per unit time from the imaging model to the heat management model based on the image content, print mode being emulated, mechanical timings, and other special white-space skipping or slow down algorithms. The steps to be followed include:

1. Image Source - The original image(s) should be representative of the intended customer's applications, and can come from:
   a) PC-based applications.
   b) Scanners.
   c) Other image sources.
2. Image-Processing - The original image is rendered into a bit-mapped representation as it would be in the intended product. This includes:
   a) Image decomposition (if required).
   b) Color correction.
   c) Halftoning.
   d) Specialized image-processing (contrast and edge enhancement, etc.).
3. Re-Shuffling of Image Data - The bit-mapped image data is re-shuffled to account for:
   a) The number and locations of the colored jets.
   b) The layout of the printheads.
   c) The print mode being simulated (i.e., single pass, two pass checker-boarding, etc.).
4. Interface Between Image and Thermal Models - The re-shuffled image data is read in, and the duty cycle for the printhead as a function of time is output based on:
   a) The firing frequency and scanning speed of the printhead (i.e., number of pixels printed per unit time).
   b) Acceleration and deceleration of the printhead during turn-around times at the end of scan lines.
   c) White space skipping (i.e., short scan lines for blank parts of image).
5. Thermal Model - A unidirectional thermal model describes the time history of the temperatures within the printhead and associated heat dissipating mechanism. This includes:
   a) A mechanism to vary the energy per pulse based on readings from a sensor within the printhead or heat sink.
   b) Custom algorithms to slow down or stop printing when temperatures at given locations in the system exceed pre-determined limits.
   c) The interaction between heat transfer and fluid flow within the printhead.
   d) Thermal elements whose properties are determined from detailed 2-D and 3-D numerical models and based on the heat dissipating mechanism being studied.

Following the steps above, almost any image (or consecutive images) can be "printed" with the model. In addition to the complete temperature history throughout the system, the model also outputs the time required to print each document in a given job mix. Thus, for some high area coverage documents, the build up of heat within the printhead may become excessive after printing many copies of the document, and printing may be slowed. Alternately, some documents may not stress the heat dissipation mechanisms, and will print at "full speed" regardless of how many copies of the document are printed.

The model relies on experimental data to determine the temperature range and operating bounds within which no failures will occur. Relevant failures may be caused by ingestion or the accumulation of air bubbles within the printhead when operated at elevated temperatures. This can lead to deletions in prints due to missing drops. Since the ejected drop volume (and thus the printed spot diameter) varies with the temperature of the printhead, additional constraints may be required in order to maintain optimal print quality. In either case, the model can be used to test various designs, trade-offs, and strategies aimed at eliminating failures and extending performance latitudes. These results can then be used to assess the effectiveness of the printing system in meeting customer requirements.

Image-Processing Path

Images to be printed can come from a variety of sources including PC applications, facsimile devices, or scanners. In order to generate the final print, each jet within each printhead of the ink-jet printer must be told when to fire a drop as it scans over the paper so as to produce printed spots at the appropriate locations. For the purposes of the model, this process should follow that which is to be employed in the actual printer being studied.

The following steps outline the procedures used.

1. Generation of original image - This can be done using a PC-based application, scanner, or using a pre-existing electronic image.
2. Image Processing – This may include image decomposition (to transform from a PDL to an 8-bit per pixel format), color correction, image enhancements, or other specialized techniques.
3. Halftoning - The 8-bit per pixel image must be halftoned into a 1-bit per pixel representation.
4. Re-shuffling of image data - The bit-mapped image data must be re-arranged in accordance with the configuration of the printhead(s) within the printer, and the location of colored jets within each printhead as each swath of the image is printed. Re-shuffling of the image data must also be performed to enable the various multi-pass print modes commonly associated with ink-jet printers.

The above process represents what occurs in a real printing situation from when the user gives the command to print up to the time when the printer begins producing the final output. The procedures can be modified to simulate various proposed image-processing methods and/or printer architectures.

A software module was written to re-shuffle the bit-mapped image appropriately and count the number of pixels per unit time fired from each printhead. This module provides an interface to the thermal portion of the model. In this way, the thermal portion of the model can react to real image data as it would be presented in an actual printer.

Thermal Model

Approach

There are a number of time scales involved in printhead operation. The shortest one is associated with the power generation in individual heaters and it is typically several microseconds. The heater temperature can reach 500-600 °C during this period. This is followed by the drop generation process, which usually takes tens of microseconds. The final step in the drop generation process is the ink refill that must be completed before it is time for the next firing. Naturally this time scale is characterized by the operating frequency; it is about 80 microseconds for 12 kHz.

The energy input to generate an individual drop is normally very small ($< 15\ \mu J$). The reason for the heater temperature to reach such high values is that the heat is applied within a very small region over a very short period of time. Indeed, by the end of the drop generation process this local heat build-up diffuses out into the heater plate where the mean increase in temperature is unmeasurably small. Therefore, the detailed thermal calculations for the nucleation process can be essentially decoupled from the overall heating of the printhead.

The exact three-dimensional thermal analysis of a printhead in the continuum sense is a very complex and formidable task. The reason is that the spatial and temporal resolutions need to be fine enough to describe the individual channels and the complete drop generation process in them. This means a micron-size mesh generation throughout the array length (typically 10 mm long) and a fraction of a microsecond for the computational time step. This is far beyond our state-of-the-art computational capability for all practical purposes.

However, many thermal problems are not associated with the drop formation time scales described above. They are rather caused by the cumulative build-up of heat as a result of repeated firing at high frequency and high area coverage. Under these circumstances, these very short time scales do not need to be resolved. Instead, time-averaged values over many drop cycles can be used for the heat input and the ink flow rate in thermal modeling. For the time scales of interest, individual channels do not need to be treated in detail, as the distance between them is rather small compared to the diffusion length scales and to the other geometrical dimensions. In simulations, therefore, it is justified to represent the heaters and the channels as locally 2-dimensional that maintain their cross-sectional geometry along the length of the die. In this picture, the individual heaters are replaced by one continuous stripe of heater element and the nozzles are replaced by a slit along the die.

The validity of this modeling approach has been confirmed by extensive testing against experiments over the past several years. For example, R. Berg [1] who used infrared thermography reported that the agreement in the transient response between this model and the measurements were within several percent. One set of the results is given in Table 1.

Table 1. Comparison between modeling and experiment for a printhead fired at 9 W. The temperature was measured near the die.

Time (s)	Temperature (°C) Simulation	Experiments
1	49.7	46.2
5	57.5	57.2
10	62.9	63.1
16	68	67.9
20	70.6	70.2
25	74.6	73.7

In light of the foregoing discussions, the distinction between 2-D and 3-D models is realized if only a section of the die is fired or if there is an asymmetry associated with the heat sink. In relation to the former case, there may be a duality between area coverage and frequency: a 50% area coverage distributed uniformly along the die (say, firing every other channel) at 12 kHz would effectively represent the same thermal loading as a 100% area coverage at 6 kHz. This is due to the lack of spatial and temporal resolutions discussed earlier leading to the specification of the thermal load over a single stripe of heater element. The duality would be lost, however, if the 50% area coverage in the above example was obtained by firing all consecutive jets on one half of the die.

In many cases, a 2-D model can be used successfully without a significant loss of accuracy in the thermal response. This is partly due to the length of the die being much longer than its other dimensions. For example, if all the jets were fired in one third of the die, the peak temperature rise above the heat sink would essentially be the same as if all the jets were fired in the die. The thermal response in this case could be determined accurately by a 2-D simulation.

Unidirectional Model

For a successful printhead design, it is essential to recognize that most print documents require duty cycles far less than 100 percent. The reasons are a) documents usually contain a lot of white space; for example, the area coverage for a typical text document is about 6%, b) continuous printing is not possible due to printhead turnaround and paper change, and c) printing speed may be low (multiple passes) for high-area-coverage documents such as graphics. A typical print job, therefore, can be described by a relatively small DC component with a random sequence of superimposed bursts. All current Xerox designs employ heat sinks to smooth out these transients and to help dissipate some of the thermal energy.

A budget-conscious thermal design should take into account factors such as idle times, thermal bursts, temperature-dependent changes in drop volume and pixel energy, etc. In addition, over-engineering should be avoided. For a typical desktop application, for example, the printer may be slowed down after a certain number of high-coverage documents without disappointing the customer. Therefore, a key variable in the thermal design process would be the productivity, i.e., printing speed versus number of pages printed.

Technically speaking, two or three-dimensional models could be directly used to carry out the design iterations described above. However, the labor and the computational resources required would make this unfeasible. The design process is just too demanding. Therefore, a one-dimensional numerical model has been developed as a design tool to do these simulations efficiently. This is a conservation model composed of a unidirectional finite-difference conduction part and a lumped-mass part. The unidirectional part assumes that the heat transport takes place along a centerline connecting different subsections of the printhead from the die to the heat sink and that the temperature profile in any plane normal to the centerline is uniform. The cross-sectional area is allowed to change with distance along the centerline. The printhead is made up of many building blocks (subsections) each of which has a user-defined number of elements, element size distribution, and a prescribed set of material properties. It is also possible to assign an arbitrary distribution of heat generation to these building blocks. For example, the natural air cooling is taken into account by prescribing a convection heat transfer coefficient to those elements that represent the heat sink, whereas the pixel power input is directly applied to a block that represents the corresponding portion of the die. The dynamic behavior of the ink involves convective transport and cannot be described by conduction alone. This part of the printhead is modeled by a lumped-mass model and implicitly coupled to the unidirectional part through effective thermal resistances and masses. The amount of cooling (or heating) by the ejected ink is taken into account in this way.

The thermal interaction between the ink and the die is a complex one that depends on the details of the die geometry and the associated fluid dynamic aspects. Two and three-dimensional numerical models were made using commercially available computational programs: finite-volume models by FLUENT [2] and finite-element models by FIDAP [3]. Steady-state and transient thermal responses of various printheads were studied in detail with these models to explore the effects of geometrical features, material properties, lateral conduction, and so on. It was found from these simulations that the effective resistances used by the lumped-mass model could be obtained from the steady-state response of the printhead. The simulations also indicate that there can be large temperature gradients across the die. Studies showed that a scaling law based on normalization with the input power can be established from steady-state analysis. Extensive numerical testing revealed that transient response of the 1-D model developed by this approach gives an excellent agreement with the full numerical models. An example of this is given in Table 2.

Among many capabilities of the 1-D model are the temperature-dependent pixel energy control, and the dependence of drop volume and air cooling resistance of the heat sink on the printhead temperature. In addition, one can describe the initial, inlet, and the ambient temperatures separately. The effect of front face heating due to the presence of a dryer can also be taken into account.

Table 2. Comparison between 1-D and Finite-Element Modeling for a printhead fired at 28 W.

Time	Heater Temperature (°C)	
(s)	1-D	FEM
0	0	0
0.05	33	32
0.25	40	44
0.5	44	48
1.0	48	51
1.5	50.5	53.5
2.0	52.5	55
2.5	54.5	56.5
3.0	55.8	58
3.5	57	59.5
4.0	58.5	60.5
4.5	59.5	61

The model offers the user a number of ways to describe the thermal load, one of which is by interfacing a database. The data base includes information on different documents such as maximum printing speed, ink type, printing mode, thermal duty cycle, etc. The user can then specify a print job where a number of documents are printed in an arbitrary sequence.

The model has a built-in thermal control scheme that runs the printer at maximum speed initially and slows it down as the printhead gets hot and then increases the speed if the printhead cools. When a change of speed takes place, the model automatically adjusts for the new operating frequency and duty cycle. The thermal control is based on the readings of the heater temperature and the mean heat sink temperature for which the cutoff values are specified by the user. The model will reduce the printing speed if either of the temperature readings exceeds its own cutoff value. The heater temperature cutoff is determined from experiments as the limit for ingestion, interference, etc. There may be other failure modes, which have been conventionally characterized by the heat sink temperature. An example of this would be the air bubble growth in the die reservoir. This limit is represented by the heat sink cutoff temperature.

As discussed previously, a document first goes through the image-processing path. The output from this step is a spatial map of area coverage to be printed. From thermal considerations, however, this information needs to be converted into the time domain, that is, the thermal load should be specified in terms of duty cycle. A separate printer model has been developed to accomplish this transformation. Based on the printhead configuration, speed, and the print mode, this model reads in the output from the image processor, adds in the appropriate idle times (e.g., white space skipping, printhead turnaround), and prepares the input data for the thermal model. This data includes the time history of the duty cycle within that document as well as the time-average duty cycle and the total print time to be recorded in the database.

Table 3. A typical image set for the productivity analysis.

image	area coverage (%)	average thermal duty cycle (%)
text	6.5	7.6
color pictorial	41	7.9
photo	91	4.3

Application

In this section, we consider the application of the systems-level model to the documents in Table 3. For a given printer architecture, these documents were passed through the image-processing path, and then through the printing-time model. As it is shown in Table 3, the area coverage can be totally different from the average thermal duty cycle depending on the printer architecture and the printing mode. Next, these documents were passed through the thermal model. The results for the printing speed (normalized by the maximum or initial printing speed) are shown in Table 4 against the number of pages printed (normalized by the total number of pages for this specific job). A speed value of less than one means that this particular printer had to slow down to keep the printhead temperature within design specifications. This chart is then used for negotiation between marketing and engineering.

Table 4. A typical productivity chart for the images of Table 3 at an ambient temperature of 35 °C.

job completed (%)	text	pictorial	photo
10	1	1	1
20	1	1	1
30	1	1	1
40	1	1	1
50	1	1	1
60	1	1	1
70	1	0.76	1
80	1	0.75	1
90	1	0.67	1
100	1	0.71	1

Conclusions

This paper describes a systems-level heat management model that simulates customer-like use of an ink jet printer. To prevent over-engineering of thermal systems and to reduce their cost, a successful design must address thermal management and image processing issues in an integral framework. The unique feature of this model is that it takes into account the print mode of the printer (i.e., single pass, two-pass, etc.) along with the real image data that might be sent by a customer's application. The final outputs of the model are printing speed for a particular document (based on the print mode and arrangement of jets), and the throughput as a function of page number printed (i.e., in a long job run). This data makes it possible to assess the throughput of the printer as seen from the customer's viewpoint under various printing conditions. In this way, the design and operating trade-off decisions can be realistically assessed for their acceptance in the marketplace.

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