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SPECIAL FEATURE: MEMS development in less than half the time

How did MEMS designers at Kodak complete an 8-10 year project in just 3 years? Hint: It had something to do with virtual prototyping.

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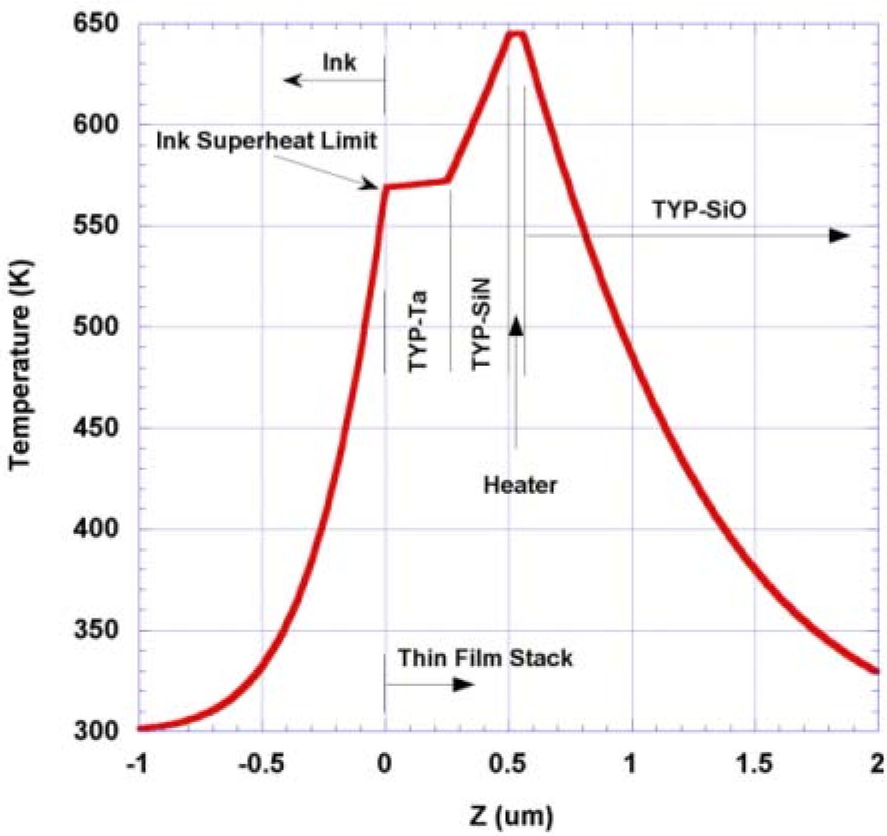
When Eastman Kodak Company decided to enter the inkjet printer market, it had no time to waste. Kodak planned to make inroads in this well-established business by using premium pigment-based inks to provide archival-quality photo prints with vivid colors designed to last a lifetime. To be cost competitive, though, Kodak needed incorporate the printhead into the printer rather than taking the traditional approach of coupling it to the replacement ink cartridge. And this meant developing a totally new printhead--the heart of an inkjet printer.

Industry experience has shown that it typically takes 8-10 years to develop an all-new inkjet printer technology. But Kodak researchers accomplished the task in only three years. They developed a design in which the ink vapor vents to the atmosphere so there is essentially no mechanical wear on the heater. One of the keys to Kodak's success was the use of simulation technology that enables them to predict the performance of a conceptual printhead design to a high level of accuracy and reliability.

Innovative ink leads to new printer line
Most inkjet printers use dye-based inks that provide vibrant colors. But dye-based inks, which use an organic dye dissolved in a solvent (similar to the ink used in a fountain pen), tend to fade over time. By contrast, pigment-based inks consist of a liquid that holds colored particles chosen for their stability. In this way, pigment-based inks are similar to oil paints.

In the inkjet printer arena, dye-based inks have always provided livelier colors while pigment-based inks have lasted longer. A key innovation that differentiated Kodak's EASYSHARE line of printers was the development of a pigment-based ink that provides the same level of brilliance as dye-based inks but lasts much longer. Kodak determined to build on this improvement by eliminating the need for each cartridge to include the costly printhead, thereby further reducing the cost of replacement ink cartridges.



Thin-film stack and ink temperature.

The challenge for Kodak engineers was to develop a printhead that could deliver this new ink precisely onto the paper and other media while providing much longer life than existing printheads. Early work at Kodak on microelectromechanical systems (MEMS) provided the foundations for a unique thermal inkjet drop ejector design. In its basic operation, the printhead works like those in other thermal inkjet printers: A short electrical pulse is applied to a resistive heater structure embedded in a thin-film stack located below a chamber that holds the ink. Approximately one microsecond after the heat is applied, the fluid next to the heated structure reaches its superheat limit and a vapor bubble begins to form. The vapor bubble expands rapidly, driving fluid through the orifice, and propelling a droplet onto the paper. In addition, some of the displaced fluid is forced back into a liquid supply reservoir. As the vapor bubble expands, energy stored in the thin fluid region adjacent to the vapor is depleted. Eventually, the bubble growth can no longer be sustained and the bubble collapses. In essence, the bubble acts as a pump that forces the droplet out of the head and onto the paper.

Incorporating the printhead into the printer

In many thermal inkjet printers, the ink in the nozzle that is not ejected collapses back onto the heater with substantial force, causing wear over time. Kodak researchers pursued an approach in which the vapor bubble vents to the atmosphere, so there is essentially no mechanical wear on the heater. In addition, the material forming the heater does not change over time as much as most thin-film heater materials. Because of this durability, the heater not only lasts through many ink tank changes, but the characteristics of the drops are stable over a period of time.

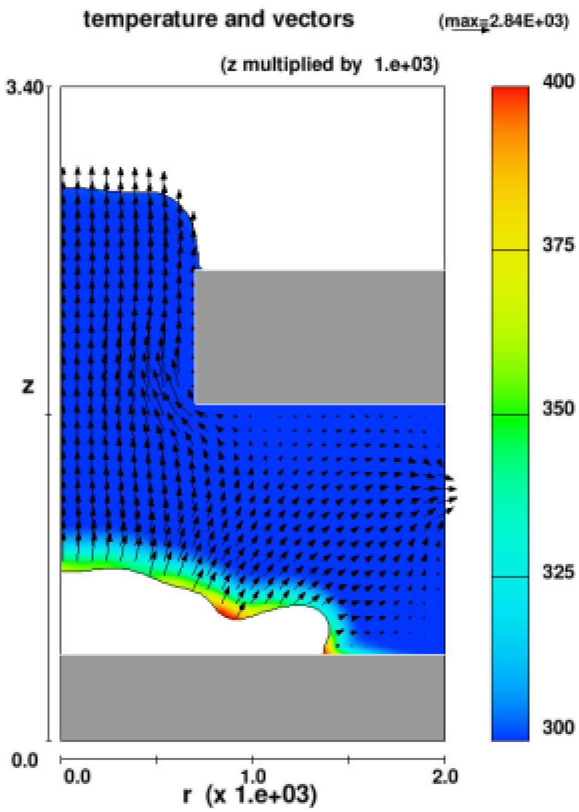
This was the result the Kodak team needed. The improvement in printhead life made it possible to consider incorporating the printhead into the printer rather than into the cartridge.

In addition, the team decided to try building the nozzles directly into the printhead. Normally, inkjet printheads have a separate nozzle plate attached to the integrated circuit that forms the printhead, creating a sandwich with fluid passages in between. It is difficult to align these components with precision, and misalignment results in dot placement errors. Building the nozzles into the printhead is an inherently more accurate method. Nozzles for KODAK EASYSHARE printers are produced using thin-film semiconductor fabrication processes. The result is a monolithic structure that provides alignment tolerances that would be impossible with traditional two-plate systems.

MEMS design challenges

After developing these concepts, Kodak researchers were tasked with optimizing the design of the new printhead. They had to answer questions such as how large to make the chamber, what diameter to make the nozzle, and how thick the nozzle plate should be. They labored under the usual constraints that apply to MEMS: physical testing will determine whether a MEMS design works but only after a time-consuming process of prototype creation. The silicon processing cycle used to produce the printhead takes about six months. If the design does not work, which is typical, then the small size of the device and the microsecond time scale of inkjet firing events make it difficult to determine why.

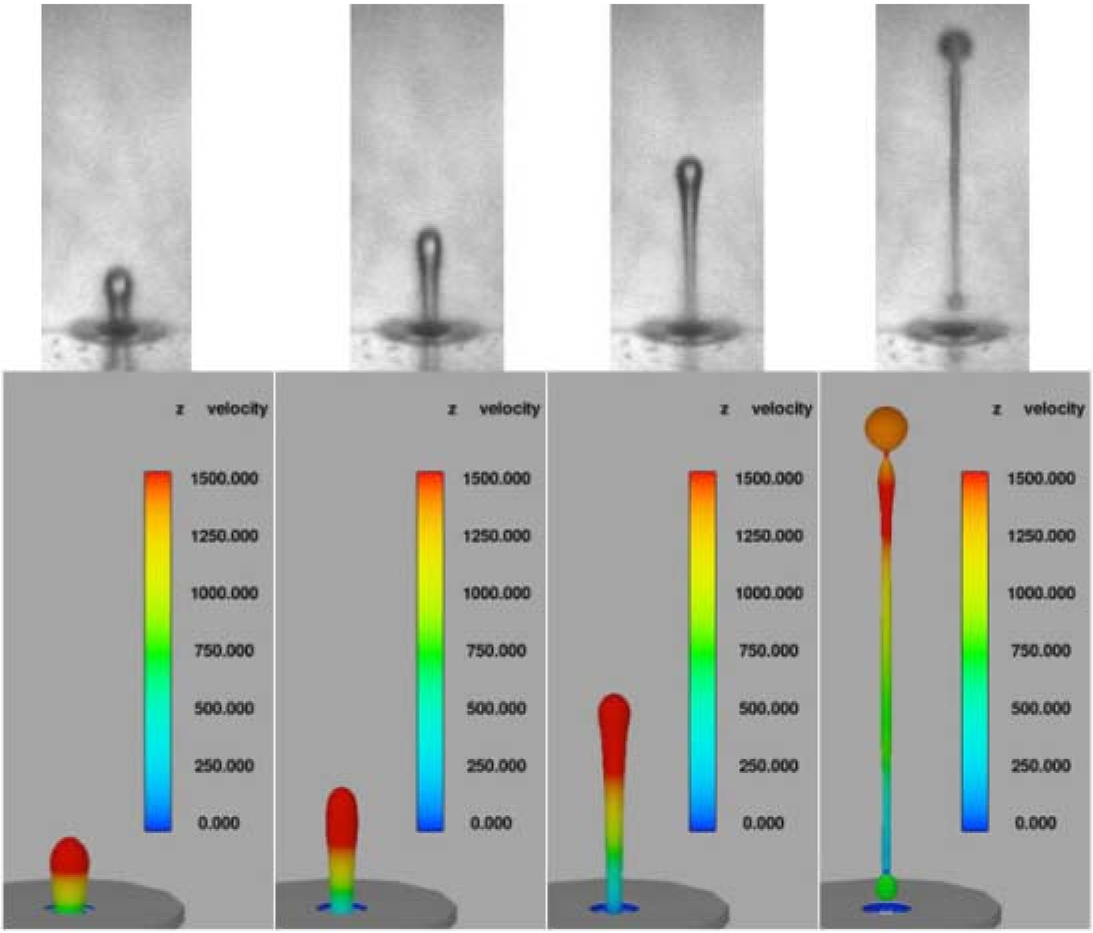
Like most manufacturers of inkjet printers, Kodak uses computational fluid dynamics (CFD) technology to simulate the operation of potential printhead designs in software in much less time than would be required to build and test a prototype. Kodak researchers recognized that to meet the time constraints of the project, they needed both very accurate simulation software and a systematic method of optimizing their design.



Homogeneous thermal bubble model.

Homogeneous bubble model
Kodak engineers met their first objective of accurately simulating the printhead operation by modeling the new printhead using FLOW-3D CFD software from Flow Science Inc. (www.flow3d.com). FLOW-3D incorporates a homogeneous bubble model that couples the formation of the vapor bubble to fluid and heat flow. A heat source within the thin-film stack is transported to the ink by conduction within the solid structure and by heat transfer at the fluid/solid interface. The vapor bubble forms explosively once the superheat temperature is reached in the fluid. The bubble is assumed to have homogeneous pressure and temperature, the dynamics of which are governed by the Clapeyron equation for the vapor. Mass and heat exchange at the vapor/liquid interface continues as the bubble expands, with the mass flux determined from kinetic theory. Surface tension and viscous forces are also included in the simulations.

Proper representation of forces and fluxes in the model depends on accurate tracking of the free surface, which is achieved by employing Flow Science's TruVOF methodology and is a significant part of the calculations.



Comparison between physical experiments (top row) and simulation (bottom row) in early experimental device configuration.

Kodak researchers were involved with Flow Science scientists in the early stages of the development of the homogeneous bubble model and contributed feedback that helped to substantially improve the model's accuracy. The model has provided excellent qualitative agreement, based on visual observations, as well as good quantitative trend prediction. Just as important, the software accurately predicts design sensitivities. In short, it provided valuable insight in support of the advanced research and development activities at Kodak. Researchers with prior simulation experience who have joined Kodak say that Kodak's simulation capabilities are substantially superior to those of their previous firms.

Design of experiments
Kodak researchers met their second objective of optimizing the design by using design of experiments (DOE) to drive their printhead simulations (see table below). The traditional approach to optimizing a product or process using computer simulation is to evaluate the effects of one design parameter at a time. The problem with this approach is that interactions between design factors and second-order effects are likely to result in a locally optimized design that will provide far less performance than the global optimum. Kodak researchers use DOE to develop tests that examine first-order, second-order, and multiple factor effects simultaneously with relatively few simulation runs. The result is that the analyst can iterate to a globally optimized design with a far higher level of certainty and in much less time than the traditional approach.

Table: DOE factors and responses
FACTORS
Chamber height
Nozzle plate thickness
Nozzle shape
Reservoir impedance
Heater size

RESPONSES
Drop volume
Drop velocity
Drop quality
Maximum firing frequency

Kodak researchers developed a series of D-optimal designed experiments that explored the design space. These experiments determined how key performance parameters such as the drop volume and drop velocity change with respect to the geometry parameters. Kodak researchers used coarser computational meshes early in the design process in order to evaluate many alternatives in the least possible amount of time. As the design began to stabilize they moved to finer computational meshes in order to increase the accuracy of the simulation results. In addition to the numerical results, the graphical output of the simulation was very useful in helping researchers derive insights by visualizing flow fields and free surfaces.

By using DOE to drive CFD, Kodak researchers were able to optimize the design of the printhead in considerably less time than competitors. The advantages of simulation were especially apparent late in the project when researchers discovered a more optimal ink formulation for one of the colors. The ink was quickly reformulated to capitalize on these advantages. But would it be necessary to spend a year or more redesigning the printhead? Fortunately, the Kodak team had already run sensitivity studies on the ink properties, so without running a single additional simulation it quickly determined that the existing printhead design would work fine. The EASYSHARE family of printers was thus launched only three years after the project was initiated, in approximately one-third the amount of time typically required to bring new inkjet technology to market.

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