Designing and Optimizing an Ink Cartridge for Use with Higher Viscous Inks

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Abstract

A study is presented which demonstrates the design and optimization of an ink cartridge to be directly connected to the print head and to be used with higher viscous inks. A higher viscous ink is desirable for achieving a smooth drop formation with a low satellite content. On the other hand the increase of ink viscosity will also increase the ink flow resistance within the whole ink supply system. All the commonly used drop on demand firing ink jet heads require a back pressure in the ink supply system for balancing the capillary forces of the nozzle orifices. A high flow resistance of the supply system will add another component to the back pressure of the cartridge, which is dependent of the amount of nozzles fired at a time. This may result in an uneven print appearance - for example areas will print lighter than characters. This is because the ink drop volume is dependent on the negative pressure. Hence the design target for the cartridge should be:

- a minimization of the impact of the flow resistance throughout the whole operation window of the print head and cartridge,
- an even back pressure curve with a moderate increase during the cartridge ink supply period and
- a high ink yield of the cartridge.

From a detailed discussion of the design process important parameters are derived, concerning:

- the material selection,
- the cartridge construction and engineering and
- testing and approval.

In the result a cartridge functionality is achieved, which allows printing with an arbitrary work load throughout the operation window with small restrictions in the low temperature regime.

Introduction

Computer printing in the industrial environment demands for “paper crunching” devices, which are:

- highly reliable,
- capable of running large paper volumes at maximum speed with high print quality,
- able to print for long times without operator intervention,
- printing under a wide range of ambient temperature and humidity conditions and
- insensitive to dust, shock and other impacts.

Dedicated to this field of application, which previously was a domain of impact printing, is Tally’s T3016 Sprint Jet printer with two 128 nozzle piezo ink jet print heads as the printing technology core. Ink and back pressure are provided from one or two (color version) tanks sitting below the print head module on the carriage. The moving tanks are connected to a stationary cartridge via a flexible tubing. Ink is supplied by a peristaltic pump on request of a ink level sensor signal in the moving tank. Head maintenance is provided by a print head capping and servicing station. The purge ink is fed back to the stationary cartridge into a separate waste ink bag.

The ink is based on a low volatile hydrocarbon carrier liquid with a high content of black or colored pigment dispersion. The ink viscosity is about 11mPa*s at room temperature. Features of this ink supply system are:

- always a constant back pressure level,
- low flow resistance impact on the back pressure because of short tubings between moving tank and head and
- big supply ink volume from the stationary cartrige.

The advantages of the oil based inks are:

- smooth drop formation with low satellite content due to the high viscosity,
- instant smear resistance on most of the common plain paper stock,
- the low volatility, which counts for long service intervals with a low nozzle clogging tendency and
- an arbitrary mixability of the color dispersants.

In order to get more experience on ink supply systems a study was started targeting the feasibility of a simple ink supply system for this area of application.

The goals to achieve were:

- simplicity of the whole supply system,
- ink storage on the print head carriage,
- ink leakage protection,
- ink supply conditions as constant as possible throughout cartridge life and over all print conditions and
- simple waste ink handling.

Foam Cartridge Choice - General Aspects

As the simplest approach a foam based cartridge system was chosen because of:

- the simplicity of configuration and
- the variation bandwith of adjustment parameters.

Problems encountered are:

- geometry constraints - position of print head and cartridge with respect to each other as shown in Fig. 1,
- carriage acceleration, when printing swath by swath,
- temperature allowance and
- flow resistance.

Figure 1 shows the geometric constraints for positioning of the ink cartridge with respect to the print head.

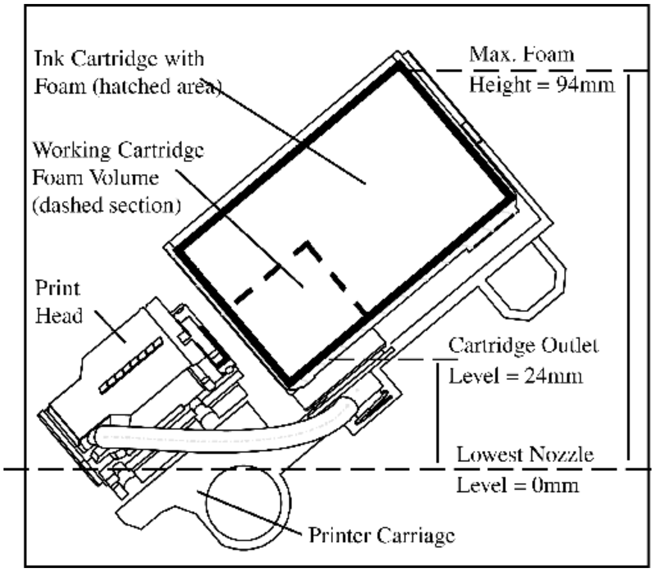

Figure 1. Printer carriage with print head and cartridge in their geometric position in the printer. The foam area within the dashed square represents a cross section of the volume of the "Working Cartridge", which was a cube of that size. Further data in text below.

These geometric requirements are very challenging for a cartridge design, since it is positioned very high above the print head compared to conventional foam cartridge geometries. The high ink viscosity with respect to water based ink adds even more difficulties. The print head in use is from Xaar Jet AB and requires a back pressure range of -1 to -4 hPa, independently of the work load or duty cycle. The adjustment of a foam to the proper back pressure range is accomplished by thermal compression in one dimension. This gives a pretty linear relationship between back pressure and compression factor. However the linear increase is counterbalanced by an exponential rise of the flow resistance, which is dependent on the 4th power of capillary radius (Hagen-Poiseulle-Law).

Therefore we started very conservatively by restricting the cartridge volume to a small fraction of the total space as indicated by dashed lines. This "Working Cartridge" should serve as an independent ink supply for the print head and be refilled from a bigger ink container on an ink empty request. The discharge characteristics is shown in Fig. 2.

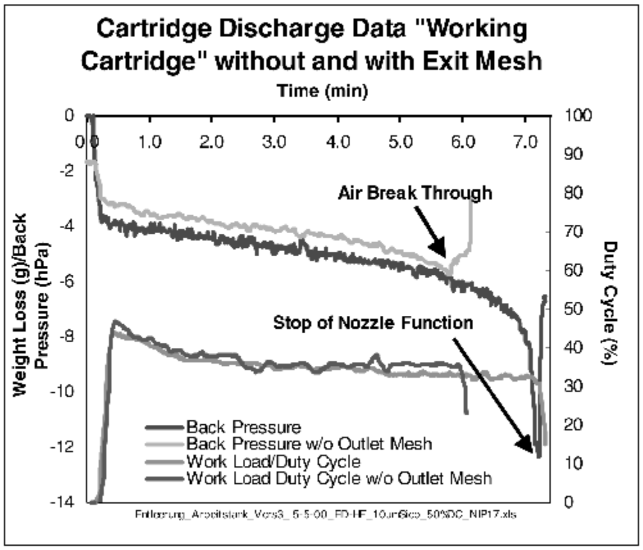

Figure 2. Discharge characteristics of the "Working Cartridge" with and without mesh at the ink outlet

Cartridge parameters:	
Foam Material:	PU-Ester
Foam Volume:	8ml
Pore Count:	80ppi @ 30kg/m³
Compression:	2,5x
Ink load:	6,3g
Ink Yield w/o Mesh:	5.1g
Ink Yield with Mesh:	5.6g
Outlet Mesh:	ø9mm 10µm Mesh

The upper curves show the back pressure on left y-scale, developing over time, the lower curves the work load on the right y-scale. This is the ratio of all nozzles fired at the actual frequency to all nozzles fired at maximum frequency (8kHz in our application). As clearly seen - the introduction of a 10µm steel mesh in the ink outlet of the cartridge increases the ink yield but also rises the flow induced back pressure.

Cartridge Testing Setup

The cartridge testing setup is quite common - except that a print head is employed as the ink pump. Fig. 3 on the next page shows a schematic sketch.

Cartridge and print head are positioned according to the printers geometry constraints (see Fig. 1). The heads nozzle plate is sealed with a drop catching device, which protects from ink drop fog and guides the ink into a vessel placed on a balance. The back pressure is measured at the level of the lowest nozzle. The following ink drop patterns can be generated presently:

- all nozzles firing with variable frequency,
- all nozzles firing at 8kHz with a symmetric on-off-period of 5ms (latest addition to the set up) and
- manual on-off switching of the fire patterns.

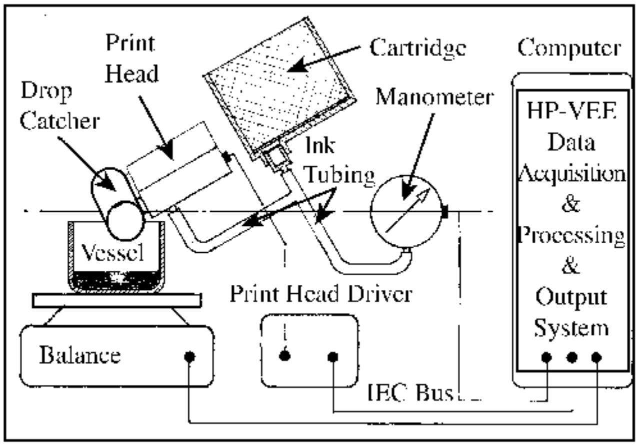

Figure 3. Schematic cartridge test setup. The dashed line through manometer and print head show the level of the lowest nozzle with respect to the position of the other components as already explained in Fig. 1.

Ink weight, back pressure and timing are computer processed via HP-VEE software into an Excel sheet.

Using a print head as an ink pump is advantegous because it allows for an arbitrary choice of firing patterns and a track of the print head properties, but it is difficult to control a potential nozzle failure during operation.

Cartridge Design - Ball Park Numbers

Two physical effects dominantly rule the cartridge behaviour: **The ink-foam capillary interaction force**, yielding the ink storage in the foam and balancing the gravitation force of the ink column and the capillary forces of the ink nozzles. The capillary fill height Δh is given by:

$$\Delta h = \frac{4 \cdot \sigma \cdot \cos \alpha}{\rho \cdot g \cdot d} \tag{1}$$

where σ is the surface tension, α the contact angle, ρ the ink density, g the gravitational acceleration and d the capillary diameter.

The “Ohm’s law” for laminar fluids in circular tubings-Hagen-Poiseuille law, responsible for the pressure drop Δp in a flowing liquid, which is given by:

$$\Delta p = \frac{128 \cdot \eta \cdot l}{\pi \cdot d^4} \cdot \dot{V} \tag{2}$$

where η is the dynamic ink viscosity, l the length and d the diameter of the tube and is the ink volume flow.

A simple experiment was carried out determining the capillary rise of the ink in different tubings. Fig 4 shows a result on Teflon tubings. They yield a little less height than our actual tubings (<10%), but a much better reproducibility.

From Fig. 4 it is evident that at small capillaries below 1mm diameter the ink fill height is very sensitive to small diameter variations.

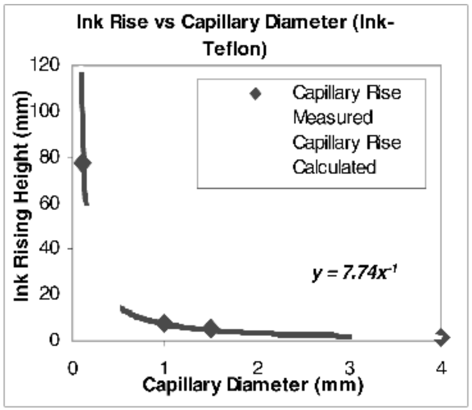

Figure 4. Ink capillary rising height in teflon tubing with various diameters.

Formulas and data can now be used be used to determine the required foam properties - here is the way to go:

1. Select The Appropriate Capillary Diameter

A back pressure of -1hPa at the lowest nozzle is achieved with a capillary fill height of about 106mm, giving a capillary diameter of 73µm according to Fig. 4.

2. Select a Foam Material and Determine the Compression

In earlier foam compression experiments the capillary diameter/compression ratio was found to be constant. With an 80 pores/inch foam the capillary diameter estimate is 317µm. Thus the foam needs to be compressed by a factor of 4.3 to give an pore diameter equivalent of 73µm.

Doing so the static ink hold parameters are defined. This proceeding is verified by the experimental results which are presented further below. However it has to be kept in mind that only a fraction of all capillaries is usually within the target range. It is commonly understood, that compression narrows the pore distribution, which helps to equalize the ink hold properties and increase the number of useful capillaries. As the next step the ink flow properties need to be determined.

3. Determine the Maximum Ink Flow Per Capillary for a Pre-Determined Flow Pressure Drop

Eq. (2) should be calculated with the following numbers:

Capillary diameter:	73µm (as above)
Capillary length:	70mm (foam diagonal)
Viscosity:	$11 \cdot 10^{-3}$ Pa·s
Pressure drop allowance:	200Pa

This gives a volume flow of 180pl/s per capillary. The maximum ink flow of the print head in use is 38µl/s - all nozzles fire at a repitition rate of 8kHz. Hence it needs roughly 211.000 pores, where the ink has to be drawn simultaneously. Consequently:

4. Determine the Foam Discharge Area, Where Ink Has To Be Drawn Simultaneously At Maximum Duty Cycle

After compression the main pore diameter is 73µm. For simplicity it is assumed that the 73µm pores are tightly packed in a regular pattern yielding an area density of 18765 pores/cm². So the discharge area is 11.25cm² or a square of 3.4cm side length.

This is different with respect to common cartridge designs for water based inks. There is not only a smaller discharge area, but also very often an additional compression zone in the foam or even an additional highly compressed "pill". This increases the capillary force, thus promoting the ink presence in the outlet area and preventing a potential air access to the ink supply.

Cartridge Description

The results above encouraged us to skip the "working cartridge" and to go for a big one, filling the whole available space. Fig. 5 shows the general outline.

Special attention was paid to the ink collecting space around the ink outlet. A so called "kitchen sink" design was chosen with three planes slowly descending towards the ink outlet. Spacers in a regular order were introduced into the sink to:

- prevent the foam from filling the sink and protecting the space for liquid ink around the outlet and
- form a barrier against excessive ink movement during cartridge acceleration.

The slanting planes of the sink form a knife edge volume with the foam bottom. It will be filled with ink by capillary force from the edge, when the back pressure is present. Thus additional air in this area will be directed to the outlet when the cartridge passes the activation process.

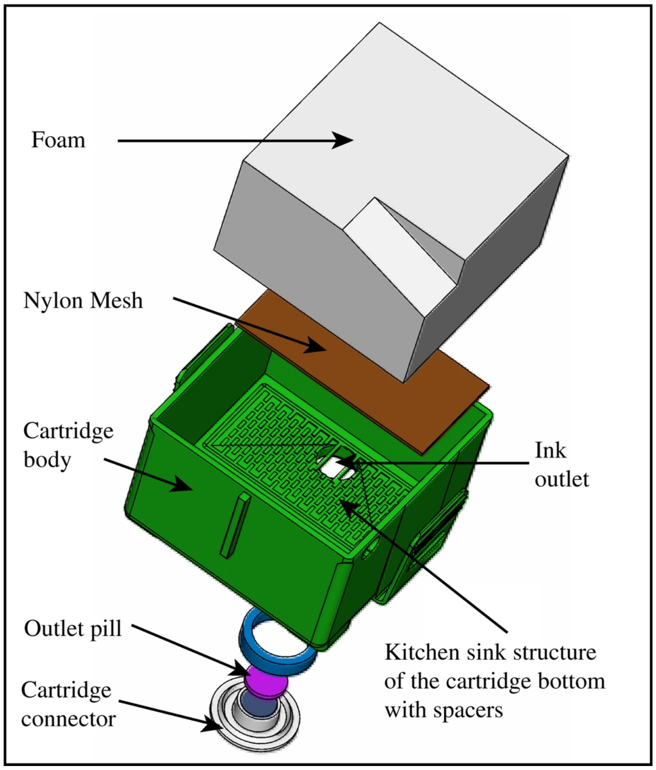

Figure 5. Exploded volume model of the foam cartridge

The Nylon mesh, covering the sink structure, is introduced to protect the ink path from foam debris and from an early air breakthrough, which might be due to early emptied foam areas caused by foam production/compression inhomogenities. The effect of the mesh as an air breakthrough barrier was shown in Fig. 2.

A low compression foam pill is fitted to the cartridge outlet, serving as a drop catcher, when the cartridge is removed. The cartridge connector as the counterpart on the carriage is covered with an 80µm steel mesh, which serves to hold the ink in the tubing by capillary force and the head when the cartridge is removed.

Results

Results are presented for the impact of:
- the work load,
- the Nylon mesh and
- the temperature

on the back pressure.

Figure 6 shows discharge curves with and without the influence of the Nylon mesh in the cartridge bottom.

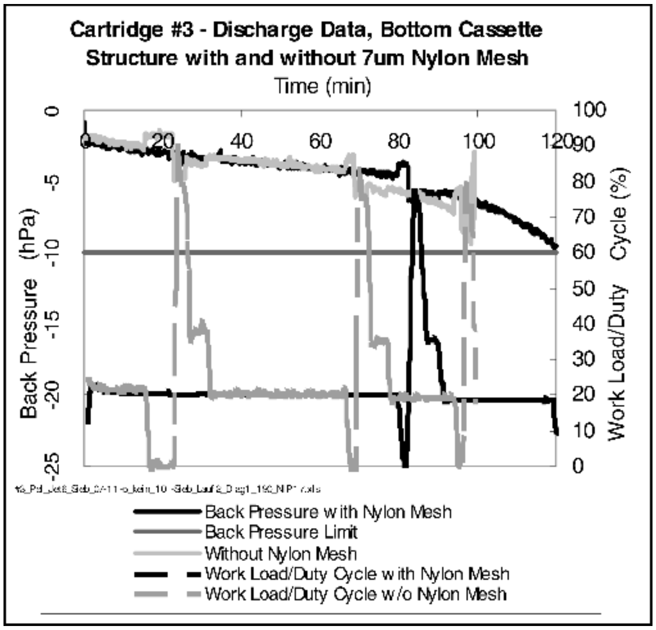

Figure 6. Discharge Data of cartridge 3 with and without Nylon mesh.

Cartridge Parameters:

Foam material:	PU-Ester
Foam volume:	160ml
Foam density:	60kg/m³
Compression:	2.8x
Ink load:	91g
Ink yield:	53g
Cartridge bottom:	Cassette structure with/without Nylon mesh
Outlet mesh:	No

Work load variations have been achieved by manually switching the firing frequency.

The cartridge was an earlier stage version with a bottom structure of equal depth and a cassette like alignment of the spacers. Concerning the influence of the Nylon mesh the comparison of the two back pressure graphs shows a non noticeable difference in the first half of discharge. In the second half the decline of the discharge curve without Nylon mesh is steeper presumably because now air from already discharged foam areas can enter into the cartridge bottom and thus hamper the ink flow and increase the flow resistance.

As a first consequence from the cartridge behaviour a back pressure limit of -10hPa was introduced. This exceeds the manufacturers specification, but the experience shows, that with the bottom Nylon mesh installed, all cartridges could be discharged safely to this level without loss of functionality of the printing system.

Looking at the ink flow induced back pressure reveals the relationship shown in Fig. 7.

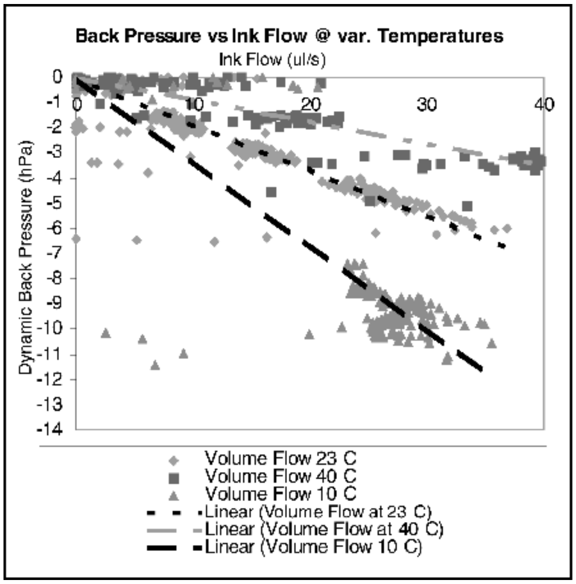

Figure 7. Back pressure dependence on ink flow at various temperatures.

Parameters:

Foam Material:	PU-Ether
Foam Volume:	160ml
Pore Count:	55ppi, @31kg/m³
Compression:	5.4x,
Cartridge Bottom:	Cassette-Structure
Outlet:	ø9mm 10µm-Mesh

Three cartridge discharge curves at three different temperatures of the cartridge have been processed in this diagram. This was accomplished by heating or cooling of the cartridge body respectively. The different back pressure values have been achieved by manually switching the firing frequency. The back pressure-volume flow data pairs have been sorted by ascending ink flow values. A lot of scattering comes into the data because the volume flow values have to be taken from consecutive weight values.

The three data point sets represent the cartridge discharge flow pressure at the temperatures, 10°C, 23°C and 40°C respectively. This is also the operating temperature window for the printer. The linear trend lines are justified by equation 2 and the origin at zero ink flow because of the static back pressure has been subtracted from each data point. The 10°C data set exceeds the back pressure of 10hP at an ink flow above 25µl/s.

Figure 8 shows a cross section at an ink flow of 20µl/s. Additionally the ratio of back pressure and viscosity is plotted. In absence of further influence on should obtain a horizontal line.

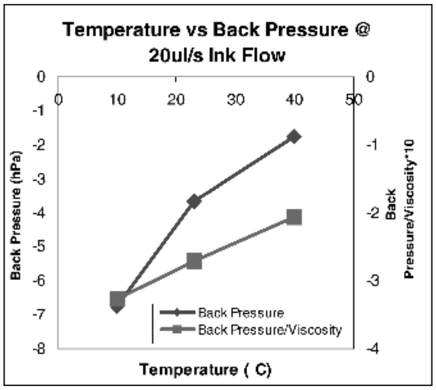

Figure 8. Temperature vs back pressure at an ink flow of 20µl/s and ratio of back pressure and viscosity-cartridge date from the previous figure.

It is evident that the back pressure decreases more than a single viscosity dependence would predict. Responsible for this deviation is most probably an additional capillary expansion and thus a capillary diameter increase with rising temperatures. Nevertheless a printer control scheme should decrease the printing work load at low temperatures to avoid any starvation of the print head nozzles which results in light print appearance, printout deformation through distorted nozzles or even an early end of the cartridge. Fortunately the printers have a closed chassis and produce their own heat during operation, so that this restriction will be overcome within reasonable time of operation.

Finally a discharge curve according to the present engineering stage is shown in Fig. 9 on the next page. Here two foam slices are put on top of each other. The upper one has a cut off leaving a spare room in the cartridge. Experiments have been carried out with this configuration, where the ink from print head activation and purge procedures was returned back into this area of the cartridge. This is advantageous because:

- no extra waste ink container in the printer is needed,
- a very simple storage of the waste ink is realized and
- the waste ink column reduces the back pressure in an advanced discharge status of the cartridge.

This can be successful realized with oil based inks and this cartridge design because:

- the oil vapor pressure is neglible - the ink hardly dries,
- foam and mesh prevent debris from being fed back into the ink supply path.

This scheme will be further developed.

In the jetting pattern behind the back pressure curve in Fig. 9 all nozzles were fired at a repitition rate of 8kHz and with a symmetric on-off-period of 5ms, yielding a duty cycle of 50%. This should simulate a bar code like print pattern with a heavy work load. It means that the print head rapidly switches between 100% and 0% duty cycle. The firing was repeatedly interrupted to obtain also the evolution of the static back pressure over the cartridge discharge. It is seen that the static back pressure slowly decreases within each off-period, slightly more in the off-periods towards the discharge end. This can be explained as a relaxation effect by which partly ink flows from narrower capillaries to wider ones, which are at a lower filling level from the last discharge. This can happen when capillaries have irregular walls and are interconnected with ink passages sideways. The core diameter is quickly emptied by the printhead firing. But the wall cavities of the empty capillaries exert enough capillary force to draw ink from neighbouring capillaries which are on a higher ink level. So the ink can flow downwards, partially refill empty capillaries and thus decreases the back pressure. This balancing process should be slow because the capillaries in action are narrow.

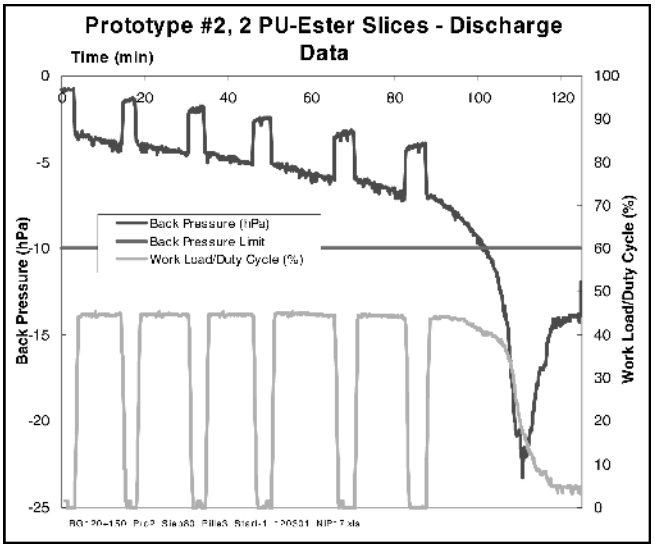

Figure 9. Discharge data of prototype #2 cartridge with two PU-ester slices, further explanation in the text.

Cartridge parameters:

Foam Material:	PU-Ester 2 Slices
Foam Volume:	160ml,
Pore Count:	80ppi @ 30kg/m³
Compression:	5x lower, 4x upper slice
Ink load:	96g,
Ink yield (-10hPa):	68g
Cartridge Bottom:	Sink-Cassette-Structure 7µm Nylon Mesh
Outlet:	80µm-Mesh

The ink yield of 70% is not very exciting, but a reasonable value in this environment. Any improvement is subject to a very careful cartridge and foam optimization process. In any case it might be difficult to draw more ink from the foam, because of the extremely strong wetting properties of the ink oils, which will hold back a lot of ink even in an extremely emptied cartridge.

Conclusion

The design and optimization of a foam cartridge for use with higher viscous ink has been presented. The discharge parameters have been estimated and the cartridge has been laid out according to the results. For the experimental verification a cartridge testing setup, which employs an ink jet head, has been developed. Discharge curves were obtained, which show the development of the back pressure in relation to:

- the foam material,
- the foam compression,
- the ink flow rate, which is the work load/duty cycle of the print head,
- the discharge status,
- the influence of additional mesh elements and
- the temperature.

As the result a cartridge was presented which allows printing within the operational window of the printer with only little restrictions to work load in the low temperature region. Further optimization with respect to higher ink yield and less temperature dependence is under way.

References

Several patents pending.

Acknowledgments

The authors are grateful to Gerhard Schmidt of Tally for setting up the data acqusition system and Gerhard Beurer of Tally for his advices on several print head functions and his helpful remarks on generating this paper. Part of the work has been carried out in collaboration with the Pelikan Hardcopy Production AG and the support of the Pelikan developer`s staff is kindly acknowledged.

Biography

Henning Frunder holds a Ph.D. in Physics from the University of Munich. After working seven years at Siemens, now Océ, on Laser printing technologies, he joined the Tally Computerdrucker GmbH in 1991. Since then he is working on several laser and ink jet printer projects. In the recent years he was mainly involved in the field of printing inks and ink supply schemes. Henning Frunder is the author of several patents and publications in the field of non-impact printing technologies.