

Ink Drying in Inkjet Printers

Domino UK Ltd

1 Problem Statement

The first problem put to the Study Group for Maths in Industry by Domino UK Ltd concerns ink drying and blocking nozzles in a printer. The goals were as follows:

1. To propose mechanisms for the growth of a plug of dried ink in the open end of a Drop-on-Demand drop generator,
2. To suggest cures to this problem,
3. To consider why oscillating the meniscus appears to alleviate the problem.

2 Background

Many kinds of inkjet printers contain nozzles that are essentially open ended tubes filled with ink. Droplets are ejected from the open end by an acoustic disturbance generated within the tube. The difficulty that arises is that if the ink is at all volatile, the ink at the open end is likely to dry out and form a blockage. As it is desirable to use volatile inks, this problem needs to be explored.

It is the nature of such a printer to be operated sporadically. Therefore, there may be times of the order of minutes between successive drop ejections. It is also given that the ink is a mixture of solvent, ink pigment and polymer. Specific details of the ink parameters are given in the Appendix. The nozzle diameter is about $50\ \mu\text{m}$, and the length of a blockage is considered to be of the order of one or two diameters. It is also noted that the inks that quickly form a blockage at the end of a narrow tube do not form a surface skin when left in a container of much larger diameter (10^3 times larger).

3 Proposed Mechanisms for ink drying

3.1 Phase-separation and adhesion

For some three-component mixtures, the mixture can be a solid, liquid or a two-phase mush, depending on the concentrations. Figure 1 illustrates a phase diagram for such a mixture, where the broken line is the trajectory of concentrations as solvent is reduced.

Looking at the boundary between solid and liquid, where the concentration jumps between C_{es} and C_{el} , we conserve mass across the boundary:

$$V[C] = \left[D \frac{\partial C}{\partial n} \right],$$

where $[]$ denotes a jump in a quantity, and D denotes diffusivity.

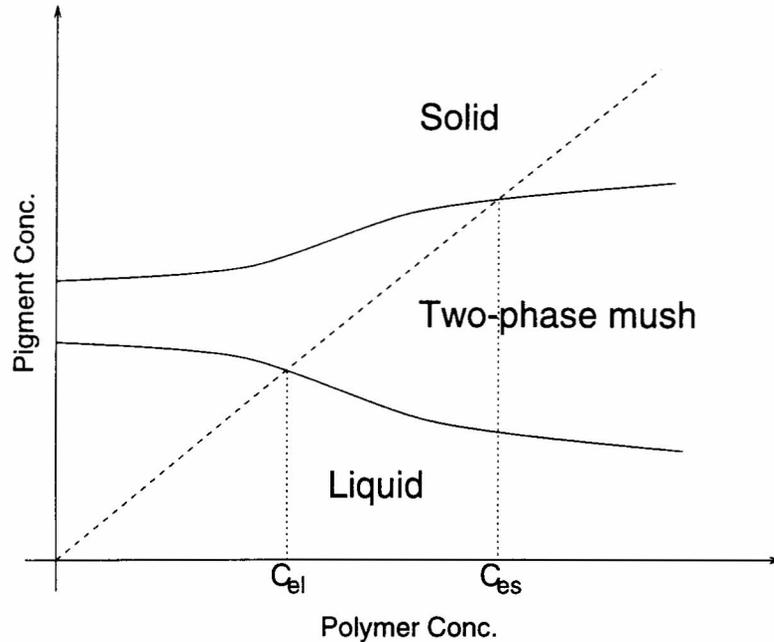


Figure 1: Phase diagram

Now, observing that a $50\ \mu\text{m}$ spherical drop of ink which spreads out on the print surface to twice this diameter evaporates in approximately one second, we estimate a typical evaporation velocity of the ink as $V = 10\ \mu\text{m/s}$. Combining this velocity with the diffusivity of polymer $D = 10\ \mu\text{m}^2/\text{s}$, we estimate the thickness of the layer where polymer can diffuse away from the surface on the timescale of evaporation as $10\ \mu\text{m}$.

If nucleation occurs at the surface, there will be a solid layer as soon as the concentration of polymer reaches C_{el} . This layer between the ink and the air has a concentration profile shown in Figure 2, where z is the vertical distance from the initial height of the mixture.

If, however, the solid can only nucleate at the wall, a solid rim will form around the edge of the container, as shown in Figure 3. The build-up of polymer is expected to be enhanced by a smaller contact angle, because this produces a thin layer near the wall with large surface area relative to volume.

3.2 Gel with Mechanical Strength

The concentration of polymer increases, as in the first theory, due to evaporation of the solvent and mass transfer occurs by diffusion. No phase-separation occurs in this model, and no nucleation is necessary.

This theory suggests that the mixture gels when the polymer concentration, C , reaches some critical level C_g . In this layer, the envelopes of the polymers are considered to pack together like spheres. The gel would appear to be a porous matrix of threads of polymer with some mechanical strength, as shown in Figure 4. Here we assume $D \approx 10\ \mu\text{m}^2/\text{s}$.

There are two variations on this model regarding transport of solvent and polymer:

1. Diffusion - In the gel layer, δ , the movement of solvent and polymer is governed by diffusion. Diffusion through the gel is that of liquid in between gel particles, and the concentration in this region is $C < C_g$. This resembles a porous medium.

2. Capillary Pressure - Also considering the porous medium, the solvent is transported

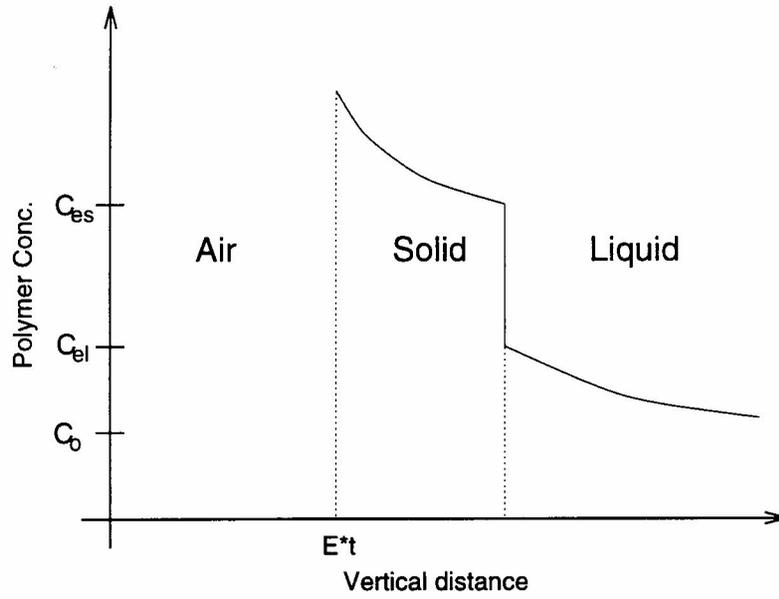


Figure 2: Concentration profile in surface layer

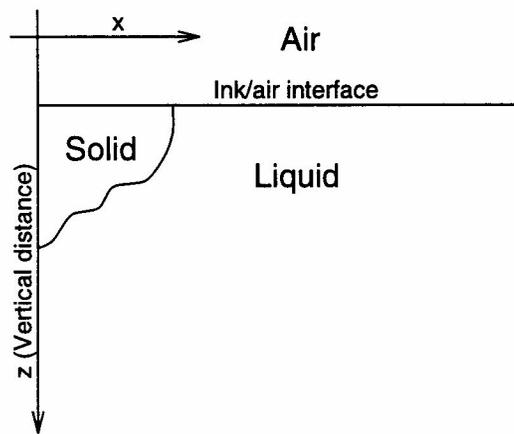


Figure 3: Build-up of solid at wall

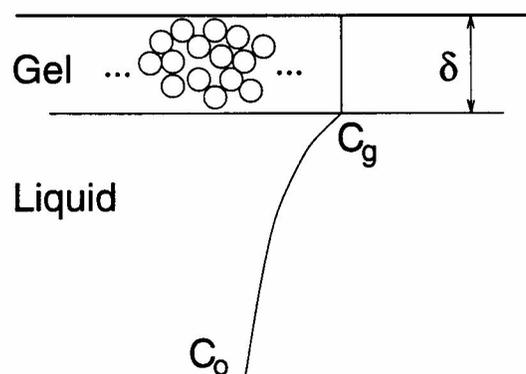


Figure 4: Concentration profile of gel layer in beaker

across the gel not by diffusion but by capillary pressure arising from high curvatures of the fluid surface in the pores. The meniscus between gel particles would create a pressure which would draw up more solvent towards the surface, much like the transport of water up the stem of a plant as it evaporates out of the leaves.

The gel layer increases in thickness because the solvent from beneath the skin is able to rise and pass through, evaporating into the air and leaving behind more polymer.

The gel is assumed to be likely to break up when it has effectively low strength, as in the skin over a large diameter vessel like a beaker ($5 \times 10^{-2} \text{m}$). For a narrow vessel such as the inkjet nozzle ($5 \times 10^{-5} \text{m}$), the strength of the gel layer may be sufficient to survive and grow to a depth comparable to the diameter and plug it up.

3.3 Convection

Convection can be driven by a number of mechanisms, including a temperature gradient (e.g. cold water over hot), a density gradient (e.g. salty water over fresh) or a surface tension gradient (e.g. blowing on hot coffee). In the ink drying problem, it is natural to consider a temperature gradient (which physically becomes a density gradient) due to evaporation of solvent. There is cooling at the air/ink interface as the latent heat required to evaporate solvent is removed from the ink. This results in a thermal boundary layer where the ink is more dense. To quantify the potential for convection, we recall the Rayleigh number. The Rayleigh number is the dimensionless parameter that measures the ratio of a destabilizing temperature gradient to the stabilizing diffusion. In the present case, where cooling is driven by an applied heat flux (due to evaporation) rather than an applied boundary temperature, the appropriate definition is

$$Ra_{flux} = \frac{\alpha g f d^4}{\kappa^2 \nu \rho c_p}$$

where

- α is cubic expansivity
- g is acceleration due to gravity
- f is heat flux = $V \rho L$
- V is evaporation rate
- ρ is density
- L is latent heat
- κ is thermal diffusivity
- ν is viscosity
- c_p is specific heat

For a particular geometry and set of boundary conditions, there is a critical Rayleigh number above which natural convection will occur. Classic solutions for Ra_{crit} are 1708 between two flat plates, and 216 for a fluid in a conducting tube. For the ink drying problem, it was estimated that

$$Ra_{flux} = \begin{cases} 10^7 & \text{3 cm beaker} \\ 10^{-4} & \text{30 } \mu\text{m tube} \end{cases}$$

For this reason we can expect convection in the beaker but not in the nozzle. The convection in the beaker would cause mixing and reduce the concentration of polymer near the surface. There was some discussion about polymer and pigment being less dense

than solvent. However, any such stabilizing effect only applies in a much thinner region near the surface, so thermal convection is expected to dominate in the beaker.

4 Proposed Remedial Measures

4.1 Surface Coating

Considering the mechanism described in section 3.1, a solution would be to stop polymer building up on the walls. A surface coating that likes solvent (amphiphilic) but dislikes polymer would inhibit nucleation and prevent build-up of solid. Such coatings can be electrically deposited inside the nozzles. However, it is likely that the solvent and polymer have similar affinities otherwise they wouldn't like being mixed together, so it may be unlikely to find a coating that reacts differently towards the solvent than the polymer.

4.2 Tube geometry

Three remedies were suggested which involved the geometry of the nozzle and air/ink interface.

a) Drawing the ink back into the tube would trap the solvent vapour more, and inhibit evaporation at the air/ink interface.

b) Drawing the ink back into a wider chamber where vapour can be further trapped and convection may be set up. A larger air/ink interface would decrease the strength of the gel layer and may prevent blocking.

c) Bathing the exit in solvent vapour so an equilibrium is set up, thus reducing the tendency to dry ink.

4.3 Oscillating the meniscus

It was mentioned during the problem presentation that wobbling the meniscus was found experimentally to inhibit blockage formation. As this remedial measure is not new to Domino, it is mentioned here incidentally. It is helpful, however, to note that the oscillation may have two effects on blockage formation.

a) Breaking of the polymer gel that is trying to build up at the surface, thus inhibiting a mechanically strong gel layer from developing.

b) Setting up mixing in the tube which convects excess polymer away from the meniscus.

The mechanism governing this mixing in the nozzle could be due to the phenomenon of acoustic streaming. The details of secondary streaming in oscillatory flow merits a separate section and is discussed below.

5 Prevention of nozzle blocking by acoustic streaming

Small amplitude high frequency oscillation in the ink nozzle can produce a steady secondary streaming flow which would disperse the surface layer of concentrated polymer. The question is how to enhance its effect on delaying formation of a blockage in the nozzle.

The phenomenon of acoustic streaming in a pipe requires two conditions. First, that the fluid in the pipe undergoes small amplitude high frequency oscillation. This sets up a Stokes layer on the wall of the pipe, accelerating back and forth at some lag behind the driving oscillation. Second, there must be some asymmetry in the pipe, which causes the Stokes layer to move farther in one direction than the other. The secondary flow occurs because this wall layer has a net acceleration along the tube.

[Refs: Hall, J. Fluid Mech. vol 64, 1974 (tube); Grotberg, J. Fluid Mech. vol 141, 1984 (channel)]

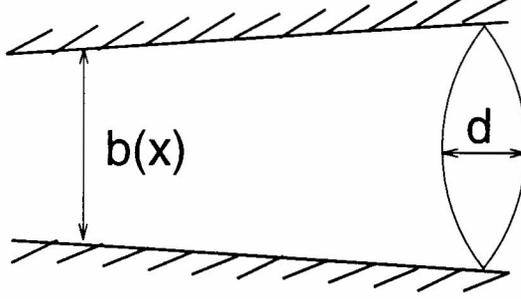


Figure 5: Tapered channel

Figure 5 illustrates a tapered channel, as described in Grotberg (1984) where the channel height is $b(x)$ with a small taper angle $\epsilon \approx b'(x)$. The displacement amplitude is d (small compared to height b) and angular frequency ω . The important parameters are the oscillatory Reynolds number

$$Re = \frac{\omega b^2}{\nu},$$

and

$$\lambda = \frac{\epsilon d}{b} \quad (\ll 1).$$

For high Reynolds numbers, the Stokes layer thickness $\sqrt{\frac{\nu}{\omega}}$ is small compared to the channel height b . However, it is found that streaming velocity varies rapidly over a larger boundary layer of thickness $\frac{1}{\lambda} \sqrt{\frac{\nu}{\omega}}$. Figure 6 shows the velocity profile near the wall during this secondary streaming.

The steady streaming velocity in the inviscid core scales as

$$u_s \sim \frac{\epsilon \omega d^2}{b},$$

so that the streaming flux across the cross-section scales as

$$\Psi \sim \epsilon \omega d^2.$$

At Reynolds numbers of order one, the Stokes layer thickness is of order b and the streaming velocity now scales as

$$u_s \sim \frac{\epsilon \omega^2 d^2 b}{\nu},$$

so that the flux is now

$$\Psi \sim \frac{\epsilon \omega^2 d^2 b^2}{\nu}.$$

and is plotted in Figure 7. As the frequency is a parameter which can be easily changed experimentally, we recommended an attempt to increase the flux by increasing the frequency.

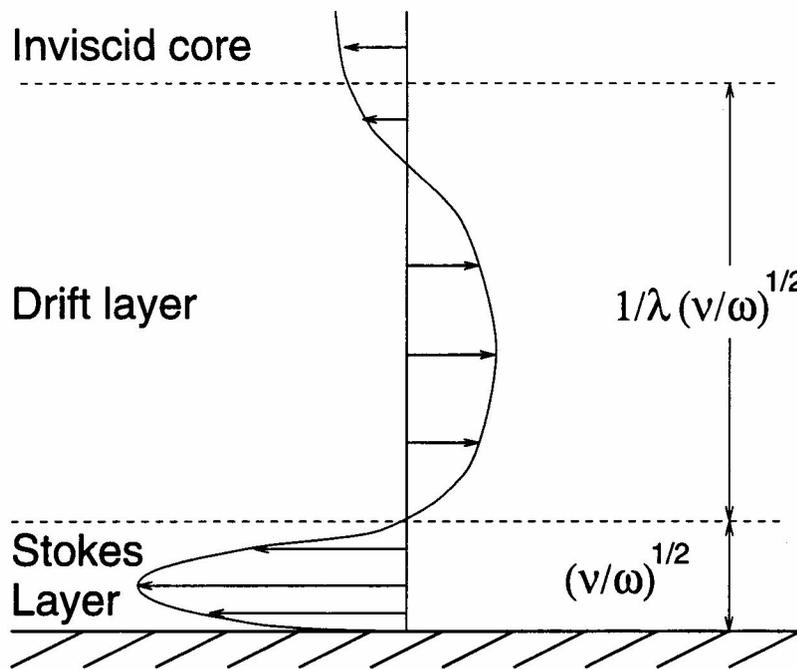


Figure 6: Velocity profile near wall of channel

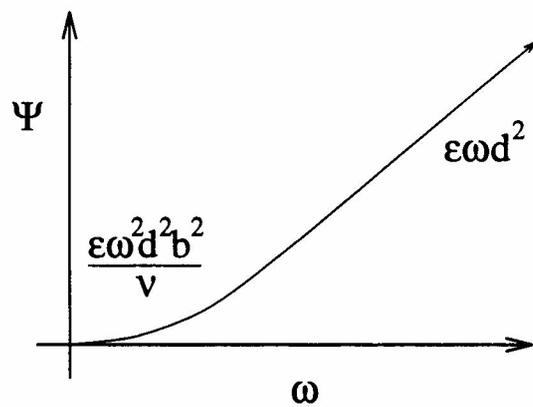


Figure 7: Flux versus frequency

5.1 Other Streaming Possibilities

There were some other remedies mentioned which involved this secondary streaming flow.

a) At $Ca \ll 1$, the meniscus acts like a solid boundary so that fluid in the Stokes layer decelerates as it approaches the meniscus. This acts like an asymmetry, and causes the boundary layer to thicken and will produce a streaming flow. Figure 8 illustrates the general appearance of this secondary flow but does not imply the direction of this flow.

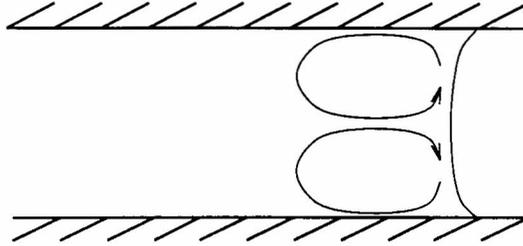


Figure 8: Streaming flow with high Ca meniscus

b) At high Reynolds number, flow past a bluff body will separate downstream of the obstacle. When the mean flow reverses, there is now separation at the front of the obstacle, as shown in Figure 9.

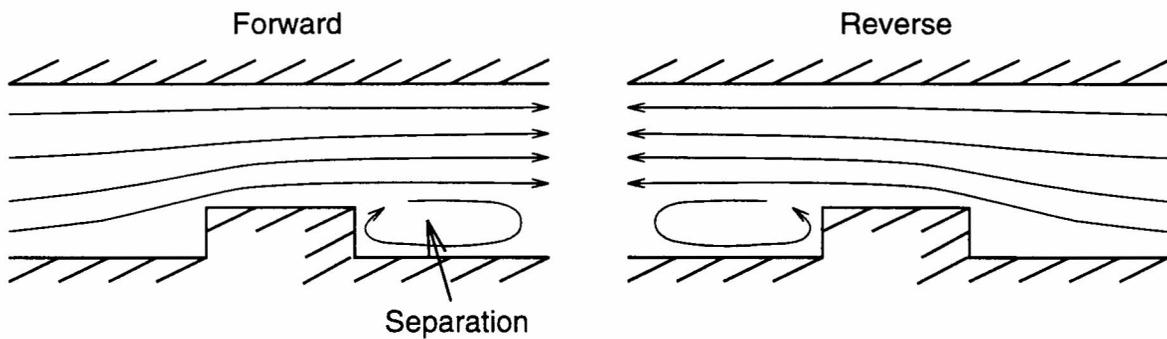


Figure 9: Reversal of separation region

The net effect is a streaming flow towards the obstacle, as depicted in Figure 10.

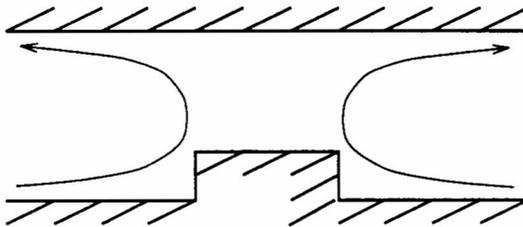


Figure 10: Net secondary streaming flow

6 Conclusions

A few mechanisms were proposed to describe the ink-drying process. Further experiments to observe and quantify the nozzle blocking would support or refute these mechanisms. It is believed that the oscillation of the meniscus prevents nozzle blocking because it sets up a secondary streaming flow in the nozzle. This process could explain the observed benefit and may be exploited in more deliberate ways.

Appendix: Ink Specifications

Concentration of polymer	9% w/w
Total solids in ink	14% w/w
Molecular weight of polymer	5-10,000
Diffusion coefficient of O ₂ in solvent	(25°C) $1 \times 10^5 \text{cm}^2/\text{sec}$
Diffusion coefficient of polymer through solvent	(25°C) $1.2 \times 10^{-7} \text{cm}^2/\text{sec}$
Viscosity of MEK solvent	0.8cP (25°C)
Viscosity of ink	2.5-3.5cP (25°C)
Radius of gyration for polymer	~ 10 nanometers
Ratio of ink spot to ink drop	1.5-3
Frequency of oscillation of meniscus	few 100 Hz
Frequency of operation of drop generator	3-6 kHz
Length of dried ink plug	1-2 diameters
Ketone based inks apparently do not undergo phase change when drying	
Ink residue apparently floats	
Layer at bottom is thicker than wall layer when ink dries in a beaker ($\approx 15\text{cm}$)	
Concentration at which polymer gels is unknown	

List of Participants

The Study Group participants who worked on this problem were: Richard Day, Oliver Harlen, John Hinch, John King, Andrew Lacey, John Lister, John Ockendon, Jonathon Wattis and Grae Worster.