Electro-Rheological Model of HP-Indigo ElectroInk

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Abstract

ElectroInk is a dispersion of micron and submicron size polymer particles containing nanometer size colorant pigments in non-polar fluid. ElectroInk is in the core technology of digital printing press machines developed and manufactured by HP Indigo Division the world leader in the field of digital press machines. ElectroInk is a complex fluid exhibiting non-linear rheological properties. During the print process electrical field is applied to the ink that causes the ink particles to move in the field. Also, as the ink propagates from the container to the final substrate (paper) to be printed on, the concentration continuously increases; the ink is subjected to changes in temperature, pressure, shear, and electrical field; all transforming the rheological properties. As the concentration increases the ink ceases behaving as simple dispersion of non-interacting particles. Instead, the ink is better described as an interwoven structure of two continuous phases one being an elasto-viscous solid like substance made of from strongly interacting particles and dissolved liquid the other being the pure solvent.

This model reminding a wet sponge is called the two-continuous phases model of ElectroInk. The movement of individual particles is replaced by the deformation of the solid like part described by the tools of mechanics and electrodynamics of continuous media. This model adequately describes the transfer process of the ink from roller to roller in the press under electrical field and predicts the relevant parameters leading to 100% transfer which is necessary to meet the principal requirement to digital printing vis. that each printed page can be different.

In this presentation a short introduction to Indigo's special technology will be given followed by some general findings on the unique rheological and electrical properties of ElectroInk, and the two-continuous phases model will be introduced and applied to electrically assisted ink transfer process.

Experimental data showing good agreement with the model will also be presented.

Introduction

Hewlett-Packard Indigo Division develops and produces digital press machines. These machines posses the capability that each page can be different from the previously printed page. This is made possible by Indigo's unique ink named ElectroInk. ElectroInk is a mixture of a dielectric fluid carrier, polymeric particles bearing colorants and additives. Due to some of the additives the polymeric particles acquire electrical charge thus electrical fields can act on them (Fig. 1). During the process the ink concentration changes from dilute one in the ink reservoir to completely dry on the substrate (Fig. 2). In order to ensure that each page can be different, 100% transfer of the colored part of the ink from roller to roller is required (i.e. no colorant left behind).

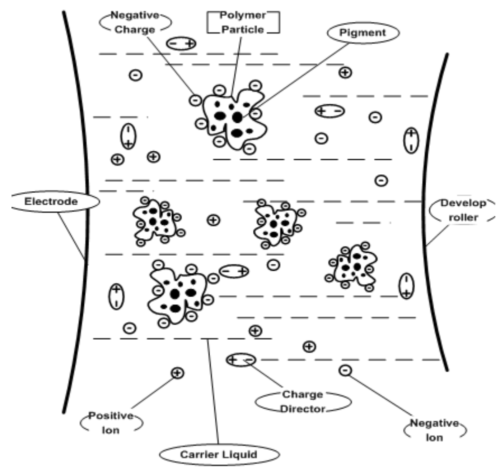

***Figure 1**. ElectroInk - Schematic*

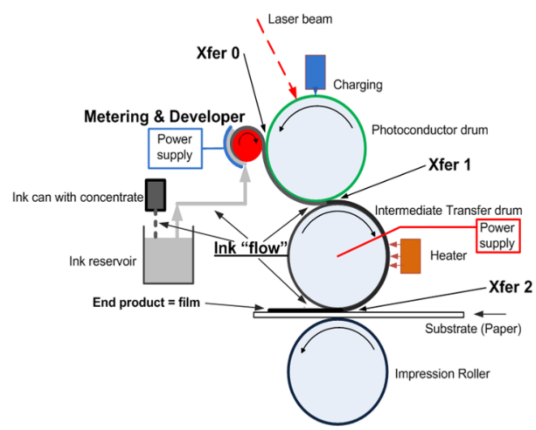

***Figure 2**. Ink transport in the press - Schematic*

The Two-Continuous Phases model

While in dilute ink the approximation of non-interacting particles that supposes only the presence of Stock's law type forces produced by the carrier liquid may provide a good enough description of the flow properties, at higher concentrations, starting about 10% by volume, as in the transfer processes Xfer 0 and Xfer 1 (refer to Fig. 2), the particles are strongly interacting and the rheological model of the ink should be quite different. Experiment shows that at these concentrations the ink exhibits finite yield stress to flow. At small shear the ink, like solids, exhibit high modulus and low loss tangent in oscillatory experiments. When the shear is larger than certain value referred to as the yield stress, the modulus drops, the ink starts flowing and the loss tangent goes up (Fig. 3).

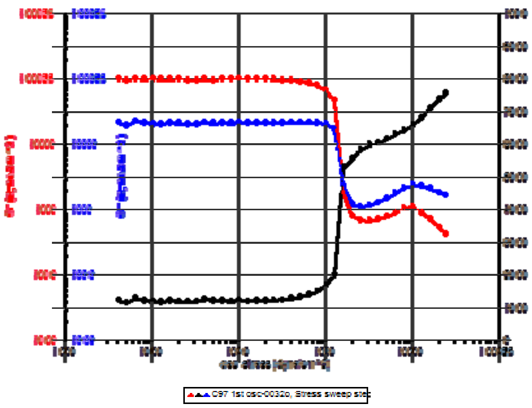

Figure 3. *Oscillatory flow test at 10Hz*

The yield stress increases roughly exponentially with

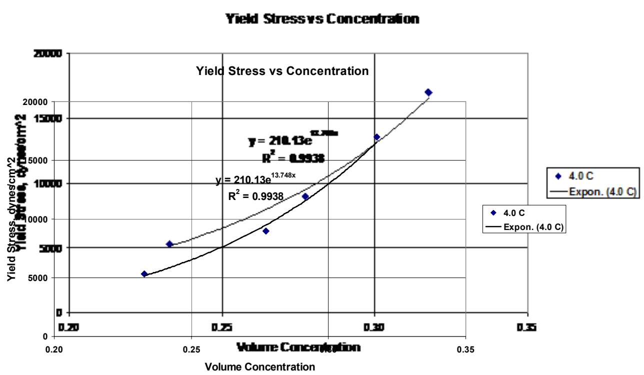

Figure 4. *Variation of the yield stress with concentration*

Such behavior can be explained by the Two-Continuous Phases model of ElectroInk in terms of an interwoven structure of two continuous phases one being an elasto-viscous solid like substance made of strongly interacting particles and dissolved liquid and the second phase being the pure solvent.

The transition from dilute dispersion of non-interacting particles to the Two-Continuous Phases model can schematically be illustrated as shown in Figs 5a – 5f. We start with diluted ink in which non-interacting particles are randomly dispersed (Fig 5a). As the concentration increases (Fig 5b) the particles get closer to each other and the increasing interaction between them creates a structure (pictured schematically in Fig 5c by network). External mechanical barriers imposed on opposite sides (Fig 5d) confine the mixture in moving. Thus applying external field on the particles the "network" is pushed to one of the barriers and gets deformed (Fig 5e). The external field can be both gravitational and electrical. Gravitational field exerts pressure on the network when the particles have higher density than the surrounding media (which is the usual case). Electrical field acts directly on the particles which bear net electrical charges. Finally the network is replaced by elasto-viscous continuum (Fig 5f).

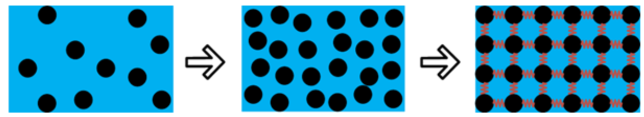

Figure 5a – 5c. *Variation Building the model (Explanation in the text)*

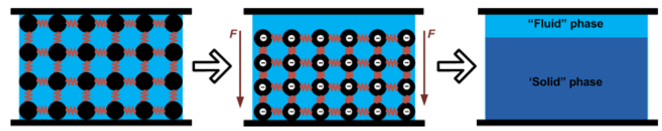

Figure 5d – 5f. *Variation Building the model (Continued)*

Thus, contrary to dilute ink modeled as a liquid in which solid particles are dispersed, the Two-Continuous Phases Model treats the ink rather than a solid in which the liquid is dispersed. The elasto-viscous "solid" part behaves like a wet sponge; when pressed it releases liquid (therefore the term "Sponge model").

Accordingly, for calculating any deformation the techniques of continuum mechanics and electrodynamics should be applied, e.g. in sedimentation experiments the "sponge" in pressed under its own weight (Fig 6.).

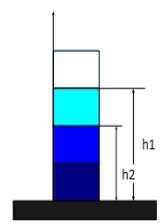

Figure 6. *Sedimentation process: The upper layers press the bottom layers*

Experimental evidence

Sedimentation experiments have shown that the concentration of the sediment increased logarithmically with both the speed of centrifugation and the initial concentration – in full agreement with the calculations carried out using Pascal's law of hydrostatic pressure. The process can be explained as follows: the sediment concentration increases under the acceleration pressure. With increasing concentration the yield stress goes up. When the yield stress equals to the pressure the concentration increase stops. In contrast to this, the model of non-interacting particles predicts constant concentration of the sediment (according to the densest packing).

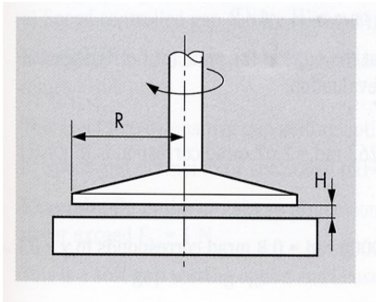

Figure 7. *Electro-rheological measurement: Voltage is applied to the plates*

Electro-rheological measurements were carried out in TAI AR-2000 rheometer using parallel plate geometry and applying voltage to the plates (Fig 7). Typical results are given in Fig 8.

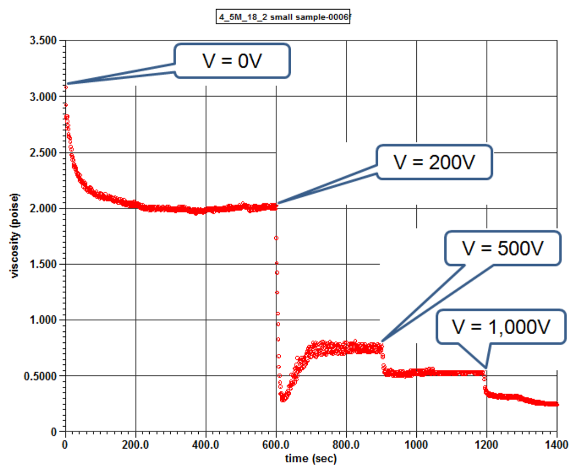

Figure 8. *Change of apparent viscosity with electrical bias*

As one can see, the apparent viscosity decreases when voltage is applied across medium concentration ink. Actually what happens is that the solid part ("the sponge") bearing static electrical charges gets squeezed under the influence of the applied field (like under the own weight in sedimentation experiments) and releases some of the absorbed liquid. Since the liquid has a much smaller viscosity the total viscosity decreases. As the voltage is increased the change is smaller since the "sponge" gets harder and less compressible.

(It has to be noted that conventional electro-rheological fluids behave differently; they exhibit viscosity increase in electrical field. The reason is that most electro-sensitive fluids contain polar but not charged particles that orient themselves along the field and build up "bridges" between the plates of the viscometer [1]. In contrast to this, in ElectroInk the particles bear a net electrical charge which results in much larger forces than the dipole-electrical field interaction.)

Application of the Two-Continuous Phases model to the electrical ink transfer process

The transfer of ink in Xfer 0 and Xfer 1 (refer to Fig 2) is an electrically induced process. In Xfer 1, for example, the ink arrives at the photoconductor drum and goes over to the intermediate transfer drum. The transfer process can be broken down to 3 steps (Fig 9).

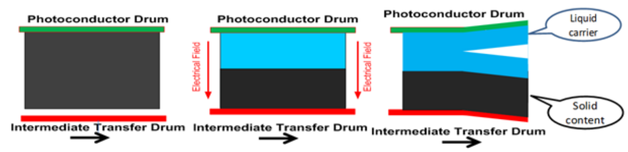

Figure 9. *Electrical transfer - Schematic*

The ink arrives at the contact of the drum as a homogenous material. A voltage is applied to the intermediate drum relative to the photoconductor. Thus in the nip between the photoconductor drum and the intermediate transfer drum the solid part of the ink containing the colorants gets squeezed and releases some liquid. Upon exit from the nip the drums surfaces separate and the much less viscous liquid splits into two layers. One layer goes with the photoconductor drum but, if the parameters are adequate, this liquid does not contain any colorants (See simulations below).
A simple simulation of splitting at the exit supposes only two layers, one containing the solids and the second being the pure liquid. The viscosities of the layers are different. The conservation of the mass and non-slip conditions on the surfaces are observed. On the interface separating the layers the shear stress is continuous and the velocities of the two layers are equal. Simulations were carried out in the "lubrication" approximation [2]. Some typical results based on viscosity ratio of 400 between the phases are can be seen in Figs 10a-c where the calculated velocity profiles in the gap are shown during exit from the nip. The plots have the following meaning: Y-axis: the relative distance between the drums: 0 at the intermediate transfer drum, 1 at the photoconductor drum; X-axis the relative velocity across the gap (1 at the drums and zero at the splitting).

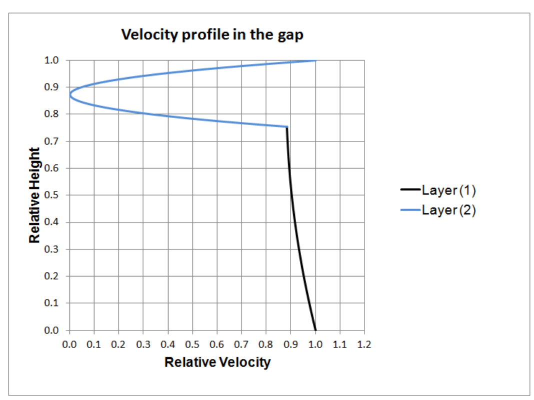

Figure 10a. *Velocity profile in the gap. Liquid phase: 10%.*

The velocity changes across the gap from maximum at the drums surfaces to 0 where the splitting takes place. When the liquid phase is thick enough the splitting occurs in the liquid. Since the liquid is free of colorants the transfer to the intermediate transfer drum is 100% and stable (Fig 10a). As the relative thickness of the liquid decreases the splitting point moves to the interface (Fig 10b). This corresponds to 100% but unstable transfer. When the relative amount of the liquid is less than a certain critical value (in this case 5%) the splitting occurs in the solid phase and less than 100% colorants are transferred to the intermediate transfer drum (Fig 10c).

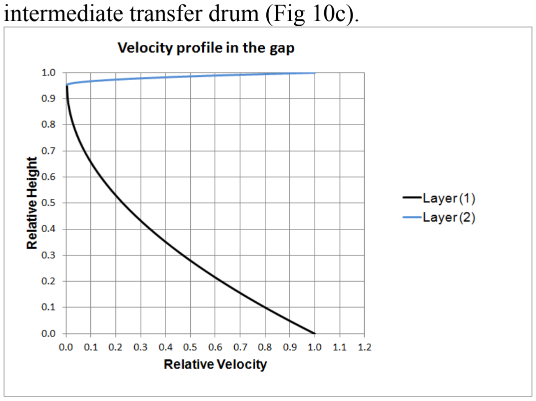

***Figure 10b**. Velocity profile in the gap. Liquid phase: 5%.*

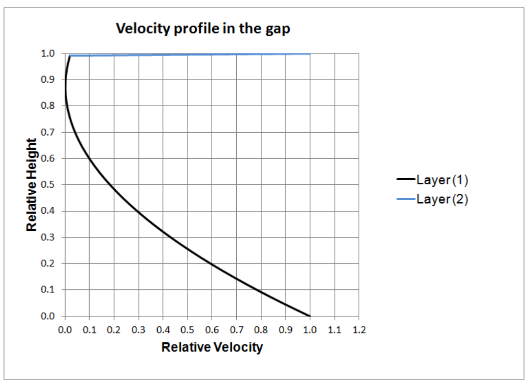

***Figure 10c**. Velocity profile in the gap. Liquid phase: 1%.*

Conclusions

The Two-Continuous Phases model of ElectroInk

- Provides better agreement with the experimental observations than the classical dispersion model
- Adequately describes the transfer process of the ink from roller to roller under electrical field in HP-Indigo presses
- Is capable of predicting the relevant parameters leading to 100% transfer.

References

[1] Larson, Ronald G., The structure and rheology of complex fluids, Chapter 8, Oxford University Press, New York, 1999, ISBN 0-19-512197-X

[2] Middleman, Stanley, Fundamentals of Polymer Processing, Chapter 7, 1977 McGraw-Hill, Inc. ISBN 0-07-041851-9

Author Biography

Peter Forgacs[1] (peter.forgacs@hp.com) has received his PhD degree in physics from the Eotvos Science University, Budapest, Hungary in 1978 and undertook a post-doctoral training in the Polymer Research Institute at the University of Massachusetts in1982-1984. In 1989 he joined Hewlett-Packard Indigo Division (at that time Indigo Co.) in Israel for managing the Laboratory of Physical Properties in the R&D Materials Science Section. His main topics of interest are rheology, adhesion, tribology, measuring techniques and surface characterization of solids.