THERMAL EFFECT ON THE PENETRATION OF AN INK DROPLET ONTO A POROUS MEDIUM

Maosheng Ren and Herman Wijshoff

Research and Development, Océ-Technologies B.V., 5900 MA Venlo, the Netherlands

Abstract

Inkjet technology is widely used, not only in graphical printing applications but also in industrial applications ranging from spreading of stains on textiles to the making of biosensors. When a liquid ink droplet impacts on a porous substrate, it tends to spread along media surface as well as penetrate into substrate voids.

A numerical study with the volume of fluid method of the commercial software Flow3D is performed on the spreading and the penetration process of ink droplets into porous media. In general, a porous medium is composed of coarse particles or fibres; the flow losses inside pores may be proportional to the square of the flow speed rather than the speed itself. This dependence is a function of the local Reynolds number, based on the average particle or fibre diameter.

The flow absorption in a porous media obeys a generalized Darcy's Law, which is a simple proportional relationship between the instantaneous flow rate through a porous medium, the viscosity of the fluid and the pressure gradient. The model is simplified to a one-phase fluid and flow inside porous media according to Darcy's Law is implemented via an extra resistance term $\mathcal{K}$u in the momentum equation. Here u is the microscopic flow velocity so that the drag coefficient $\mathcal{K}$ must be appropriately defined when using porous media models based on a volume flow rate. The moving wetting front in the substrate was solved numerically and matched well with the experiments. Results of numerical computation were presented for infinitely thick isotropic substrates.

By varying the temperature difference between the droplet and the substrate, differences has been observed in the flow behaviour of the spreading and absorption. Furthermore, a model for porous media has been used to describe the influence of thermal effect in the spreading and penetration process. The model predicts a reasonable penetration velocity and time for the fluid flows in the porous media. From a process engineering point of view, the model and numerical tool used may provide a step towards a computational design of porous receiving layers as, e.g., in ink-jet applications.

1 Introduction

Inkjet technology is widely used not only in graphical printing applications but also in industrial applications ranging from spreading of stains on textiles to the making of biosensors. Ink chemistry and formulations not only dictate the quality of the printed image, but they also determine the drop ejection characteristics and the reliability of the printing system. Many different types of inks have been developed and used in ink-jet applications.

Water-based inks are commonly used in home and small-office ink-jet printers such as in the Hewlett-Packard Edgelines and DeskJet series, Canon BJC series, and Epson Color Stylus series ink-jet printers. In the case of water-based inks, evaporation of water is taking place, but this drying mechanism is often very slow. Furthermore, the drying process of ink lowers color optical density and decreases spot resolution on paper. These drawbacks become the bottleneck of the water-based ink.

Therefore, a so-called toner-like ink is introduced and it often also called phase-change ink which is solid at room temperature. The ink is jetted out from the printhead as a molten liquid. Upon hitting a recording surface, the molten ink drop solidifies immediately, thus preventing the ink from spreading or penetrating the printed media. The quick solidification feature ensures that image quality is good on a wide variety of recording media. Figure 1 shows a SEM photograph of toner-like ink drops printed on the surface of an uncoated (plain) paper. Note that the ink drops maintain their hemispherical shape.

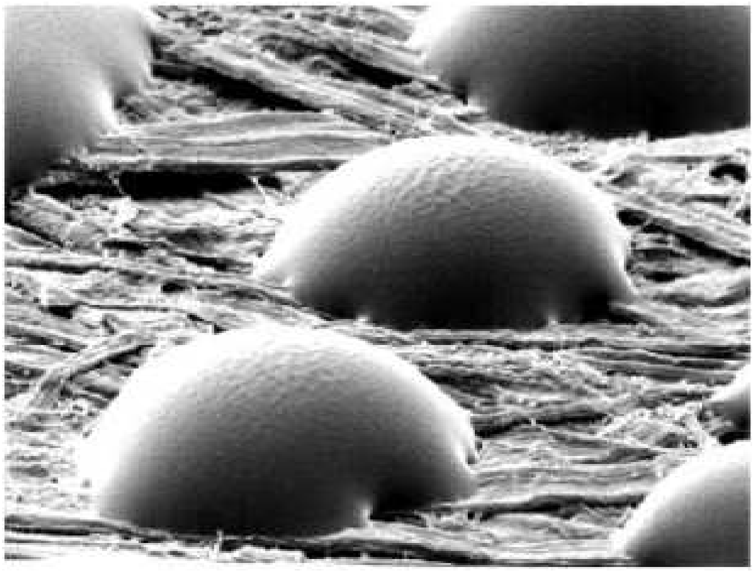


Figure 1: A SEM photograph of phase-change ink drops on the surface of a plain paper, [1].

However, most of the uncoated paper is randomly void material such as plain papers. The ink tends to spread along the paper fibres and penetrate into the bulk of the paper, if the viscosity of ink is still low enough. However, dependent of the temperature, the viscosity of ink increases as the temperature goes down to room temperature. As a result, the ink droplet spreading and absorption will stop. Depending on the media temperature, the spreading and penetration will be different.

Nevertheless, just within the past few years, the market for the special coated ink-jet media has exploded, especially in the home photo quality and large-format ink-jet printing areas. Recent availability of printhead technologies with high resolution (such as Epson Micro head, Hewlett-Packard SPT head) certainly has made a positive impact on this trend. Most of the special coated ink-jet media are microporous.

In this paper, we discuss a generalized problem of drop impacting the microporous media. A numerical study with the volume of fluid method of the commercial software Flow3D is performed on the spreading and the penetration process of ink droplet into porous media. In general, a porous medium is composed of coarse particles or fibres. The flow losses inside pores may be proportional to the square of the flow speed rather than the speed itself. This dependence is a function of the local Reynolds number based on the average particle or fibre diameter.

By varying the temperature difference between the droplet and the substrate, differences has been observed in the flow behaviour of the spreading and absorption. The aim of this contribution is to describe the influence of thermal effect on this process. As a result, the spreading and penetration at the coated layer can be controlled.

2 Problem definition

A droplet size of 30 *pl* with high temperature T_1 impacts on a porous media at room temperature T_0 as shown in Figure 2. The fluid dynamics and heat transfer can be divided into three stages:

- Flight phase: the hot ink droplet is flying in the air and the temperature of the droplet hardly changes. The time of flight over a short distance (e.g. $1mm$) with an impact velocity of u = 6 m/s is around 0.1 ms.

- Impact and spreading phase: it depends on the impact surface. For a solid surface impact, there are spreading, splashing and rebounding. Spreading is driven not only by kinetic energy from the impact, but also by the surface energy of the droplet. For a small droplet with high viscosity, splashing plays no role, with Weber number small than 80, [2]. Splashing increases with high surface roughness and hydrophobicity, [3, 4]. Because we study the ink droplet impact on a porous media, there are no splashing and rebounding to be considered.

- Absorption phase: it is only for the porous medium. The process is governed via a Darcy's law. The wetting-front speed is related with the pore geometry, ink viscosity and surface tension.

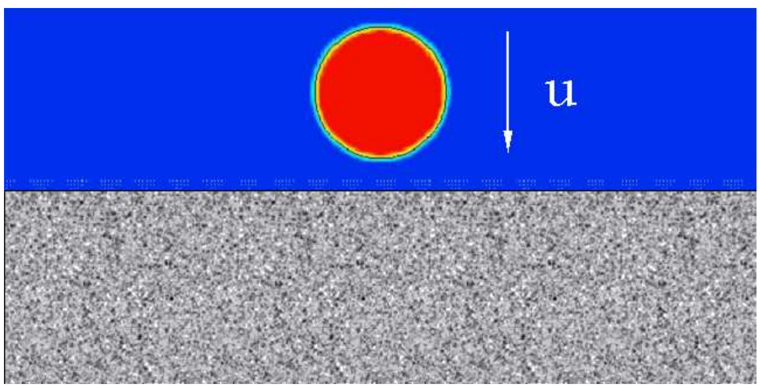


Figure 2: Problem definition, the impact of ink droplet into porous media.

In the current study, we focus on the spreading and absorption process of a hot ink droplet. Figure 2 shows a sketch of the problem, a droplet penetrating into a porous substrate. The liquid is assumed with a constant density ρ, dynamic viscosity η and surface tension σ and the model is axisymmetric.

In the absorption phase, capillarity is a driving force for the penetration of the fluid into the substrate. Its magnitude is characterized here by a constant capillary suction, P_{cap} , acting across the wetting front. The capillary suction can be viewed as measure for the mean pore diameter of the layer. In the scope of this paper, the porous substrate is considered as an infinite homogeneous isotropic layer. The porous layer is characterized by its porosity, ϕ, and a permeability κ. The permeability of a layer is determined by the property of the medium, such as the pore diameter d.

3 Results and discussions

3.1 Spreading and impact in a non-porous media

Assuming an ideal impact, a numerical study with the volume of fluid method of the commercial software Flow3D is performed on the spreading process of ink droplet onto a solid surface. The numerical simulation is based on an axisymmetric model. The initial conditions are: drop diameter 45 μm and impact speed u = 6 m/s. Furthermore, the substrate is a solid surface (with contact angle $\theta = 60^o$) and the viscosity of droplet is $\eta = 10$ $[mPa \cdot s]$ at $T = 130^o$ and surface tension is around $\sigma = 28$ $[mNm]$.

It should be noted that the ink viscosity behaviour is strongly related with the temperature. Figure 3 shows the measured complex viscosity as function of temperature T. It can be seen that the viscosity has a dramatic jump when $T < 333K$ (60^oC).

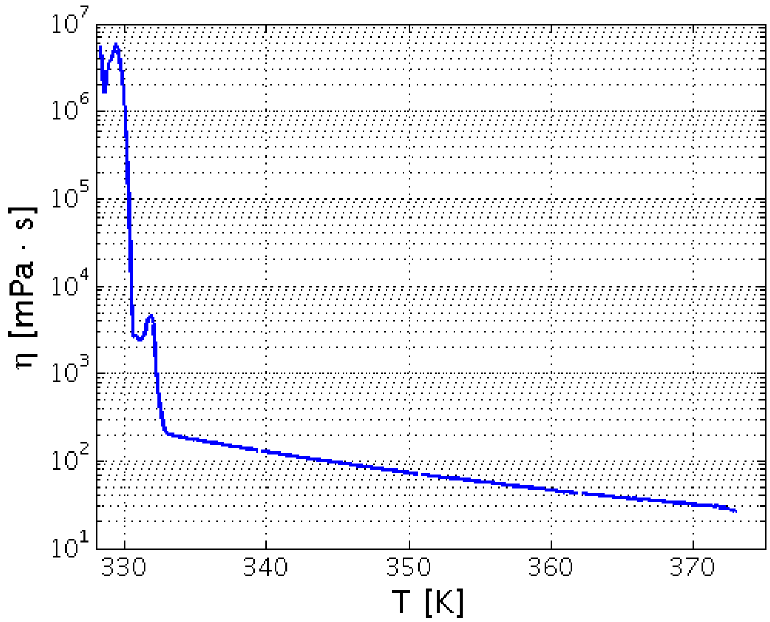


Figure 3: Measured ink viscosity as function of K (linear-log). Eyring approximation is used in the simulation.

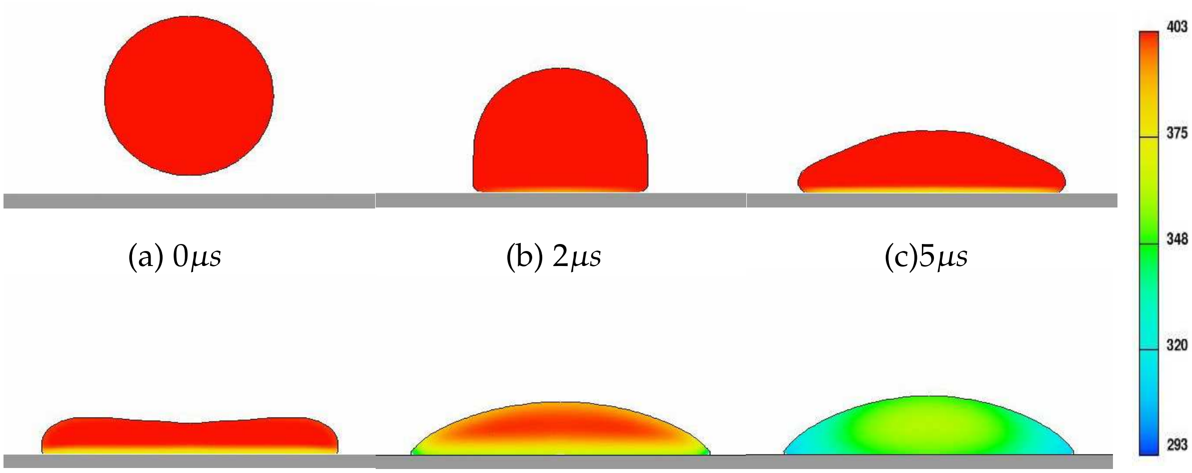
For the simulation, we use a fit followed by the Eyring approximation, which is used in the simulation (also for $T < 60^oC$). Furthermore, we did not consider the contact angle variation influenced by the temperature change.

Figure 4 shows temperature snap-shots at various moment of the impact process. Figure 4 (a) shows a droplet with temperature 130^oC is flying and impacting on a substrate with a temperature of 20^oC.

As function of time, the droplet temperature adopts to the substrate temperature. In other words, the temperature drops quickly as predicted by the diffusion equation, which is determined by the thermal conductivity of the medium. Theoretically, after the hot droplet impacts on a cold media, the droplet cools down to media temperature within 1 millisecond, see Figure 5.

The temperature inside the droplet after $50\mu s$ is not homogeneous any more. This is because of the high thermal conductivity of the medium. Therefore, the temperature profiles at different heights inside a drop are different. Figure 5 shows the temperature at different positions, where lines indicate different points with the height above the substrate.

After the impact phase, the droplet spreads on the solid surface, see Figure 4. The spreading is not driven by the impact kinetic energy any more, but via the surface energy, where the drop size and speed have no influence at all. The equilibrium stage of spreading is determined by a minimal surface energy. The bond number indicates the relationship between the gravity force and the surface tension force, $Bo = g\Delta\rho d^2/\sigma$. Here the Bond number is quite small, therefore droplet shape becomes a spherical cap.



(a) $0\mu s$ (b) $2\mu s$ (c)$5\mu s$

(d) $10\mu s$ (e) $50\mu s$ (f)$500\mu s$

Figure 4: Calculated temperature filed inside a droplet as the impact on a solid surface. Color indicates the temperature level in Kelvin. Red indicates $T = 130^oC$ $(403K)$ and blue is $T = 20^oC$ (293 K).

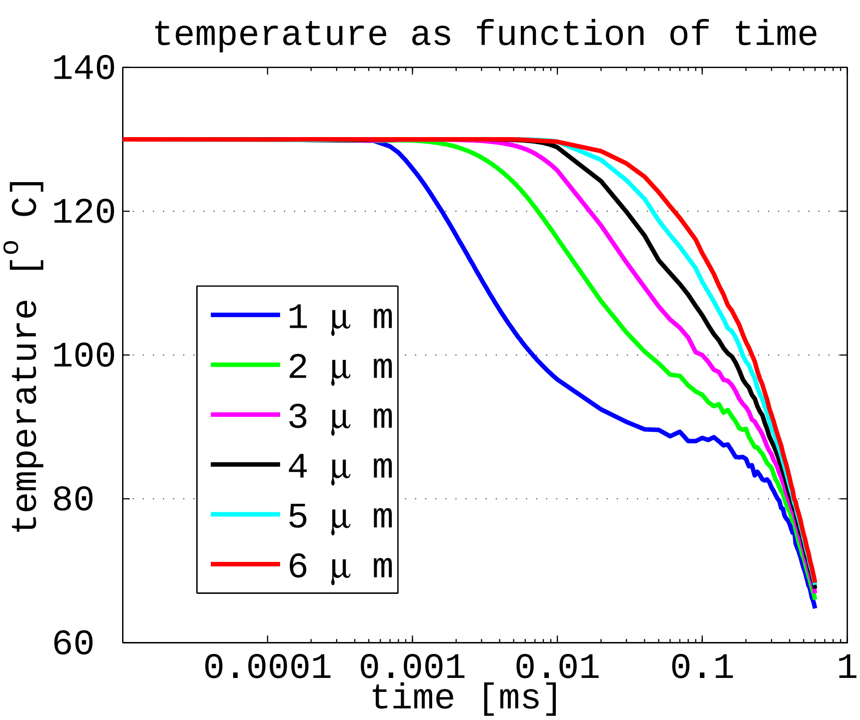


Figure 5: Temperature at different positions above the substrate as function of time, and lines indicates different points with the height above the substrate.

3.2 Spreading and absorption in a porous medium

A numerical study with the volume of fluid method of the commercial software Flow3D is performed on the absorption and spreading process of ink droplet into porous media. The numerical simulation is in an axis-symmetric model. The flow inside porous media is implemented via an extra resistance term $\mathcal{K}\mathrm{u}$ in the momentum equation. Here, we define u as the microscopic flow velocity so that the drag coefficient $\mathcal{K}$ must be appropriately defined when using porous media models based on a volume flow rate.

$$\frac{\partial \mathrm{u}}{\partial t} + \mathrm{u} \cdot \nabla \mathrm{u} = -\frac{\nabla P}{\rho} + g + \frac{\eta}{\rho}\nabla^2 \mathrm{u} - \mathcal{K}\mathrm{u} \tag{1}$$

The flow absorption in a porous media obeys a Darcy's Law, which reads

$$\mathrm{u}\phi = -\frac{\kappa \nabla P}{\eta} \tag{2}$$

where ϕ the porosity and κ permeability which is a measure of ability material transporting fluids. Here we use the Carmen-Kozeny approximation for the permeability; κ is proportional to the pore size square, d^2. Recalling equation (1) and neglecting unsteady, convection, diffusion and gravity terms, then it becomes

$$\nabla P = -\rho \mathcal{K}\mathrm{u} \tag{3}$$

Substituting it into equation (2), therefore, the drag coefficient $\mathcal{K}$ can be rewritten as:

$$\mathcal{K} = \frac{\eta\phi}{\rho\kappa} \tag{4}$$

However, until now we did not take account in the flow capacity of the porous medium. The flow behaviour will be different for saturated porous flow and for unsaturated one. Therefore, there are different types models to approximate the saturated flow [5] (media filled with maximum capacity) and unsaturated flow [6] (media still under maximum capacity). In this paper, the saturated flow model has been used in the simulation.

When a porous medium is composed of coarse particles or fibres, the flow losses inside the pore may be proportional to the square of the flow speed rather than the speed itself. This dependence is a function of the local Reynolds number based on the average particle or fibre diameter d. Linear and quadratic flow loss equations can be combined into a single expression for the drag coefficient:

$$\mathcal{K} = \frac{\eta}{\rho}\left(\frac{1-\phi}{\phi}\right)\left[a_0(1-\phi) + b_0\frac{Re\phi}{d}\right] \tag{5}$$

with ϕ the porosity; $Re = \rho \mathrm{u} d/\eta$ Reynolds number and d pore diameter; $a_0 = \alpha/d^2$ and $b_0 = \beta/d$ with α for the most materials is 180 and $\beta = 1.8 - 4.0$, which depends on the surface roughness [7]. The first term is derived from Darcy's Law and related with porosity, while the second term accounts for the corrections when the Darcys Law is not valid any more for a high Reynolds number.

Figure 6 shows numerically calculated snap-shots at various moments of the impact process. The drop has a diameter of $d = 45\mu m$ and the speed of impact is $\mathrm{u} = 6$ m/s. The substrate is a porous medium, the viscosity is $\eta = 10$ [mPa.s] at 130^oC and the surface tension is around $\sigma = 28$ [mNm]. The porosity is $\phi = 15\%$ and the pore diameter is around $d = 50$ [nm].

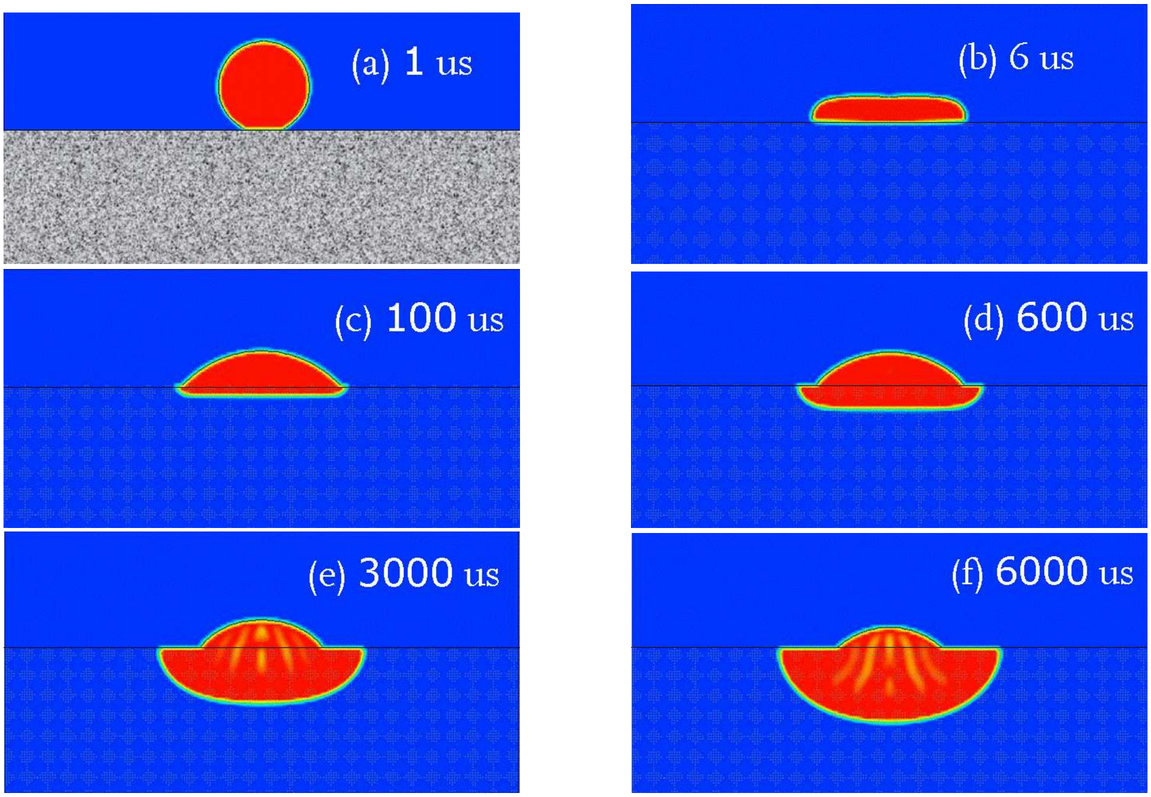


Figure 6: Calculated volume of fluid of a droplet impact on a porous medium, fluid spreading and absorption with function time at (a) 1 s (b) 6 s (c) 100 s (d) 600 s (e) 3 ms (f) 6 ms.

It can be seen that the capillary force is the dominant driving in the spreading phase. During the impact, there is no fluid absorption into the porous medium at all, because of $We > Re^{1/2}$ [2]. Here the Weber number is around $We = 50$ and the Reynolds number is around $Re = 25$. The capillary pressure is determined by the geometry of the pore. For a pore diameter $d = 50$ [nm], ideally assuming the pore shape of cylinder, the Laplace pressure can be derived from Youngs equation, and reads:

$$\pi d\sigma\cos\theta = P_{cap}(\pi d^2)/4 \qquad \rightarrow \qquad P_{cap} = 4\sigma\cos\theta/d \tag{6}$$

where θ is the contact angle between ink and medium. The above expression suggests the smaller pore size d is, the higher the capillary pressure is. High capillary force makes the ink absorption faster and deeper into the porous medium.

However, from the Carmen-Kozeny approximation for the permeability, κ is proportional to d^2. It suggests the larger the pore size is, the higher permeability is. High permeability makes fluid easier get into the porous medium. There is a contradictory trend demanding the pore size between the capillary pressure and the medium permeability. Therefore, we expect that there is an optimal pore size for a better flow absorption.

Furthermore, similar shape of wetting front has been observed from the experiments. Figure 7 shows an example of a toner-like ink penetration into a micro-porous layer. It can be seen that the moving wetting front in the substrate was solved numerically and matched well with the experiments. By varying the temperature difference between the droplet and the medium, differences have been observed in the spreading and absorption behaviours.

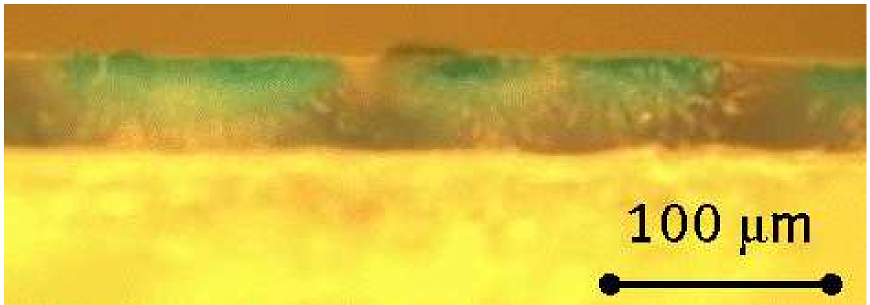


Figure 7: A microscopic view of fluid penetration into porous media.

4 Conclusion

The flow impact on a porous media has been simulated and modelled. For axisymmetric configuration, a simplified one-phase fluid model has been suggested and it is good enough for estimation of the absorption process in the porous medium. The moving wetting front in the substrate was solved numerically and matched well with the experiments. Results of numerical computation were presented for infinitely thick isotropic substrates.

By varying the temperature difference between the droplet and the substrate, differences has been observed in the flow behaviour of the spreading and absorption. Furthermore, a model for porous media has been used to describe the influence of thermal effect in the spreading and penetration process. The model predicts a reasonable penetration velocity and time for the fluid flows in the porous media.

The flow dynamics in the medium is dependent on the materials property, such as pore size and permeability. A smaller pore diameter gives a higher capillary pressure, leading to a strong penetration driving. On the other hand, small pore size leads to a lower permeability, resulting in a significantly longer sorption time and a larger stain area. From a process engineering point of view, the model and numerical tool used may provide a step toward a computational design of porous receiving layers as, e.g., in ink-jet applications.

References

[1] H. P. Le, ”Progress and Trends in Ink-jet Printing Technology”, *Journal of Imaging Science and Technology* 42(1) (1998).

[2] L. Wachters and N. Westerling, The heat transfer from a hot wall to impinging water drops in the spherical state, *Chem. Eng. Sci. & Techn.* 21, 1047 (1966).

[3] M. Toivakka, Numerical investigation of droplet impact spreading in spray coating of paper, *Proc.TAPPI 8th ACFS* (2003).

[4] X. Zhang and O. Basaran, Dynamic surface tension effects in impact of a drop with a solid, *J. Coll. Int. Sci.* 187, 166 (1997).

[5] N. Alleborn and H. Raszillier, Spreading and sorption of a droplet on a porous substrate *Chem. Eng. Sci.* 59 2071-2088 (2004).

[6] N. Alleborn and H. Raszillier, Dynamics of films and droplets spreading on porous substrates, *Proc. 9th TAPPI ACFS*, 177 (2006).

[7] Flow-3D users manual, *Flow Science* (2005).