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INFILTRATION AND DIMENSIONAL SCALING OF INKJET DROPLETS ON THICK ISOTROPIC POROUS MATERIALS

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ABSTRACT

We study the imbibition of picoliters (pL) sized inkjet droplets on controlled pore glass membranes (CPG). We do so using a variety of liquids, i.e., water, formamide and diiodomethane, as well as the CPG substrates, and measure the evolution of the imbibition process using high speed digital imaging. Here, experiments were conducted with a wide range of initial drop volume (100–600 pL) on 2–280 nm CPG membranes. We derive scaling laws through dimensional analysis of the equations of motion, and consider experimental parameters and liquid properties.

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INTRODUCTION

Liquid penetration into porous material is a spontaneously occurring process if the wetting angle of the liquid is less than 90° [2]. The phenomena, sometimes referred to as spontaneous imbibition [3] is of importance in a variety of processes, with examples in agricultural irrigation [4], graphic inkjet printing [5,6], fiber-based absorbency products [7], three dimensional printing[8], functional microstructures for electronic and microfluidic applications[9], powder granulation [10,11], and even handwriting [12].

Infiltration in a three dimensional interconnected porous network is often classified according to the thickness of the substrate in relation to the initial size of the drop. Two classifications are clearly evident in the field, i.e., *thin* and *thick infiltration* [6,13,14,15,16,17,18]. *Thin infiltration* refers to the case where the region under the drop is saturated and the infiltration proceeds in the radial direction only. The *thick* case refers to situations where the region under the drop is unsaturated. This case is somewhat more complicated as the liquid front advances in all directions. Some authors [19,20,21,22] consider a porous network that is made of parallel unconnected tubes, closely related to the Lucas-Washburn type of capillary rise [23,24]. This model simplifies the computation of the infiltration rate and at the same time allows some conclusions to be drawn regarding the spreading behavior of an infiltrating drop. In one case this model was used to explore the inertial regime of drop impact [25].

The experimental literature in the area is substantial. A number of groups have studied imbibition in model porous network made of parallel unconnected tubes. Examples of these are the work by Denesuk *et al* [19] in soda-lime-silicates, or Grzelakowski *et al* [26] in nanoporous alumina. For imbibition in interconnected porous materials, we find a number of representative cases including paper [5,6,27,28], powder beds [10], and filter membranes [16]. Of interest in the area is the work of Starov *et al* [16,17,29,30,31], who studied both *Thick* and *Thin* infiltration cases. For the thick infiltration case, Starov *et al*. found scaling laws for a number of different fluids that were dispensed on similar porous media. In this study – to the best of our knowledge – we extend the scaling laws for the first time for cases with different substrates.

DIMENSIONAL CONSIDERATION

We consider the problem of a fluid drop with a total volume v_{tot} (m³), draining into a uniform porous medium, see Fig. 1. We define two domains, the upper domain comprising of the fluid on top of the porous medium and the lower domain defined by the region of fluid inside the porous medium. For simplicity, in the subsequent



Figure 1. A schematic of a drop imbibing a thick porous substrate (thick infiltration). The functions h(x,t) and f(x,t) represents the profiles of the drop and the imbibed liquid front, respectively. The functions a(t) and b(t) are half of the drop and the liquid front width at y=0, respectively.

presentation we define the upper domain as the "drop" and the lower domain as the "imbibed fluid". In this section we will focus only on the motion of the imbibed fluid. We begin the analysis by defining the superficial velocity of the imbibed fluid as $\mathbf{u} = (u, w)$, where u (m/s) and w (m/s) are the velocity components in the xand y directions, respectively. We consider the porous substrate to be isotropic with permeability k (m²). At the interface the imbibed fluid extends from the origin to $x = \pm b(t)$ (m). Motion in this case is driven by capillary pressure p_c (Pa) acting normal (outward facing normal) to the surface y = f(x, t), and, the pressure in the drop p_d (Pa) created by the surface tension and radius of curvature of the surface described by z = h(x, t) (m). Fluid enters the lower domain in the region $x \le a(t)$ (m).

At this point we turn our attention to defining the conservation laws. The dominant terms of the equations of motion are given by [2]:

$$\nabla \cdot \boldsymbol{u} = \boldsymbol{0} \tag{1}$$

$$\nabla p = -\frac{\mu}{k} \nabla \boldsymbol{u} \tag{2}$$

where μ (Pa/s) is the viscosity of the liquid. Eq. 1 represents mass conservation and Eq. 2 is Darcy's law. In this section we do not intend to solve this system of equations, but rather render the equations dimensionless, in order to define the governing groups for developing scaling laws. To do so we need to define characteristic pressure, velocity, length and time scales.

We begin by discussing the characteristic pressure. The motion of the imbibed fluid is driven by the capillary pressure p_c acting on the lower surface of the imbibing fluid and by the Laplace pressure inside the drop p_d , created by surface tension σ (N/m) and local radius of curvature r_d (m) of the drop. The magnitude of p_d is given by $p_d = -\frac{2\sigma}{r_d}$, and that of p_c can be estimated using the average pore radius r_p , giving $p_c = -\frac{2\sigma}{r_p}$. In the cases discussed in this work r_p is in the order of 2–300 nm and r_d is in the order of millimeters, making p_d negligible in comparison to p_d . Therefore p_c is taken as the characteristic pressure of the problem.

We continue the discussion by examining the characteristic length, i.e. l_c (m). It would be natural to choose the initial diameter or height of the drop as a characteristic length scale. In fact, a number of authors have done so [18,20,32]. The trouble we find with this scale is that measuring this value on a porous substrate is difficult, if not impossible. As imbibition is spontaneous it is difficult to define t = 0 accurately and both the diameter and the height of the drop vary rapidly in the region $t \rightarrow 0$. Because of this, we set:

$$l_c = \sqrt[3]{\frac{v_{tot}}{\epsilon}}$$
(3)

where ε (m³ m⁻³) is the bulk porosity.

We now examine the characteristic velocity w_c (m/s). This scale must be defined through a physical argument. The characteristic speed must be related to the driving pressure p_c and to the resistance to flow. By balancing the magnitudes of the terms in Eq. 2, we see that

$$w_c = \frac{p_c k}{\mu l_c} \tag{4}$$

Finally we turn our attention to defining the characteristic time t_c (s). As we have already defined a velocity and length scales, we set t_c to be:

$$t_c = \frac{l_c}{w_c} = \frac{\mu l_c^2}{p_c k} \tag{5}$$

which represents an advective time scale.

As will be discussed subsequently, in our experimental measurements we are only able to measure the volume of the imbibed fluid and the base diameter of the drop. As such we attempt to determine the function

$$\frac{v_i(t)\epsilon}{v_{tot}} = f(\frac{t}{t_c}) \tag{6}$$

experimentally, where $v_i(t)$ (m³) is the volume of the imbibed fluid.

EXPERIMENTAL

Five porous glass plates of controlled pore size (CPG, www.vitrabio-biosearch. com) were used as the isotropic porous material. The average pore size r_p , porosity ε , specific surface area s (m² m⁻³) as well as the dimensions of the plates, are listed in Table 1.

Before commencing of the imbibition experiments, the glass plates were cleaned using the following five step procedure:

- (i) Each glass plate was immersed in diluted chromic-sulfuric acid for one hour to remove organic residue.
- (ii) The plates were then washed in 5 cycles of 5 minutes each, of sonication in purified water (Milli-Q plus unit, Millipore USA). The samples were then dried in a vacuum oven (90°C, one hour).
- (iii) The plates were subjected to three cycles of 5 minutes immersion and sonication in acetone (≥99.9%, Sigma-Aldrich), and then dried in a vacuum oven (90°C, one hour).
- (iv) Step (iii) was repeated using ethanol and water.
- (v) Immediately before each measurement the plates were taken to a PDC-32G plasma cleaner (Harrick Scientific, USA) where they were treated for 30 s at high intensity.

The infiltration measurements were performed with purified water (Milli-Q plus unit, Millipore USA), formamide (99.5%, Sigma-Aldrich, Germany) and diiodomethane (99%, Sigma-Aldrich, Germany). The properties of the fluids are given in Table 2.

Porous CPG plate	Dimensions (cm·cm·mm)	r_p (nm)	$\varepsilon (m^3/m^3)$	$S(m^2/cm^3)$
Sample A	2.2.0.3	2	0.195	503
Sample B	2.2.0.3	10	0.538	412
Sample C	2.2.1	60	0.535	75
Sample D	2.2.1	100	0.516	61
Sample E	2.2.1	200	0.617	99
Sample F	$2 \cdot 2 \cdot 1$	280	0.691	71

Table 1. Properties of the porous CPG plates

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Table 2. The physical properties of the fluids used in the imbibition experiments. The viscosity measurements were performed on a Kinexus rheometer (Malvern Instruments Ltd, England) using a double gap geometry, at a shear rate of 50 s^{-1} and a temperature of 25° C. Surface tension values are taken from [33]. The contact angle was measured in this work by imaging the shape of the droplet on an impermeable silicon wafer

	Viscosity μ (mPa s)	Surface tension σ (mN/m)	Contact angle θ (Deg)
Water	0.89	72.0	0
Formamide	3.34	58.0	0
Diiodomethane	2.6	50.8	50

The infiltration measurements were performed using a DataPhysics OCA40 micro instrument (www.dataphysics.de). As shown in Fig. 2, fluid is dispensed from a piezoelectric unit and impinges on a target substrate located below. The time-evolution of the imbibition process is imaged using high speed digital imaging camera (2245 fps) coupled to a 20x long working distance lens (www. nikon.com). In a typical experiment we set the resolution to 1780 ± 10 pixels/mm with a field of view of 260 µm. All measurements were conducted under constant ambient conditions of $43 \pm 3\%$ relative humidity and a temperature of 23° C. It should be noted that to create a particular initial volume of fluid on the CPG, a prescribed number of drops need to be released from the piezoelectric dispensing unit. We calibrated the number of drops released *n* from the piezoelectric dispensing unit to the total volume v_{tot} by imaging the impingement on an impermeable surface. This is shown in Fig. 3. The piezoelecectric dispensing unit released drops at a rates between 1200–2500 drops/s. In total, 20 different experi-







Figure 3. Volume calibration curve. A linear curve is fitted to the data of a series of experiments done on a silicon wafer. In each exp. the number of impinged droplets n is varied and the total volume v_{tot} of the drop is measured. The slope of the curve g is the average volume of each impinged droplet.

ments were conducted for the conditions shown in Table 3. The parameters k and p_c were estimated using

$$k = \frac{c\epsilon^3}{s^2(1-\epsilon)^2} ; p_c = \frac{s(1-\epsilon)\sigma cos\theta}{\epsilon}$$
(7)

where the Kozeny-Carman expression for permeability is used [34], with *C* being the Kozeny constant and is set at 0.2, and the expression for p_c is taken from the work by Marmur [1].

Results and discussion

The discussion around the drop spreading behavior is mostly done in a qualitative manner, with the purpose of introducing the process to the unfamiliar reader. For a more detailed discussion around drop spreading the reader is referred to [30] and [6]. Typical example of drop imbibing a CPG plate is seen Fig. 4, where 5 water droplets are impinged on the top surface of a vertical CPG plate. The drop expansion begins already during the impingement (Fig. 4a–c), continues to some extent after impingement is over (Fig. 4d), and finally it retracts until it is completely absorbed by the substrate (Fig. 4e,f). Some asymmetries are seen during this process, resulting in uneven spreading. We note that these asymmetries, a result of local inhomogeneities on the CPG top facets, are not observed in any of the other experiments.

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Exp. Number	Liquid	Sample	$-Log(k)$ $(Log(m^2))$	-p _c /10 ⁶ (Pa)	n	v_{tot} (pL)	l _c (μm)	<i>t_c</i> (<i>s</i>)	w_c ($\mu m/s$)
1	Formamide	А	20.0	119.9	1	105	80	19.84	4
2	Formamide	А	20.0	119.9	4	420	128	50.00	3
3	Formamide	В	18.0	20.4	1	105	57	0.63	92
4	Formamide	В	18.0	20.4	4	420	91	1.58	58
5	Formamide	С	16.6	3.8	1	105	57	0.12	490
6	Formamide	D	16.5	3.3	2	210	73	0.17	429
7	Formamide	Е	16.5	2.9	5	515	92	0.19	490
8	Formamide	F	15.9	1.8	2	210	66	0.06	1130
9	Water	А	20.0	148.8	1	25	43	1.23	35
10	Water	А	20.0	148.8	5	125	74	3.59	21
11	Water	А	20.0	148.8	10	250	93	5.70	16
12	Water	В	18.0	25.4	2	240	76	0.24	322
13	Water	В	18.0	25.4	3	360	87	0.31	281
14	Water	В	18.0	25.4	5	600	104	0.44	237
15	Diiodomethane	А	20.0	69.7	1	85	76	24.13	3
16	Diiodomethane	А	20.0	69.7	4	300	120	60.80	2
17	Diiodomethane	В	18.0	11.9	1	85	54	0.76	71
18	Diiodomethane	В	18.0	11.9	4	300	86	1.92	45
19	Diiodomethane	С	16.6	2.2	1	85	54	0.14	380
20	Diiodomethane	С	16.6	2.2	4	300	86	0.36	239

Table 3. List of the parameters according to Exp. number including: liquid, Sample, logarithm of the permeability Log(k), capillary pressure p_c , number of impinged droplet *n*, total impinged volume v_{tot} , characteristic length, time and velocity, l_c , t_c and w_c , respectively.

The difference between drop spreading on a porous and on a non-porous substrate is seen in Fig. 5. The case of non-porous substrate is shown in Fig. 5a-c, where a 100 picoliters (pL) formamide droplet was impinged on a silicon wafer. The case of a porous substrate is shown in Fig. 5d–f, where 4 consecutive formamide droplets, 100 pL each, were quickly impinged on sample B, giving a total drop volume v_{tot} =400 pL. Spreading on the silicon wafer occurs in a continuous way, which is expected in the case of a completely wetting liquid. Drop spreading behavior on the CPG plate is composed of three successive periods: (i) expansion period, where the drop width increase, (ii) a constant width period, where the



Figure 4. Snapshots of infiltration Exp. where 5 water droplets, 60 pL each, are impinged on the top surface of a vertical, thin (0.1 mm) CPG plate (sample C). Liquid infiltrated the plate already during the impingement (**a**–**c**). Later, the drop retracts (**d**–**f**) until it completely absorbed in the sample. Scale bar is 100 μm.



Figure 5. Left: Snapshots of drop spreading on nonporous silicon wafer compared to that on a porous CPG plate. Scale bar is 0.1 mm. **Right:** plot of ${}^{a(0)}{}_{a_0}$ for the same experiments. Note that the elapsed time in the case of Sample B was shifted 1.8 ms backwards for the sake of clarity.

contact angle decreases, and (iii) a retraction period, where the drop decreases in width until it is completely consumed. To illustrate the differences between the two types of substrates, a plot of $\frac{\alpha(t)}{\alpha_0}$ vs. *t* is shown in the right hand side of Fig 5. We note that a_0 in the case of the porous material is not well defined, since the elapsed time starts with the initial impact between the first impinged droplet and the substrate, meaning that $a_0 \rightarrow 0$ according to that definition. Therefore, and for this case only, time zero is chosen as the time when impingement is over, i.e., at t=1.8 ms (see Fig. 5d), giving a_0 a finite value.

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The behavior of a(t) described above, or more precisely, the contact line speed $\frac{da}{dt}$, can be understood as two superimposing velocities [6,17]: one is the expansion velocity v_{+} (m/s) and the other is the retraction velocity v_{-} (m/s), reading:

$$\frac{da}{dt} = v_+ + v_- \tag{8}$$

Here, v_+ is the result of capillary interactions on the surface of the substrate that wishes to expand the drop, and v_- is the result of a hydrodynamic action[6], i.e., the transport of liquid from the drop into the substrate, eventually causing the contact line to retract. Eq. 8 describes well the behavior seen in Fig. 4 and Fig. 5, where in the case of the non-porous silicon wafer $v_- = 0$, so that the drop spreads continuously, and in the case of the CPG plate $v_- > 0$, so that during the first spreading period $v_+ > v_-$, during the second constant width period $v_+ \cong v_-$, and during the third retraction period $v_- > v_+$.

Dimensionless representation of the imbibition data

We can now write the dimensionless volume group V and time groups T, accordingly:

$$V = \frac{\epsilon}{v_t} v_i(t) \tag{9a}$$

$$T = \frac{c\epsilon^2 \sigma cos\theta}{s(1-\epsilon)\mu} \left(\frac{\epsilon}{v_{tot}}\right)^{\frac{2}{3}} t$$
(9b)

Validation of these groups is made in Fig. 6, showing plots of formamide drop infiltration on samples A-F and comparing between plots of infiltrated



Figure 6. Infiltration of formamide drops in CPG plates. Left: infiltrated volume v_i plotted versus time *t*. Right: dimensionless volume *V* plotted versus dimensionless time *T*. Good similarity is seen between all samples and impinged volumes once dimensionless groups are used. Experimental details are listed in Table 3.

volume v_i versus time t (Fig. 6, left) to the dimensionless plots of V Vs. T (Fig. 6, right).

Clearly, the dimensionless plots produce good similarities between all measurements. In order to further examine the degree of universality of V and T, measurements were repeated for water and diiodomethane on some of the samples, with results shown in Fig. 7. The experimental parameters are listed in Table 3. Good degree of similarity is seen here as well, regardless of the type of liquid, average pore size, or v_{tor} .







Infiltration rate

Finally, we look into the infiltration rate in terms of a power law relation, i.e,:

$$V = T^{\alpha} \tag{10}$$

where α is the value of the power law exponent. A plot of $\ln(V)$ Vs. $\ln(T)$ for Exp. 1–20 is shown in Fig. 8, together with a linear curve fitted to all the data. Good similarity is seen between different data sets, showing a tendency to fall on a common master curve, as shown by the relatively high value of the adjusted R^2 that equals R^2 =0.95. The resulting exponent value α =0.7, is higher than the Lucas-Washburn exponent [23,24] α_{LW} =0.5, also obtained by Marmur [1] for the case of unidirectional imbibition in isotropic porous material from infinite reservoir. The difference is quite expected considering the different geometries in each of the cases: In Marmur's case [1], liquid from an infinite reservoir is imbibing a porous substrate through an interface with a constant cross-section, and the liquid front advances only in the direction normal to that interface. In the case of an imbibing drop into thick porous sample, the liquid front expands in both the radial and normal directions, and the drop base radius a(t) experiences large variations, as shown in Figs. 4 and 5.



Figure 8. Plot of Ln(V) vs. Ln(T) of Exp. 1–20. The data exhibit good similarities, as shown by the fitting procedure resulting in adjusted R-square value of R^2 =0.95. The calculated exponent value is α =0.7, significantly different from the exponent calculated for the vertical capillary model [1] α_v =0.5. This difference is expected considering the differences in geometries between the latter model and this work (see text for discussion).

geometries between the latter model and this work (see text for discussion).

Concluding remarks

Drop infiltration on thick isotropic porous material was investigated using dimensional analysis and extensive experimental work. Proper dimensionless groups, namely *V* and *T*, were derived and their significance was established. The universality of these groups was explored using experimental matrix that combined variations in: (i) material properties (specific surface area and porosity), (ii) liquid properties (surface tension, viscosity and density), (iii) wetting properties (contact angle), and (iv) drop volumes. The power law exponent α characterizing the infiltration rate was shown to equal $\alpha = 0.7$, which is a result of a liquid front that expands in the radial and normal directions, combined with a largely varying drop base radius a(t).

In the consideration leading to the definitions of V and T (Eq. 9a and 9b) it is assumed that inertial effects are negligible, and the only pressure that drives the imbibition is the capillary pressure at the liquid front. These assumptions is supported by the universality obtained using those groups (Figs, 6–8).

We see this work as a significant step in understanding the subject of drop infiltration on porous material. Nevertheless, work is still needed in order to find analytical solutions describing both drop infiltration and drop spreading, since the two are important aspects in applications such as inkjet printing. Once a dimensional scaling is achieved the aim is to validate it and use it for inkjet printing using relevant parameters for substrate and inkjet inks.

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LIST OF ABREVIATIONS

Dim dimensionless Exp experiment

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meter
nanometer
millimeter
time
second
milliseconds
Pascal (pressure unit)
Newton (force unit)
millinewton
radians
picoliters

LIST OF PARAMETERS AND THEIR UNITS

х, у	(m)	Cartesian coordinates
t	(s)	Elapsed time
V_i	(m^3)	Imbibed volume
V_{tot}	(m^3)	Total impinged volume
l_c	(m)	Characteristic length scale
t_c	(s)	Characteristic time scale
V	(Dim)	Dimensionless volume group
Т	(Dim)	Dimensionless time group
t_{tot}	(s)	Total absorption time
T_{tot}	(Dim)	Dimensionless drop absorption time
α	(Dim)	Power law exponent value
h(x, t)	(m)	Drop profile function
f(x, t)	(m)	Imbibed liquid profile function
a(t)	(m)	Half of the drop width at the drop substrate interface
a_0	(m)	Initial half drop width
b(t)	(m)	Half of the liquid front width at the drop substrate interface
#sk	(m^{3}/m^{3})	Bulk porosity
μ	(Pa s)	Liquid dynamic visocity
k	(m^2)	Permeability
С	(Dim)	Kozeny constant
S	(m^{-1})	Specific surface are
p_c	(N/m^2)	Capillary pressure
σ	(N/m)	Surface tension
θ	(Rad)	Contact angle
\mathcal{V}_+	(m/s)	Expansion velocity
\mathcal{V}_{-}	(m/s)	Retraction velocity

g (m⁻³) Volume of a single impinged droplet *n* Number of impinged droplets

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Transcription of Discussion

INFILTRATION AND DIMENSIONAL SCALING OF INKJET DROPLETS ON THICK ISOTROPIC POROUS MATERIALS

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Jean-Francis Bloch Grenoble University

I just need a clarification concerning your model. The first equation you have is a continuity equation where \mathbf{u} is a local velocity. The second one, I do not understand because you have used in fact the classical Darcy Law but that is correct when you have the mean over a global system. My question is why you did not use, for example, the Navier-Stokes equation, which is exactly the same scale. If you are using the Darcy Law, it means you are already considering a mean to determine your permeability and then there is a problem because you have the mean of the whole space for the permeability but the capillary effect is local because it depends on saturation. So here, I need a clarification because, afterwards, you had some scale effects and so on.

Asaf Oko

The question is what do we scale our system with; local or global parameters? In this case, where we have a fully saturated porous material behind a sharp liquidfront, it is not partially saturated, it is fully saturated. It is not local length scales such as pore diameter that scale the process, but global parameters such as the size

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of the system. We have tried to consider local scaling parameters and it simply did not work.

Jean-Francis Bloch

But it can be capillary forces affecting the liquid front. I was able to understand the movements from the capillary effect and you have some modification of the saturation which is local.

Asaf Oko

It is a good question that disturbed me quite a bit: if the capillary pressure is the driving force, how come the pore diameter is not scaling the phenomena? The answer is that any local saturation differences or local roughness occurring at the liquid-front are insignificant to the entire process. For example, two neighbouring pores with different diameters may create a local roughness in the liquidfront. However, considering that our material has narrow pore size distribution and average pore size on the nanometre scale, this roughness is negligible compared to the size of the entire system.

Stephan Kleemann Munich University of Applied Sciences (from the chair)

This may change once you make the step from your isotropic material to the paper.

Asaf Oko

Yes, I would have to consider that.

Pooya Saketi Tampere University of Technology

Most of the commercialised piezo-dispensers have the ability to control the stroke and stroke velocity of the piezo-actuator and that will definitely affect the velocity of the droplet which is dispensed. You have removed the inertial forces from your model but I think that you need at least to report the velocity that you are shooting these droplets. I can show droplets, even very small droplets of 20 or 15 nL, which, if you shoot them with high speed, turn into satellite droplets. So it is really necessary that you include that information. How you are controlling the repeatability of your piezo-dispenser? Because if you shoot 5 or 6 droplets in a row, you need to have a control on the repeatability of these droplets.

Asaf Oko

We measured the volume of each drop that is dispensed and confirmed that it was constant and repeatable. Considering the inertial effects, it is true that we did not consider how fast the droplets travelled, however, we derived Reynolds and Darcy numbers with respect to the flow inside the porous material and saw that they are very small, meaning that inertia inside the material is negligible. This picture did not change regardless of the liquid we used, even though different liquids were dispensed at different velocities. My conclusion is that the energy from impact between the drop and the porous material is dissipated quite quickly and has no influence on the penetration.

Li Yang Innventia

I would like to ask you a question about the capillary force, which you express in terms of porosity; you said that is more convenient and that is true. But on the other hand, you used a model material which has a well defined pores, so the pore diameters are more or less similar. In this case probably it does not matter if you use the diameter or use the porosity because they are uniform pores. My question is that if you use other material such as paper the pores are not the same, is that approach still available?

Asaf Oko

Our scaling is based on two parameters: capillary pressure and permeability. The expression for the capillary pressure is derived using arguments concerning the difference in surface energy between dry surface area and wet surface area, and the expression for permeability is the Kozeny-Carman equation and uses specific surface area and porosity. It is useful because it does not use average pore radius which is hard to calculate in many examples of anisotropic porous materials. If we could have measured permeability directly than we would not need specific surface area at all. Actually, the best option would be to measure capillary pressure and permeability instead of using models to estimate their size.

Ramin Farnood University of Toronto

In your graph that showed results of all your experiments (figure 8), the data collapsed almost onto the same curve, and I emphasize on the word almost, because there seems to be some variation in the data. If you were to fit the different sets of data separately, would you see a range for alpha? The second thing I want to ask, what are your thoughts in terms of applying this to paper. Would you

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obtain a higher or lower alpha given the fact that the fibres change dimension due to the absorption of water?

Asaf Oko

I think the results collapse well enough. Some points belonging to experiments with Diiodomethane deviate more than others. Diiodomethane had a static contact angle of 50 degrees, I suspect that the dynamic contact angle is even higher which would push this data set towards the master curve. About swelling, I do not think it is relevant for the time scale of imbibition of a single inkjet drop, although if you wait long enough after the drop has absorbed, you will see swelling, which indeed I observed myself.

Juha Salmela VTT

There is actually work by Pasi Raiskinmäki from 2004². He did his thesis around this phenomenon and it included experimental work and he also used the lattice Boltzmann simulation method. According to his results, impact velocity actually defines the amount of ink that penetrates initially into the paper or any porous structure, and, according to his findings from simulation and experiments, this is especially the case with increasing porosity. So, according to him, velocity plays actually quite a big role, even bigger than porosity in some cases.

Asaf Oko

Did he use tomographic images of real paper?

Juha Salmela

Yes, and also some simulated structures.

Asaf Oko

I think that in paper it is sometimes hard to distinguish between surface roughness and bulk pores, which may cause artifacts in calculating the penetrated volume. Anyhow, I think only a thin layer close to the surface will be affected.

²P. Raiskinmäki, "Dynamics of multiphase flows: liquid-particle suspensions and droplet spreading", PhD Thesis, Faculty of Mathematics and Science, University of Jyväskylä (2004).

Tetsu Uesaka Mid Sweden University

I have just one clarification question. Am I correct that, in this model, the size of the droplet, is this at about the micron scale?

Asaf Oko

About 50 to 100 μ m and even more.

Tetsu Uesaka

So quite a big droplet. Secondly, porosity, you are talking about the nanometre pore scale. So this means a continuum approximation is good. So in this system, I just wonder, what are we understanding here from the point of inkjet printing? For example, today most of the inkjet printing inks are reactive fluids, so I don't know whether we can apply the continuous approach which is applied to the normal porous media. So the question is, what are we trying to do here?

Asaf Oko

I hope that manufacturers of inkjet printers would be able to estimate how fast a single drop would absorb on the paper by knowing the surface area, porosity or permeability of the paper.

Tetsu Uesaka

But you said that this system will be different from the paper system. When you talk about the paper system, the size of the droplet is a very much compatible with the size of the structural units in the paper. Then the continuum model does not mean anything. On the other hand in the system that you define here, yes it is consistent, so your approach is good for your system. But I'm not sure if it has any link to the actual systems we are interested in.

Asaf Oko

I would have to try and see if there is agreement between experiments done using paper to experiments done using the porous glass. I would probably have to make several experiments in order to get some statistics. From an engineering point of view, one would want to know the big picture rather than local events, meaning that some drops will absorb much faster than others, but the average absorption time can be estimated using this approach. *Stephan Kleemann* Munich University of Applied Sciences (from the chair)

Maybe at the end, this method could be some kind of a standard method for the people developing the inkjet printer.