Influence of Substrate Properties in Drop on Demand Printing

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Abstract

Drop on demand ink jet printing has become a very important printing technology combining excellent ease of use with good image quality. Optimal image quality, however, is only possible after proper tuning of ink, media and driver settings. In this study, final image quality is correlated with intermediate phases taking place after a droplet has been jetted from an ink jet head. As such, droplet impact upon the substrate with associated spreading, liquid imbibition into the porous receiving layer, and finally evaporation of the liquid into the surrounding air are considered.

The experimental methods used are based on high-speed cinematography and proprietary phase controlled ultra short snap shots of the impact process. Different grades of papers were considered covering a wide range of porosities. A wide range of flow regimes is covered in the impact phase: spreading, retraction, oscillation and eventual splashing of secondary drops. It is shown here that the transient evolution during the impact phase is paramount in determining the initial conditions of the imbibition and could be well expressed in terms of dimensionless numbers that are defined in the paper.

It is also demonstrated that in contrast to the inertial spreading, the capillary wicking process takes place on a quite different time scale and is not easily amenable to dimensional analysis because of the strong interaction between flow parameters and substrate properties. In a third phase the liquid penetrating into the pores is shown to be evaporating into the environment at another time scale. Finally, the different results that have been obtained are compared with existing data, the possible physical mechanisms are pinpointed and explained and a unified framework of the impact process considering the image quality on substrates is suggested.

Introduction

A large number of engineering applications are concerned with drop impact. Some of these include nuclear reactor cooling where heat transfer is affected by the drop dynamics upon impact of the drop with a solid surface, or the deleterious effect of high velocity rain drops on solid structures and on soils. Detailed knowledge of droplet impingement on solid materials is also critical for overall process development and advancement of engineering operations such as spray cooling and/or spray coating.

The fluid flow associated with impinging drops is rather complicated because of the extreme deformation of the droplet surface occurring within very short time scales and is not really understood in detail. In the case of low impact velocities, the spreading phenomenon is probably controlled by the surface tension. When impact velocities become important, it has been shown that compressibility effects play a major role[1].

The studies of drop impact on solid and liquid surfaces were initiated by Worthington[2] who investigated the pattern left by drops of various fluids after their impact onto glass plates. More recently Chandra and Avedisian[3], Prunet-Foch et al[4] and Mähönen et al[5] have performed experiments varying the operating conditions and the solid targets and using much more sophisticated visualization techniques than Worthington[2]. However, none of these works has addressed all together the initial spreading, the subsequent imbibition process also called capillary wicking, and the evaporation process.

The work, which is presented here, is connected to ink-jet printing where drop impact onto solid surfaces is a ubiquitous phenomenon. The emphasis is on the characterization of phenomena related to low speed impacts on a variety of solid surfaces with different wetting properties. Experimental results of the collision and deformation dynamics of droplets impacting on targets of glass, teflon and various grades of paper are reported. In the latter case, the imbibition process has also been investigated. The objectives set in this work differ largely in the following aspects from others that are reported in the literature. Indeed as listed below:

(1) The impact of a droplet on the surfaces for different values of droplet velocity is detailed.
(2) The evolution of droplet shape (spreading diameter, droplet height) during impact on various substrates is measured. This is the so called inertial spreading phase.
(3) Results obtained on porous and impervious surfaces are compared with relevant theoretical analyses.
(4) The imbibition process for a large number of porous substrates is measured.

(5) The penetration of the drop in the substrate for various initial conditions and material characteristics is modeled.
(6) The evaporation time is measured for the liquid absorbed into the porous coating, leading to an equilibrated image that can be judged for quality by means of different techniques.

In order not to obscure the different aspects, it was chosen here to study only the impact of single drops. This is done by either using a high-speed camera, which takes photographs at successive stages of the impact process of one single droplet, or by using a proprietary pseudo-cinematography method[6] where the evolution of the drop dynamics is reconstructed with photographs of different droplets taken at successive stages of the impact process. The main assumption, which is made in the latter case, is that of determinism in the impact.

A wide range of flow regimes is covered in this work like spreading, retraction, oscillation and splashing and the results obtained are compared with existing data. The particular impacts that are presented here are for relevant dimensionless numbers (defined later) of interest in ink-jet printing. The selected results may be characterized as the interplay between inertial effects, which are shown to dominate the early spreading of the fluid and the viscous, and surface tension forces, which arrest the spreading and eventually bring the fluid to an equilibrium configuration.

A variety of porous substrates is also tested in this work. The results obtained allow first of all to categorize the papers and then help to provide an appropriate modeling of some of the effects.

Experimental

The basic experimental setup used in this work is built around droplets generating devices (either a syringe pump or a commercially available printhead), an illumination source, an optical system coupled to an image recording system, and triggering electronics. An example of the experimental setup using a Hewlett Packard HP500 printhead and a Kodak HG2000 fast video capturing system is shown in figure 1.

In order to cover a large spectrum of dimensionless numbers, the size of the drop, its velocity as well as the material properties of the fluid was varied. For the receiving substrate, the material properties were also varied, especially with regard to the porosity and absorption characteristics.

Syringe Pump (Gilson 402)

Droplets with radii in the mm range were created by pumping different ink compositions through the needle of a Gilson 402 dilutor-dispensor syringe pump. The size of the droplets was tuned by changing the diameter of the needle. The velocity of the drops was varied by one order of magnitude (0.3 to 3 m/s) by simply changing the height of fall (distance between needle and the substrate). The velocity was measured from the distance of travel between two images taken with the high-speed camera at a given frequency.

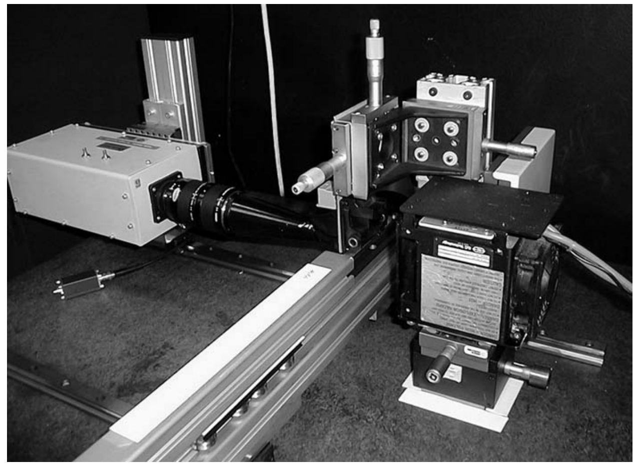

Figure 1. Experimental set-up with Xe-light, HP500 printhead, and Kodak HG2000 fast video capture

Ink Jet Printhead (Hewlett Packard HP500, Cartridge HP51626a)

Droplets with a volume of about 70 picoliters were created by sending 4 μs signals of 19V to a single connecting point of the resistor element in this head. The velocity of the drops was found to be a function of the ink composition and was varied between 5 and 12 m/s. The speed was determined by dual-exposure shot measurements using a Sensicam short shutter-time camera.

Short Shutter Time Video Camera (PCO Sensicam)

This camera was used to capture a high-resolution single image of 1024x1024 pixels with a shutter time comprised between 500 ns and 1 μs. This technique is extremely useful for ultra-short processes such as the inertial spreading of small drops. Using external triggering electronics, multiple shots taken at different times of multiple droplets were combined into 1 single “video” according to the pseudo-cinematography technique that has been described elsewhere.[6]

High Speed Video Camera (Kodak HG2000)

This camera was used to capture images of 512x356 pixels at a frame rate of 1000fps. The exposure time was set to 23 μs. The above framing rate requires intense illumination of the drop as detailed below. The advantages associated with this high-speed cinematography technique are that it does not require a perfect reproducibility from one experiment to another. Moreover, it helps to test if the phenomenon is very repeatable. The drawback of this method is the limited time resolution of 1 ms for transients so all phenomena which may happen within this time frame cannot be detected.

Illumination Source (ILC R400-1)

A cooled high intensity light source available from ILC Technology model R400-1 with front thermal glass was used as the illumination source for all experiments. The cover glass prevents un-wanted heating of the sample and also protects the very light sensitive cameras.

Ink Compositions (AgfaJet)

The inks that were used in this study were commercially available aqueous inks especially tuned for piezoelectric print-heads (AgfaJet Sherpa Cyan Dye ink) and other ink compositions. These fluids basically contained AgfaJet Sherpa Dye ink compositions and glycerol in order to change the viscosity and surface tension. The range of viscosities covered was from 1 mPa.s to 260 mPa.s and that of static surface tension of fluids was varied between 33 and 40 mN/m. These characteristics were respectively measured using a Brookfield DVII viscometer and a Krüss K9 digital tensiometer.

Receiving Substrates (AgfaJet)

Different substrate materials were used throughout this work, ranging from glass, teflon tape, ink jet polymeric blend materials and ink jet microporous and macroporous materials. Test-case porous materials were obtained by coating pigment/binder compositions on PET and measuring the resulting porous characteristics via mercury porosimetry (Hg-porosimetry), gas adsorption, and scanning electron microscopy inspection.

Analysis of Captured Images

When the drop arrives near the substrate, an electronic signal is sent to the system so as to begin the grabbing process. A single image (snap-shot) or a sequence (movie) may be captured. Once the image acquisition is completed, an edge finder algorithm accurately locates an edge from a color/gray-scale image. After the images have been processed, data are exported to industry-standard spreadsheets and databases for further analysis.

The high-speed cinematography technique does not require a perfect reproducibility from one experiment to an other. This is in contrast to the pseudo-cinematography method where in order to reconstruct the evolution of the drop dynamics; photographs of different droplets taken at successive stages of the impact process are needed. Nevertheless, the aspect of reproducibility was checked and it was found that the phenomenon was very repeatable within the limits of variation of the dimensionless parameters, which will be given in the next section.

Results and Discussion

To fulfill the objectives listed in the introduction part, drop-impinging experiments were performed on glass, teflon and papers having different coatings and varying porosities. The measurements of the final and transient spreading diameter and height were taken for impact Weber numbers covering an order of magnitude of two as stated below. No explicit reference in the literature was found where the different phases following drop impact such as inertial spreading, imbibition and evaporation are considered all together.

Phase 1: Inertial Spreading

As soon as there is contact between a drop and a solid surface, the liquid generally starts spreading out. In the limiting case i.e. when the drop is carefully placed onto the surface, the process of spreading is dominated by intermolecular forces. The dependence on time of the radius of the wetted spot and of the contact angle can be described by universal scaling laws as shown in detail first by de Gennes[7]. Very recently, it has been shown that there are different regimes and associated time windows in which each particular regime holds preferentially.[8] This topic is out of the scope of this paper and will not be considered further.

In the case of a finite velocity, the drop spreads radially into a "pancake" shape. The rate of spreading depends on a combination of parameters. Below one selected example of a large drop ejected with a given velocity, which is spreading and eventually retracting, is shown.

The example shown in figure 2 was captured using the Kodak HG2000 high speed camera at 1000 fps with a shutter time of 50 µs. Eight images (1 – 8 ms after impact) are shown. For smaller droplets at faster time scales the pseudo-cinematography technique based on the Sensicam camera is preferred.

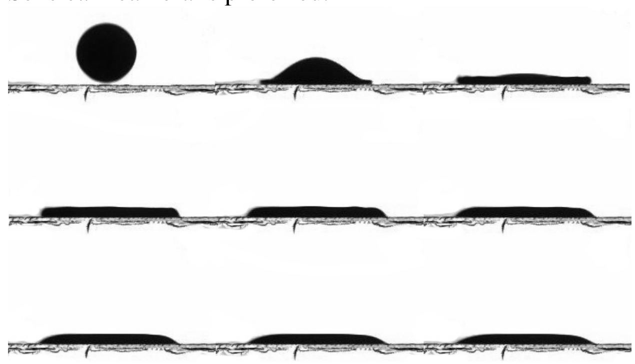

Figure 2. Experimental results of impact phase

The mathematical formulation of the problem of impact of a droplet on a solid surface leads to consider the equation of continuity and the momentum equations both in the radial and in the axial directions. The non-dimensionalization process[9] gives the following dimensionless numbers (Reynolds, Weber, Froude and Mach) respectively:

$$Re = \frac{\rho V D}{\mu} \quad We = \frac{\rho V^2 D}{\sigma} \quad Fr = \frac{V^2}{Dg} \quad Ma = \frac{V}{c} \qquad (1)$$

where D is the diameter of the drop prior to impact, V its velocity, μ the dynamic viscosity of the liquid, σ the liquid-air surface tension, g the gravity acceleration and c the speed of sound in the liquid medium.

In the case of a finite impact velocity, the rate of spreading is essentially driven by the inertia of the drop and it is slowed by viscous and surface tension effects. When the inertial energy is dissipated, the drop reaches its maximum diameter. A rough model for the prediction of this maximum diameter has been worked out from a simple energy balance equation[10] and reads:

$$\beta_{max}^2 = \frac{-(1-\cos\theta)+\sqrt{(1-\cos\theta)^2+6\alpha Ca\left(\frac{We}{3}+4\right)}}{3\alpha Ca} \quad (2)$$

where $\beta_{max,}$ equal to d_{max}/D, is the maximum spreadfactor, θ is the contact angle, Ca is the capillary number equal to the ratio of viscous forces over surface tension forces or We/Re. The semi-empirical factor α accounts for the uncertainty in the dissipation function and may depend on both fluid and operating characteristics.

Following the rules of similarity,[11] experiments conducted with a model drop (droplet diameter of the order of 2 mm) can be compared to those performed with an actual print head prototype (droplet diameter = 50 µm) if the above cited (equation 1) dimensionless numbers remain the same between the two sets of experiments. Given the low impact velocity of ink droplets, the Mach number is probably irrelevant in the problem at hand. As for the Froude number, it is hard to keep it the same for the two sets of experiments but its influence has been shown to be negligible in these experiments.

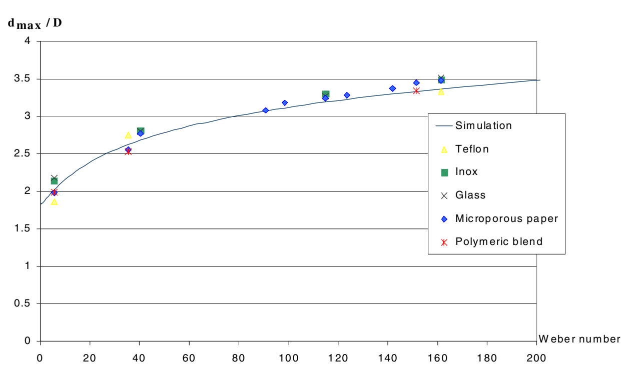

Figure 3. Experimental and numerical results of the maximum spreadfactor

In fact, a number of preliminary experiments have pinpointed out that the main controlling parameters are the Weber and Reynolds numbers, so the different experiments could be performed by varying mainly these dimensionless numbers. The tests have been conducted for a large number of substrates, both impervious and porous and having very different wetting characteristics. The results for the maximum spreadfactor are shown in figure 3. One can note that whatever the substrates are, all experimental points can be represented by one single theoretical curve obtained from equation (2).

Besides the maximum value of the spreading, it would be useful to have a model representing the drop impact transients. Indeed, the oscillation of the droplet consists of the inertial spreading of the droplet until it reaches its maximum diameter and subsequent oscillatory motions of recoiling and weak re-spreading. In this paper, following previous work[12,13] an analytical model to obtain the drop impact dynamics is used. The shape of the droplet is modeled as a truncated sphere and viscous dissipation is taken into account. A differential equation is derived for determining the drop height as a function of time during contact:

$$2E(h)h'' - G(h)h'^2 + I(h)h' + J(h) = 0 \quad (3)$$

where h is the drop height, primes and double primes represent first order and second order derivatives with respect to time. The coefficients are some polynomial equations depending on the height, flow and wetting characteristics on the substrate. Since the shape is given, the drop contact radius can also be calculated. It is related to *h* by:

$$D_b = 2\left[\frac{1}{3}\left(\frac{1}{h}-h^2\right)\right]^{1/2} \quad (4)$$

where D_b is the base diameter of the drop. In order to test the previous model, experiments have been performed using various jet droplets of different ink compositions. The variation of the controlling dimensionless numbers was set to be compatible with real ink jet printing devices. A typical example of large ink droplets impinging upon a real ink jet receptor has been shown in figure 2. (We = 115, Re = 105, Ca =1.09).

Equations (3) and (4) are solved using a standard mathematical software. In figure 4, both the experimental (full lines) and the theoretical (dashed lines) results for the transient diameter and height are plotted. The experimental points are those of figure 2, whilst for the simulation a contact angle of 20º and a dissipation factor equal to 1 are taken into account. The comparison is quite good given the uncertainty both in the measurement of critical experimental parameters such as the wetting angle and the crude assumptions, which have been made for the velocity profiles for example.

It is important to note here that as for obtaining the maximum spreadfactor, dimensionless parameters can be used to describe the full transient behavior of the impact phase. This is a very important step for the ink jet process because it simplifies drastically the modeling of the phenomenon and sets well given constraints for developing an optimal receiver composition. Irrespective of the nature of the receiving substrate, the transient behavior can be predicted to some degree based upon the speed, size and fluid characteristics of the impinging droplet and the wetting properties of the substrate.

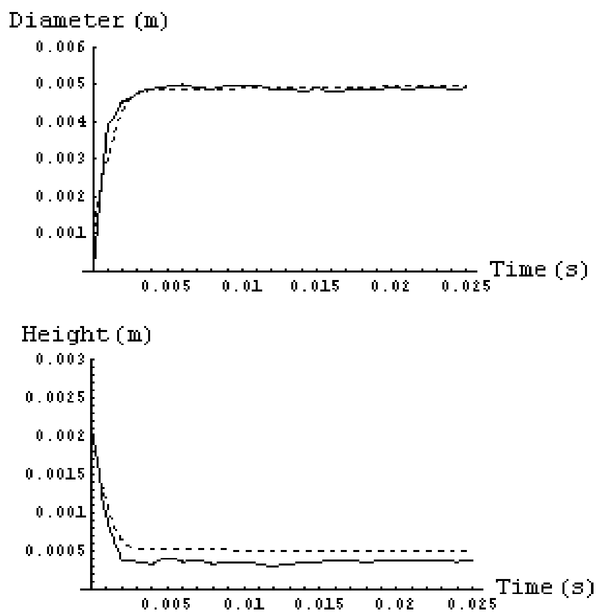

Figure 4. Comparison of experimental and numerical results of drop impact dynamics

Phase 2: Drop Imbibition

After a certain period of time an equilibrium condition is reached, determining the final shape of the liquid on top of the receiving substrate prior to penetration or absorption into the receptive coating. Extrapolation of the results based upon droplet sizes of a few mm in diameter predict that an equivalent equilibrium condition is reached for real size ink jet droplets of less than 50 µm diameter, in less than 20 µs. This demonstrates the interest in using both high speed (Kodak HG2000) and short shutter time (PCO Sensicam) video cameras.

Most experiments regarding the drop imbibition phase were conducted using the HP500 printhead, commercially available and modified AgfaJet Sherpa Dye based inks, and the HG2000 fast video capturing of the droplet impinging upon the substrates. Figure 5 shows results obtained for the deposition of the commercially available HP ink (HP51626a) on top of different substrates. Three big classes can be found among these substrates: the very fast ones are cast-coated papers and macroporous outdoor materials showing a very short absorption time, the slowest ones are the polymeric blend materials in which all the liquid has to be absorbed via a diffusion process. The third class is the intermediate one of the microporous materials showing good glossy characteristics and a much faster drying time than the polymeric blend materials.

From a practical point of view, the receiving materials of interest for the industry currently are the microporous media. They can combine sufficient image quality with good instant-dry characteristics. The mechanism of ink absorption for these materials is based upon the capillary wicking and most emphasis within this paper goes to the description of this process.

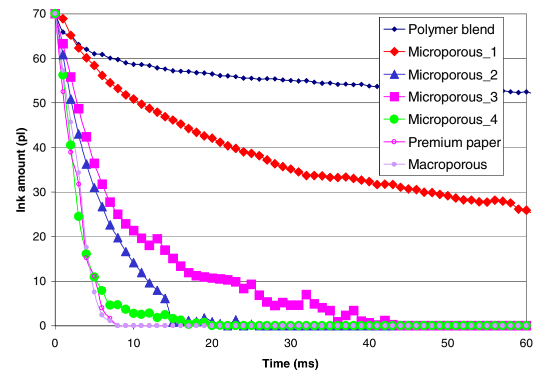

Figure 5. Drop imbibition measurement for different (microporous) receiving layers

As for the inertial drop spreading process where a tentative modeling was proposed, a simplified numerical model based on the Davis-Hocking description[14,15] is presented for the imbibition phase. This model describes the vertical absorption of a drop initially at rest into a porous layer. During sorption, the wet spot, and hence the available surface for sorption, diminishes. This finally leads to a wet spot in the porous material in the form of a paraboloid with a depth (D) equal to the initial droplet height (h) divided by the porosity. The kinematics of the flow are described by the well-known Lucas Washburn equation, giving the depth d as a square root of time:

$$d = \sqrt{\frac{r\sigma \cos(\theta)t}{2\mu}} \quad (5)$$

The pore radius is given by r. The wet spot inside the porous material has the shape of a truncated paraboloid with a volume described at any time by:

$$V = \frac{\pi r^2}{2}\left(2d - \frac{d^2}{D}\right) \quad (6)$$

All other parameters like droplet radius, droplet volume, droplet height and absorbed volume can then easily be calculated.

The model was tested using microporous test materials for which the porous characteristics were modified by changing the fillers, binders and filler to binder ratio of the porous coating layers. The porosity characteristics were evaluated using Hg-porosimetry. The main differences between the samples shown in figures 5 and 6 were the pore size distribution characteristics for the microporous media, with variations in pore volumes and mean pore sizes (15, 35, 100, 200 nm).

Using the numerical model explained above results for equivalent absorption curves as shown in figure 5, were obtained and are represented in figure 6.

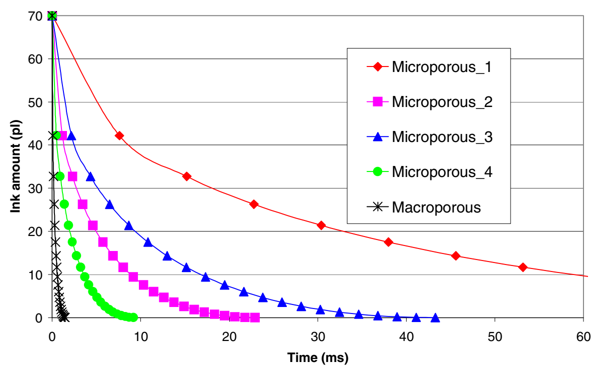

Figure 6. Simulation results for drop imbibition

Based upon these numerical results, it can be concluded that the model fairly well represents the experimental results obtained for both macro and microporous papers. It can also be concluded both from experimental and numerical results that the time scale for absorption of the ink into the receptive coating is very long compared to the time scale of the inertial spreading (almost 3 orders of magnitude). This means that both phases can be well separated and analyzed accordingly. This opens a lot of possibilities for developing interesting new materials with improved characteristics. This goes beyond the scope of this article because of lack of space but additional experimental evidence will be shown on the conference.

Phase 3: Liquid Evaporation

The ink jet print that a customer is generally interested in is not the intermediate state that is obtained after impact of the droplet or even after absorption of the liquid into the receptive coating. Indeed, once the liquid carrier of the ink has penetrated the coating layer, it will have to evaporate resulting in an image in which the color dyes (pigments) are well fixed. It could again be shown that the time scale for evaporation is at least two orders of magnitude larger compared to the time scale of absorption for an ink droplet so once again the process can be analyzed separately.

Conclusions

In this paper, the collision dynamics, the absorption kinetics and the evaporation kinetics of a liquid droplet impinging on a variety of surfaces were studied both experimentally and from a modeling point of view. The corresponding three phases are characterized by well-separated time scales. The inertial spreading phase typically takes some microseconds to be finalized, the absorption phase is around several tens of miliseconds (for microporous media), while the evaporation time scale is in the second to minute time frame. From an end-user point of view, excellent image quality as measured by using an image analysis system, is therefore not a simple reachable target. It can be influenced by the print-head jetting characteristics, the ink characteristics, as well as the media characteristics. The constraints of all these parameters are generally incorporated into the driver settings of the printer. Changing one of these parameters therefore has consequences on the other ones. If the right interactions are not analyzed correctly and taken into account, bad image quality will result.

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Biography

Guido Desie got a Ph.D. at the K.U.Leuven, in the field of physicochemical analysis of enzymatic systems. In 1987, he joined Agfa Gevaert, Belgium, where he was involved in R&D of physical properties of film materials. From 1991, he was involved in R&D of Ink Jet and Toner based digital printing techniques. He is co-author of about forty granted patent families mainly in the fields of Ink Jet and Toner Jet printing.