Druppels maken samen het verschil

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prof.dr.ir. Herman Wijshoff
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TU/e Technische Universiteit
Eindhoven
University of Technology

Druppels maken samen het verschil

Where innovation starts

Inaugural lecture prof.dr.ir. Herman Wijshoff

Druppels maken samen het verschil

Presented on February 10, 2017
at Eindhoven University of Technology

Introduction

My esteemed Dean, members of the Executive Board, fellow professors and other members of the university community, dear family and friends, ladies and gentlemen.

As mentioned in the introduction, this lecture will be about inkjet printing. What is inkjet printing? Inkjet printing is a technique that generates droplets of fluid, the ink, which are deposited onto a substrate in a certain pattern. When the fluid contains colorants, an image is created.

During my talk I will elaborate on the history of inkjet printing, which is basically one of the oldest printing techniques mankind has ever developed. Together with the development of the applications, the science of inkjet printing was also developed, which is about the manipulation of small amounts of fluid. I will show several examples how science and technology reinforced each other over the last centuries leading to the situation of today where inkjet has become a mature technology for graphic printing applications. Also for Océ, a Venlo-based high-tech document printing company and my employer for more than 30 years, inkjet has become one of the main printing technologies for the near future.

Its unique ability to deposit a wide variety of materials on various substrates in well-defined patterns has given inkjet technology a key role in many emerging new industrial and medical applications. To comply with the increasing and diverging requirements for today's inkjet technology, a fundamental understanding of the underlying processes is very important. I will conclude my talk with a discussion of the main topics of my chair “Fluid dynamics of inkjet printing”.

The history of inkjet printing

The oldest examples of human creativity are cave paintings of prehistoric origin some 40,000 years ago, figure 1. Historians hypothesize that paint was applied with brushing, smearing, dabbing, and spraying techniques. Paint spraying, accomplished by blowing paint through hollow bones, yielded a finely grained distribution of pigment, similar to an airbrush. Basically this technique is similar to modern inkjet technology.

Figure 1

Cave paintings in the cave of Altamira in Spain and in Cueva de Las Manos in Argentina [Wikipedia].

Being used for many thousands of years, for the oldest reported research on the behavior of liquid jets in western literature we have to jump to the year of 1508, when Leonardo da Vinci described the behavior of a water jet [1], figure 2. Gravity was assumed to be the force leading to the brea-up of a liquid jet, as more quantitatively derived in 1686 by Mariotte [2]. It was at about the same time that Newton published his famous “Philosophiæ Naturalis Principia Mathematica”, with Newton’s second law and the definition of Newtonian viscosity. The cohesion of a liquid, which results in the surface tension, was assumed to have only a contribution in holding the liquid together.

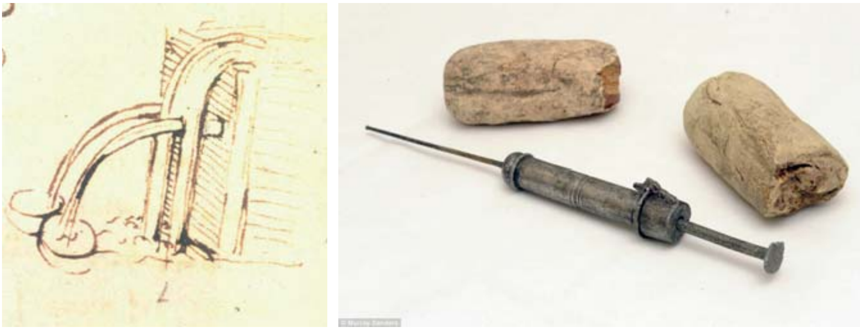

Figure 2

Sketch by Leonardo da Vinci illustrating the impact of liquid jets [1] and an antique syringe [Printerest – medieval health].

Although the first syringes were used in Roman times, Blaise Pascal is considered to be the inventor of the syringe (1650) as an application of what is now called Pascal's law. He used it in testing his theory that pressure exerted anywhere in a confined fluid is transmitted equally in all directions, and that the pressure variations remain the same. The syringe shares the same physical principles with an inkjet nozzle.

Only at the beginning of the industrial revolution, the groundwork for the description of the role of surface tension forces as driving force behind break-up was laid by Thomas Young in 1804 [3] and Pierre Simon Laplace in 1805 [4]. They finally recognized that the same force that holds the liquid together is also the driving force behind the break-up of a liquid jet. In 1822 the equations to describe the motion of non-ideal fluids were formulated for the first time by the French engineer and physicist Claude Navier [5]. In 1845 George Stokes introduced a fully understood derivation of these equations that is accepted until today [6]. So, today we refer to these equations as the Navier-Stokes equations for the application of classical mechanics to the motion of liquids.

The foundation of modern inkjet technology is attributed to the Belgian physicist Joseph Plateau and English physicist Lord Rayleigh. Plateau was the very first to publish on this field in 1843 with his experiments on the decay of a liquid column [7]. He noticed that perturbations become unstable when their wavelength is long enough [8]. Lord Rayleigh published a series of founding papers starting with “Instability of jets” in 1878 [9]. He added the flow dynamics to the linear analysis of the decay of liquid jets, and found the right typical spatial distribution of the decay patter in a liquid jet. His results were in good agreement with the measurements of Felix Savart in 1833 [10], figure 3, which were in fact the experimental foundations of the work of Plateau and Rayleigh. Savart was the first to recognize that the break-up of liquid jets is governed by laws, independent of the circumstance under which the jet is produced. He used acoustic energy to form uniform drops.

Figure 3

Perturbations growing on a jet of water [10].

The first inkjet-like recording device, using electrostatic deflection, was invented in 1858 by William Thomson, who would later become Lord Kelvin. This was the Siphon recorder and is shown in figure 4. The apparatus was used for automatic recordings of telegraph messages and was patented in 1867. A siphon produces a continuous stream of ink onto a moving web of paper, and a driving signal moves the ink horizontally back and forth. The first experiments on manipulating a stream of droplets even go back to 1749. That year, Abbé Nollet published his investigations on the effects of static electricity on a drop stream [11], figure 4. The research on the behavior of liquid jets continued, and Osborne Reynolds derived the lubrication theory for the decay of a liquid jet in 1886 [12]. Weber and Ohnesorge added viscosity to the analysis of jet decay in the 1930s [13, 14].

The discovery of the piezoelectric effect goes back to 1880 by Pierre and Jacques Curie [15]. In 1931, the use of piezoelectric material as an actuator, i.e. the deformation of a structure when applying an electric voltage, was reported [16]. The main ingredients for contemporary piezo-inkjet devices were known, but it took many decades before applications of the physical principles of drop formation were used in commercial working devices.

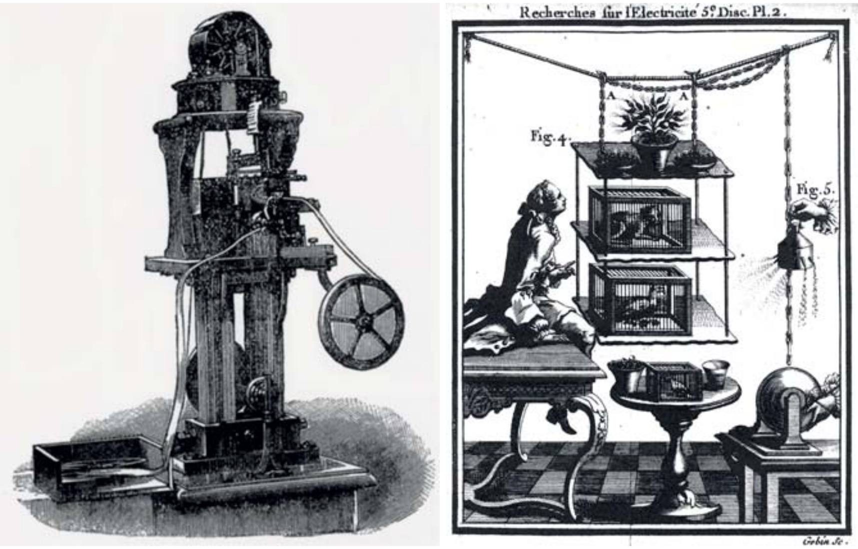

Figure 4

(Left) The Siphon recorder was the first practical continuous inkjet device. It was used for automatic recordings of telegraph messages and invented by William Thomson in 1858. (Right) An illustration from Abbé Nollet showing experiments on the effect of static electricity on a drop stream, published in 1749.

Commercial inkjet printing

The first modern inkjet printing device was patented in the 1950s [17]. It generated a continuous stream of droplets instead of a continuous jet, as in the Siphon recorder. The droplets are charged, whereby electrical fields deflect the droplets to create an image on a substrate, as shown in figure 5. This principle is called continuous inkjet printing, which emerged in the 1960s and became a commercial success in the 1970s due to the huge research efforts by IBM, and later by Stork.

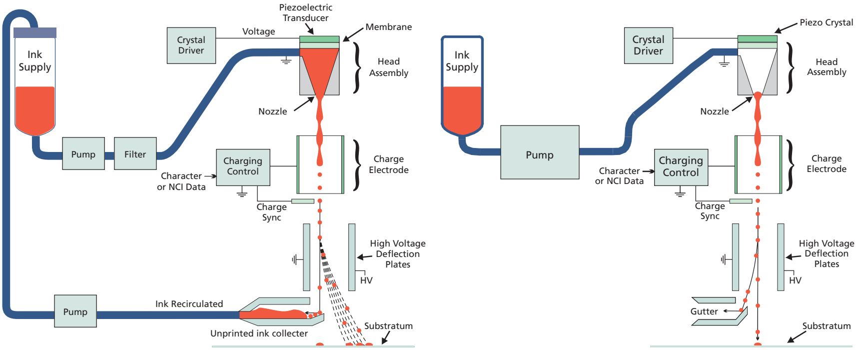

Figure 5

The continuous multi-level deflected inkjet principle and the continuous binary deflected inkjet principle [18].

The main disadvantage of this technique is the use of complicated hardware for break-off synchronization, charging electrodes, deflection electrodes, guttering, and re-circulation systems, high pressure ink-supplies and complex electronic circuitry. This made this technique less suitable for home and office printers, which would emerge in the 1980s.

Instead of continuously firing drops, it is also possible to create drops only when an actuation pulse is provided, termed drop-on-demand. The first pioneering work in that direction was performed in the late 1940s by C.W. Hansell of the Radio Corporation of America (RCA), who patented the first drop-on-demand device. However, this invention, intended for use as a writing mechanism in a pioneering RCA facsimile concept, was never developed into a commercial product [19]. Generally, the basis of piezoelectric inkjet printers is attributed to three patents in the 1970s [20] whose common denominator is, as in the first pioneering patent of 1950, the use of a piezoelectrical unit to convert an electrical driving voltage into a mechanical deformation of an ink chamber, which generates the pressure wave required for the drop formation from a nozzle. Siemens introduced its squeeze-mode printer in the late 1970s, figure 6.

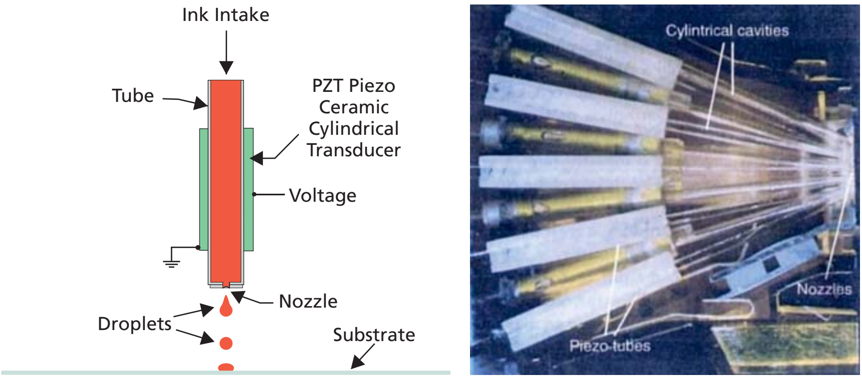

Figure 6

The squeeze-mode piezoelectric drop-on-demand inkjet principle [18], and the first printhead, the PT80 of Siemens [21].

Piezo drop-on-demand printheads can be classified by the mode of deformation, generated by the piezoelectric element. Instead of squeezing a tube, as in the Siemens device, bending of a wall with a piezoelectric layer as part of the channel as shown in figure 9 is another option. Pushing against a wall with a separate piezoelectric element and deforming a wall made of piezoelectric material as shown in figure 7 are the other options used in piezoelectric printheads. So the four types of printheads are the squeeze-, bend-, push- and shear-mode printheads

However, the first commercial success of drop-on-demand printers came in the 1980s with another technology. Instead of the deformation of a piezoelectric element, the creation of a vapor bubble was used to generate the pressure wave for jetting droplets, i.e. thermal inkjet printing. With sudden-steam printing, M. Naiman from the Sperry Rand Company basically invented this drop-on-demand technique in the 1960s. By boiling aqueous ink at specified time instances, a drop of ink could be generated. The strength of this design clearly was not immediately acknowledged, since the company did not

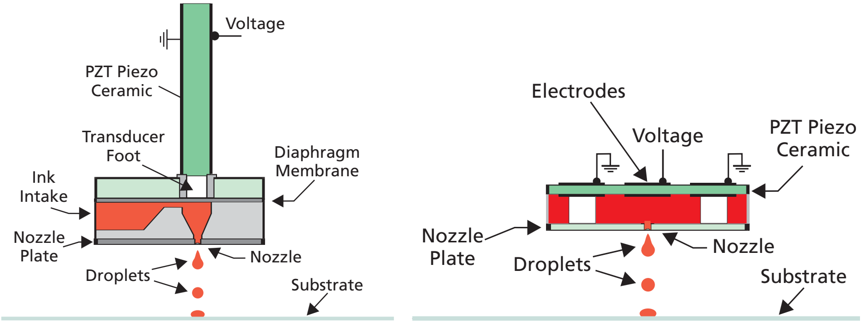

Figure 7

The push-mode and the shear-mode drop-on-demand inkjet principles [18].

implement this idea into a commercial product. The idea was abandoned until the late 1970s when Canon and Hewlett Packard (HP) picked it up.

In 1979, Ichiro Endo and Toshitami Hara of the Canon company re-invented the drop-on-demand printhead, which is actuated by a water vapor bubble, called bubblejet. They were both working on a piezo-based drop-on-demand printhead. By chance, Endo watched a spray of ink from a needle, after touching the needle with a hot soldering iron. The first BubbleJet printer using a side-shooter printhead, figure 8, was launched in 1981. In the same period HP also developed its thermal inkjet technology. John Vaught and Dave Donald, working on a squeeze-mode piezo printhead, both became inspired by the working principle of a coffee percolator. This led to the first successful low-cost ThinkJet printer using a top-shooter printhead in 1984.

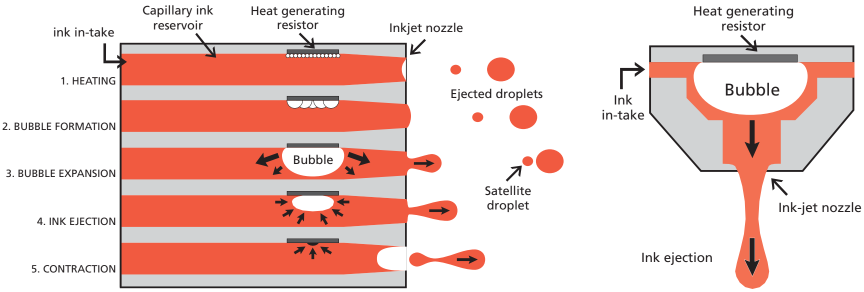

Figure 8

The side-shooter and the top-shooter thermal inkjet principles [18].

The fact that a thermal inkjet printhead could be easily miniaturized, and its low cost of manufacturing, made thermal inkjet the superior drop-on-demand inkjet technology in the 1990s for small printers used in the office and later also at home.

Meanwhile, a few other companies continued the development of piezo drop-on-demand printers, and Epson became the leader of this development after the introduction of its first bend-mode printhead in 1984, figure 9. The initial advantages of thermal over piezoelectric inkjet have been leveled over the years by the further development of the piezoelectric inkjet printhead technology. The major advantage of piezoelectric inkjet is the fact that the ink does not have to be boiled. Emerging industrial applications require all kind of liquids to be jetted, many of which preclude boiling, and this pushes piezoelectric inkjet more in the forefront.

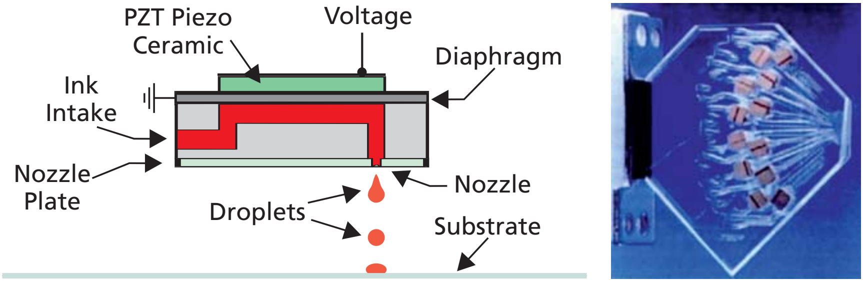

Figure 9

The bend-mode piezoelectric drop-on-demand inkjet principle [18] and the first Epson printhead, the SQ2000 [21].

Inkjet printing and Océ

Also for Océ, piezoelectric drop-on-demand inkjet became the main printing technology. The history of Océ goes back to 1871, when Venlo chemist Lodewijk van der Grinten started his research on the manufacturing of butter-coloring agents. The company took a step closer to the reprographic industries in the 1920s when the Van der Grintens started to manufacture blueprint paper, which was then commonly used for the reproduction of line drawings. Later, diazo, also a colorant chemistry-based technology, became the main printing technology for wide-format technical drawings. In the 1970s, the development of electro-photographic copiers started at Océ and in the 1980s laser printers became the main technology for wide-format and cut-sheet small format printers.

In the 1990s, Océ began its own inkjet technology development, targeting the professional printer market segments. The aim was to combine the strengths of laser printers, i.e. robust prints on plain paper, and the strengths of inkjet printers, i.e. high-quality full-color prints. This resulted in the Colorwave printer, figure 10, using piezo push mode printheads and a phase-change based solid ink. The ink is fed as solid pearls to the printheads, which remain operational during the whole life cycle of the printer. After being melted at a temperature of 130 °C, the ink is jetted onto cold plain paper where the material crystallizes to

Figure 10

The Océ Colorwave printer using phase-change inks and the Arizona printer using UV-curable inks.

generate a high-quality robust full-color print with large-format technical drawing, maps and posters as the main market segments.

Another type of wide-format printer is the flatbed printer which can print on rigid substrates like glass plates for outdoor applications. To ensure good adhesion, UV-curable inks are used which polymerize upon exposure to a UV-light source to establish a strong bond to the substrate. In the wide-format printers, the printheads scan in multiple steps over the substrate to cover the whole area, similar to the small printers used at home or in the office. With wide format, a scanning principle results in reasonably high productivity, but not with small format, e.g. like A4 sized prints. To realize high productivity with small paper format, a single pass principle is used with page-wide printheads, like the Océ Varioprint i300 printer using water-based inks, figure 11. To ensure robustness, latex particles are added to the ink, which form a robust film after the water is evaporated. This printer replaces traditional printing technologies for printing brochures, books etc. On-demand book printing saw the market changed dramatically with no longer a need for large storage space, shipping books all over the world, stock depletion, etc.

Figure 11

The Océ Varioprint i300 printer using water-based latex ink.

The demands for the printheads and the inks are being pushed to their limits:

- several types of inks are used in many different applications
- printheads must stay operational during the whole life cycle of the printer
- high productivity and reliability are required in professional printing market segments

- high numbers of nozzles, up to 70,000, are used in a page-wide full-color printer
- there is an ongoing trend toward smaller droplets jetted at higher frequencies etc.

To meet the demands for future printing systems and to enable the development of new technologies, a fundamental understanding of the underlying processes is very important [22].

Scientific inkjet research program

Measurements give us only limited access to the interior of the printhead. We need more information on the phenomena preceding the drop formation for a better understanding of the operating principles of the piezo printhead. Therefore, the modeling of the physical phenomena with available commercial codes and the development of dedicated special models are an essential part in the development of a new inkjet technology. Added to our measurements, this revealed the phenomena involved in our main goal: reliably firing droplets of ink at a very high rate with any desired shape, velocity and dimension.

Collaboration with Dutch universities of technology already started from the beginning of the inkjet technology development at Océ Venlo. The functional modeling not only concerns the numerical modeling but also the theory, which explains the results, and the experiments that validate the results. The physics behind the chain of processes in the inkjet printhead operation comprise the two-way coupling from the electrical to the mechanical domain through the piezo electric actuator, the coupling to the acoustic domain inside the ink channels to transfer the deformation into pressure waves, and the coupling to the fluid dynamic domain in the nozzle to transform acoustic energy into the kinetic and surface energy of the drop formation process [23].

Structural modeling with the commercial finite element code Ansys includes piezo-electricity. The simulation of the local deformations inside a printhead provides the input for the acoustic modeling. These simulations enable cross-talk effects, i.e. the unwanted influence of actuating neighboring ink channels, to be modeled and understood as a first step towards minimizing their effect on the printhead performance [24]. Acoustic modeling involves fluid-structure interaction. A wave propagation model, including elasto-acoustic interaction of the pressure waves inside the ink channels with the printhead structure, is the basis for an acoustic detection method to monitor the operational status of a printhead [25]. This has enabled smart driving techniques [26, 27].

Furthermore, wetting of the nozzle plate [28, 29] and air bubbles [30, 31] can also have a negative influence on the printhead performance. These effects can be detected via their influence on the acoustic properties [32, 33, 34], even the impact of small dirt particles can be detected as shown in figure 12.

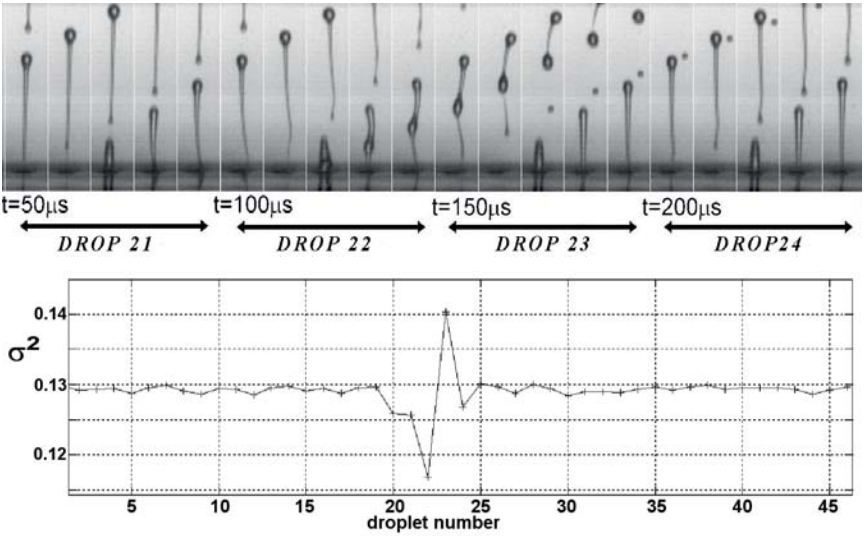

Figure 12

The drop formation recorded at 100 kfps shows a disturbance. Until drop 20 the drop formation is regular. Drop 21 displays a slight deviation in the tail. Drop 22 shows a large disturbance being jetted out. From drop 23 the droplet formation is regular again. The variation in the acoustic signal is shown below the recording.

CFD modeling with the commercial Flow3D code include wall-flexibility, free surface flow, and two-phase flow with surface tension. Analytical formulas and theories, like the slender jet equations, provide extra insight into drop formation mechanisms [35]. This is the basis for suppressing unwanted satellite drop formation and controlling the properties of the jetted drops [36].

State-of-the-art simulation methods [37, 38], measurement techniques for air bubbles inside MEMS-based printheads [39] and the drop formation process [40], provide the basis for the ongoing research on optimizing this process, which is the key process in new generation inkjet printers. The recording of the drop formation with a laser induced fluorescent technique, developed together with the group of Detlef Lohse at the University of Twente, was selected by Nature as one of the pictures of the year 2014, figure 13.

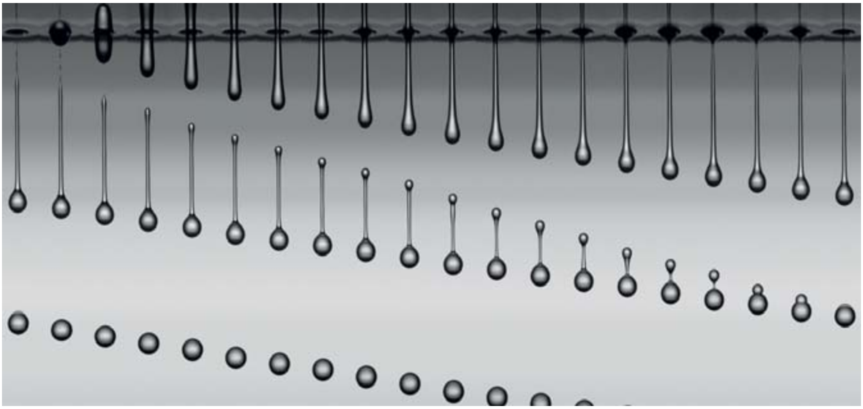

Figure 13

Time series of droplets recorded with single-flash photography. From left to right, multiple images of single droplets with a delay of 3 µs between these individual droplets. The width of the droplet is 23 µm, the tail is about 4 µm, and the secondary tail has a width below 1 µm. The figure illustrates the imaging quality of the set-up, and the absence of motion blur due to the use of the 8 ns iLIF.

The capability of monitoring and controlling the printhead status and the drop formation process have led to the current status of the piezo inkjet technology as a key enabling technology in many new emerging industrial and medical applications. The role of inkjet printing in the roadmap for digital fabrication according to the FP7 Diginova project is shown in figure 14.

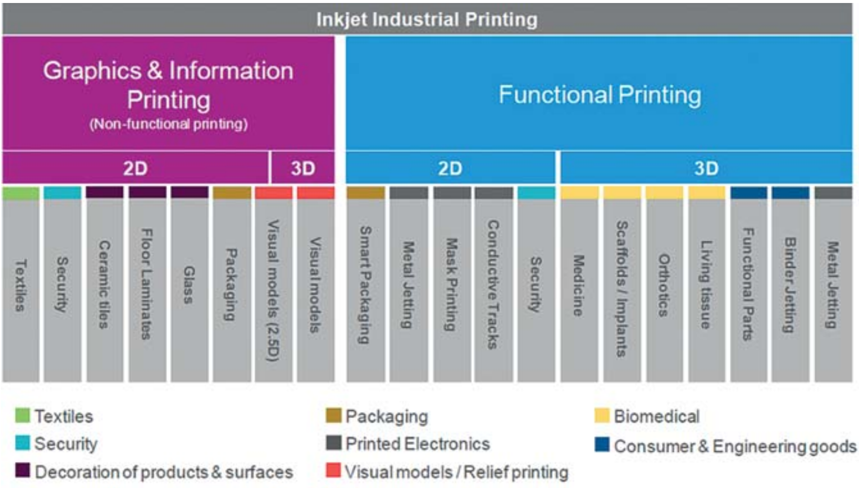

Figure 14

Inkjet based applications in the roadmap for digital fabrication.

Fluid dynamics of inkjet printing

20 years of history in collaboration with academic research groups have resulted in a consortium capable of handling the challenges posed by the further development of the inkjet printing technology, not only for graphical applications, but also for many new emerging applications in industry and medical science. Recently, a new joint research program was started as the FOM industrial partnership program “Fluid Dynamic Challenges in Inkjet Printing” between FOM, Océ Technologies, the University of Twente, and Eindhoven University of Technology. This program is the basis for the ongoing scientific research program on the inkjet printing process. Océ research on the inkjet printing process also includes many individual projects in the HTSM printing roadmap, M2i, STW and European programs.

My chair “fluid dynamics of inkjet printing” is the next step towards developing a complete knowledge basis for all fluid dynamics processes in inkjet printing, i.e. the chain of processes from the pressure wave arriving at the nozzle, via the drop formation, flight, impact, spreading and absorption into porous substrates, until evaporation or solidification on all kind of substrates. The ultimate goal of inkjet printing processes is to accurately control the deposition of minuscule amounts of liquid. The formation of droplets as key process is well controlled and the underlying physics understood as mentioned before.

Inks in printing processes are generally enhanced with surfactants to control droplet formation, spreading and absorption. The transport of surfactants within the liquid and at the air/liquid and the solid/liquid interfaces, in combination with the effect of surfactants on interface energies, leads to a complicated interaction between the transport equations and the evolution of the liquid geometry. Properties like surface tension become highly time-dependent. During jetting, the surfactants are mixed through the bulk of the ink, and this results in a high surface tension of the ink as measured via the oscillation of jetted drops, figure 15. The frequency of the oscillation is a measure of the surface tension, and the damping of the oscillation is a measure of the viscosity at a time scale of typically 100 microseconds. Most current measurement techniques for the properties of liquids are only capable of determining properties at time scales longer than at least 10 milliseconds.

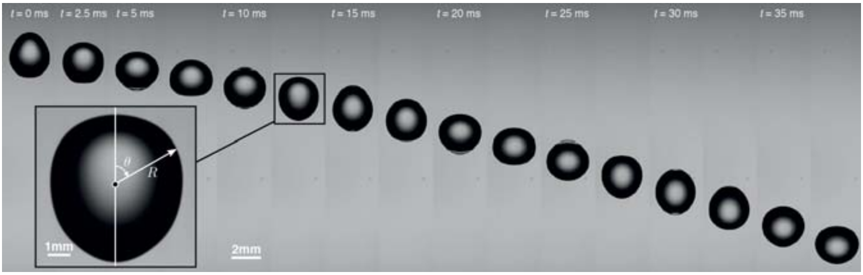

Figure 15

Representative high-speed recording of the shape oscillation of a purified water drop shortly after detachment from the tip of a needle. In the enlargement, one can see the center of mass (black dot), the distance from the center of mass to the boundary R, and the polar angle θ [41].

The next phase after the jetting of drops is the impact of drops on a substrate. The time scale of the impact phase is typically 10 microseconds for a drop with a radius of 10 micrometers. The liquid properties as determined before therefore also apply for the drop impact phase. The impacting drop will spread to a maximum extension when the kinetic energy of the drop has been dissipated. After the impact phase, the drop recoils back to an equilibrium shape. The shape of the sessile drop is then determined by the surface energies of the liquid and the solid. Because of the high surface energy of an ink drop that has just been jetted, the contact angle will be rather high. This results in a low spreading factor, which is the ratio between the contact radius of the sessile drop to the radius of the free spherical drop. This is shown in figure 16.

After the impact, the surface tension of the ink will decrease because the surfactant molecules migrate back to the surface again. This occurs at a time scale of 10 milliseconds to 10 seconds, depending on the type of liquid and surfactant. The contact angle will decrease and the spreading factor will increase. During the lowering of the contact angle, the volume of the sessile drop can decrease due to evaporation or absorption. All these processes are shown in figure 16 and cover more than seven decades on the time scale.

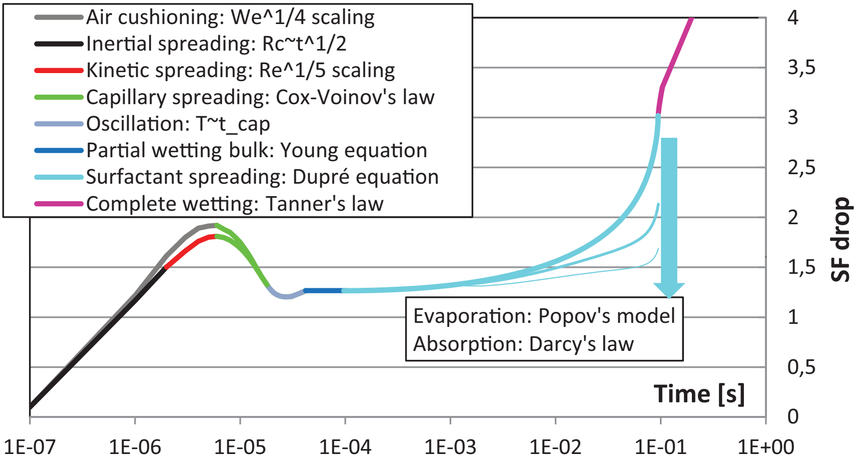

Figure 16

The spreading factor, i.e. the ratio between contact radius and radius of the free drop, of a single impacting drop of ink on a substrate. The end of the impact phase is visible as a maximum spreading at typically 5-10 μs. During impact there may be direct contact between the drop and substrate or air may still be entrapped between the drop and the substrate. This results in different force balances during impact. After impact, different mechanisms result in a different evolution of the spreading factor.

Print quality and durability are essentially determined by absorption of ink into the porous substrate and solidification. Depending on the type of ink, several solidification mechanisms need to be explored: evaporation with water-based inks, film formation with latex inks, polymerization with UV-curable inks and crystallization with phase change inks. These mechanisms are still poorly understood and need to be explored further.

Because of the very small time scales and lateral resolutions involved during the interactions of ink drops with substrates, in many cases it is not possible to obtain accurate experimental data. Therefore, modeling and simulation of the relevant physical phenomena and material properties with available commercial codes, and the development of dedicated models, techniques and algorithms are an essential part of my research plan. I will show some examples of recent achievements in the last part of my lecture now.

The first example is about the simulation of the evaporation of a sessile drop. Evaporation plays an important role, especially with water-based ink. The most volatile component of an ink will evaporate, and water is such a component.

This will change the composition of a sessile drop continuously. It is difficult to measure the local composition of the sessile droplet at a height of only a few micrometers. Numerical simulations are the only way to generate detailed information as shown in figure 17. The numerical model in this example is further developed by Christian Diddens in a HTSM project with Hans Kuerten and uses many submodels:

- the lubrication approximation for the fluid dynamic part
- the diffusion equation for the concentration of the different components
- a selective evaporation model including the interactions between the liquid components,
- component-dependent properties like density viscosity, surface energy and contact angle, inter-diffusion coefficients and activity coefficients [42].

The model has been validated with model experiments using high-speed camera recordings and confocal laser microscopy on evaporating multi-component liquid drops by the group of Detlef Lohse at the University of Twente [43].

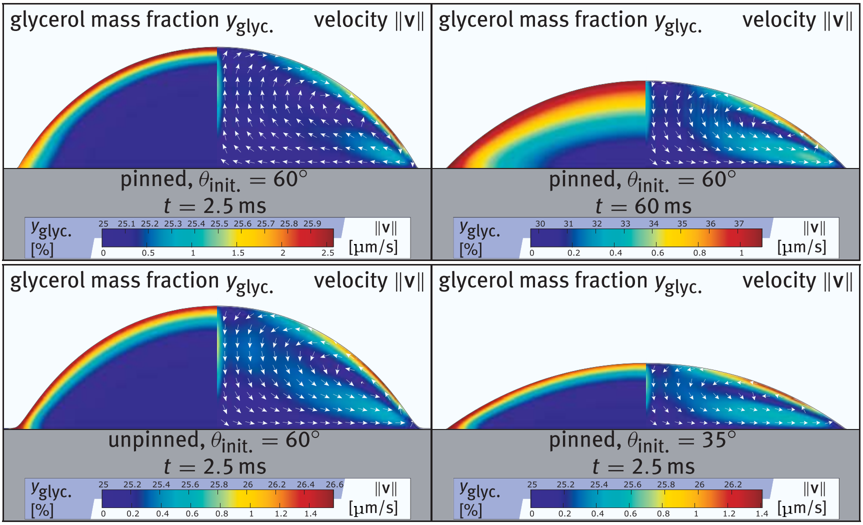

Figure 17

The glycerol mass fraction in an evaporating water-glycerol drop shows a glycerol-rich surface that further decreases the rate of evaporation of the water as simulated with a numerical model based on the lubrication theory [41].

The second example is about the interaction of a sessile drop with a substrate. Inkjet drops become smaller, hence the ratio between surface area and volume increases. Therefore, interactions will have more effect on the drop dynamics. Phase field modeling with the Cahn-Hilliard equation takes the free energy of interfaces as the starting point for the simulation of drop dynamics when coupled to the Navier-Stokes equations for the fluid dynamics. This is being explored in a NanoNextNL project with Harald van Brummelen by Görkem Simsek and Mahnaz Shokrpour. An example is shown in figure 18. At the contact line of a sessile drop, the substrate is deformed by a normal force exerted by the surface tension of the liquid drop. This is also further explored in an ERC project of Jacco Snoeijer at the University of Twente. As a consequence, the dynamics of drop spreading is determined not only by the surface energies and the liquid properties, but also by the elasticity of the substrate [44].

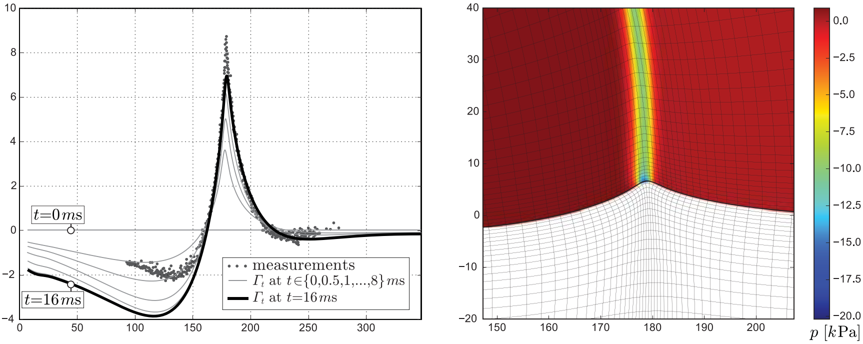

Figure 18

Left: comparison of the computed fluid-solid-interface configuration after 0, 0.5, 1, 2, 4, 8 (grey) and 16 ms (black), and rendering of experimental results (left). Right: magnification of the contact-line region at t = 16 ms with deformed fluid and solid meshes and computed pressure distribution [45].

The next example concerns the merging of drops. To create patterns such as lines and areas of different shapes by means of inkjet printing, the individual drops have to connect to each other. The coalescence of drops is therefore studied in detail. In figure 19 an example is shown of a measurement of the bridge height between two merging drops [46] together with the results of a simulation with a lattice-Boltzmann model by Dennis Hessling in a M2i project with Jens Harting. The growth of the bridge height, i.e. the merging of two drops, can be described with scaling laws.

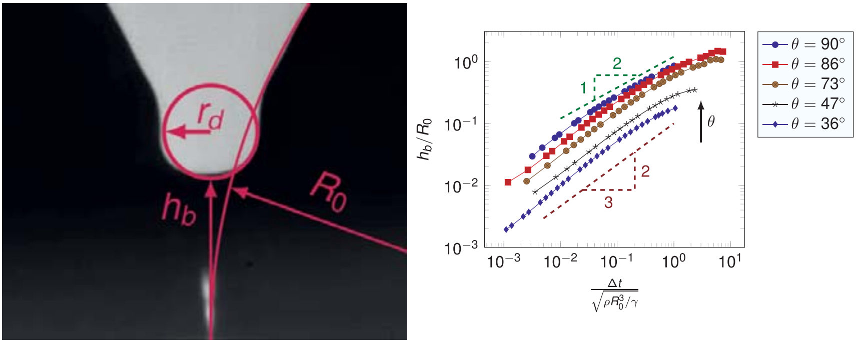

Figure 19

Measurement [46] and lattice Boltzmann simulations [47] of the height of the bridge between two merging drops show a scaling proportional to $t^{1/2}$ with a contact angle of 90°, and to $t^{2/3}$ with a smaller contact angle.

Surfactants can have a dramatic effect on the merging of drops, even a state of non-coalescence can occur when the surface tension difference between two drops is large enough [48]. Variations in surface tension result in Marangoni flow from the low surface energy area to the high surface energy area in order to reduce the total surface energy. This is a very strong flow mechanism in thin liquid films. Detailed local distributions of surface tension cannot be measured and numerical models are the only way to explore these complicated phenomena.

The next example concerns absorption. Many substrates including paper have a porous structure, so absorption plays an important role as well. The detailed geometry of a porous structure can be measured with CT or FIB-SEM for resolutions of less than one micrometer. These data can be imported into numerical models to simulate the details of the flow of ink through the porous structure, which is not accessible with experimental techniques. An example is shown in figure 20. Hamed Aslannejad from the group of Majid Hassanizadeh at Utrecht University has measured the structure of a glossy offset coated paper, which has a coating with an average pore diameter of only 100 nm. The data are imported into a commercial CFD code to simulate the flow characteristics. With measurements we can only get global data on the total flow rate; simulations show the details and help to explain the observed phenomena, which can become very complicated. Remaining issues to solve are the role of surfactants, the effect of topographic or chemical inhomogeneities, rarified gas effect in very small pores, etc.

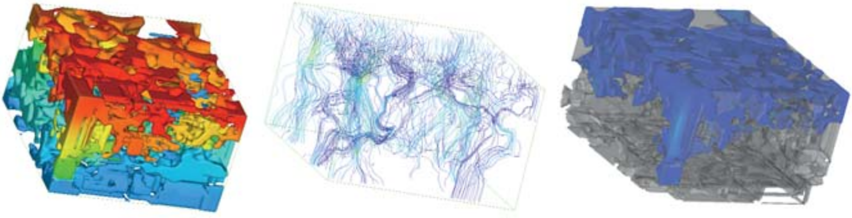

Figure 20

The pressure distribution and streamlines of a saturated flow through a glossy coating and the shape of a penetrating liquid front as simulated with Flow3D. The sample size is 5x5x3 μm^3.

In many cases, specialized multi-scale models and techniques are required to cover the large range in time and length scales. In figure 16 seven decades in time are shown for single drop dynamics and two decades more come into the picture when taking into account multiple drops. With rarified gas effects and with contact line dynamics, the limitations of continuum models are reached and molecular aspects must be accounted for. So the relevant length scales range from nanometers, the molecular scale, to meters, the size of a complete print.

As a final example I will show how to combine different length scales. Molecular dynamic simulations as extension of the continuum modeling can take into account molecular effects, and in a modified form also particle effects. Complete particles are then simulated with interaction potentials between each other and with the surrounding liquid, which can be simulated with lattice

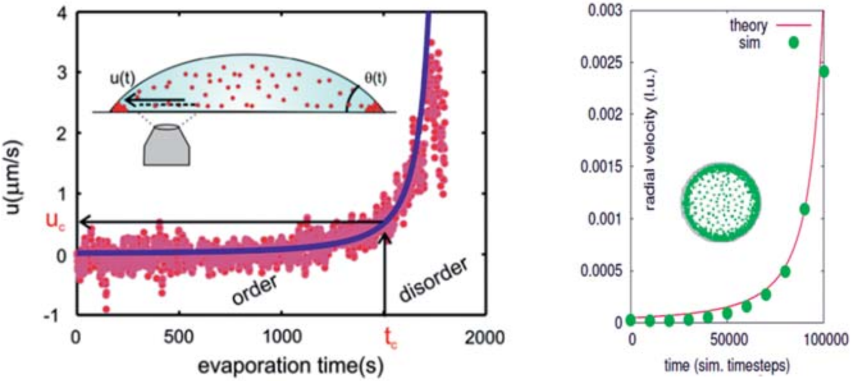

Figure 21

Lattice-Boltzmann-Molecular-Dynamics simulation of the deposition of particles in an evaporating drop show a coffee stain effect that corresponds with experimental observations.

Boltzmann as shown in figure 21. Qinguang Xie from the group of Jens Harting has simulated, for example, the coffee stain effect, which corresponds perfectly with measurements by the group of Detlef Lohse at the University of Twente and theory [49].

The examples that I have shown provide an indication of some of the many challenges that we are facing in inkjet printing, and the progress that has been made in recent years. Although impressive progress has been made for some aspects of the droplet dynamics process, for other aspects we have only just begun to scratch the surface. I look forward to exploring the exciting mysteries of small droplets, and together with my colleagues at the Mechanical Engineering and Applied Physics departments, but also with researchers in Venlo, Enschede and Utrecht I intend to unravel them.

With my chair I will intensify the already strong relationship between Océ Technologies, Eindhoven University of Technology and the University of Twente. This will provide an eco-system for master students, PhD students and Postdocs to get familiar with the key technology behind a major development in society, i.e. the transformation from the world of printing to printing the world.

Thanks

Finally, ladies and gentlemen, I would like to thank a number of people.

Many thanks go to all my Océ colleagues, especially Freek van Beek, Marc van den Berg, Arjan van der Bos, Rob Dokter, Pieter van Groos, Jan Willem van Harskamp, Roel Knops, Roy Krout, Hans Reinten, Maosheng Ren, Louis Saes, Mark Schuwer, Nicolae Tomozeiu and Wim de Zeeuw for their scientific contributions in the research together with our academic partners and the development of the modeling tools, additional to our product development driven activities. They form the basis from which the further expansion of my research activities could be established.

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Subsequently the group of Rinie van Dongen from the Eindhoven University of Technology, later the groups of Hans Kuerten, Anton Darhuber, Federico Toschi, Jens Harting and Henk Huinink from the Eindhoven University of Technology, and the group of Bene Poelsema and Stefan Kooij from the University of Twente became part of my collaboration network along with the groups of Jerry Westerweel, Daniel Rixen and Fred van Keulen at the University of Technology in Delft.

Special thanks also to Harald van Brummelen. A very close collaboration started about 10 years ago in the μNed program. Harald was in Delft at that time but came to Eindhoven, where I would join him later as guest researcher. Together with the rest of his group, this became another basis for me in my quest to resolve the physics of inkjet printing.

In the end, I want to thank the most important people. My wife Jacqueline and my daughters Veerle and Jenske, for always keeping me with my feet firmly on the ground and, most of all, for sharing their life with me.

This concludes my lecture. I thank you for your attention.

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Curriculum Vitae

Herman Wijshoff (1961) studied Applied Physics at the Eindhoven University of Technology where he received his MSc degree in 1986. In that same year, he joined the Research and Development department of Océ Technologies B.V. in Venlo. The main focus was on materials research for printing technologies. Since 1996 he has been involved in the inkjet technology development. This also marked the start of his joint research with academic research groups on the underlying physical principles.

The main partners in the joint research program are Eindhoven University of Technology, the University of Twente, FOM and STW. Herman Wijshoff received his PhD degree in 2008 at the University of Twente for the thesis 'Structure- and fluid-dynamics in piezo inkjet printheads'. He focused initially on the modeling of the functional behavior of inkjet printheads before his focus shifted to the fundamental principles behind the interactions between droplets and substrates. These topics got him more and more involved in the research at Eindhoven University of Technology, initially as guest researcher and since 2015 with an own research chair.

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