Modeling of charged droplet dynamics in an Electric Field using COMSOL Multiphysics®

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Introduction

In the field of industrial coding marking areas, Continuous Ink Jet technology (CIJ) is based on the emission of a high-speed stream of ink drops (velocity of 20 m/s at typically 100 kHz) propelled directed onto a moving medium to be printed [1,2,3,4].

The printing quality depends on drops position on the media determined first by the electrical drop charge subjected to electrostatic deflection field, and secondly by mutual drops interaction in flight (electrostatic repulsion and aerodynamic wake). For instance, in a 24-points line so called raster, there are 2 power 24 combinations which cannot be predetermined experimentally one by one. COMSOL Multiphysics enables to model these coupled effects in order to predict the location of a drops line on the medium, and this way, to create an aid to drive CIJ printer heads design.

This paper describes the coupled model which allows to compute droplets trajectory until the prediction of droplet positions on the printed media. Numerical results are compared to experimental data to validate the predictions quality and subsequently using the model as a design support tool.

Printer set up

Markem-Imaje provides, among others, continuous inkjet printers for customers in the packaging industry. The working principle is described on the figure 1. A continuous ink jet is provided by an ink circuit. In the print head, a PZT stimulation is applied to force droplets formation at charge electrodes level to get charged droplets. Then, these charged droplets go thought an electrostatic field created by deflection electrodes and are more or less deflected according to their electrical charge. Thus, a droplet line called i.e. raster can be printed. The printing quality is determined by the drop position accuracy on the media. Besides, not-charged droplets fall in a gutter to be recycled in the ink circuit.

In this study, the inkjet droplet raster is generated thanks to a commercial continuous inkjet printer (Markem-Imaje 9450 brand name). The ink system provides pressurized ink based on glycerin-water mixture (the black dye provides also electrical conductivity). The printhead is customized to be fed by electrical signals issued from a computer (Figure 1). The computer also triggers a strobe light (LED) which allows to observe the magnified (Bausch & Lomb zoom) droplets on a video screen (HP monitor). The phase shift applied between the triggering signal and the LED can be tuned. This allows the observe accurately droplet in flight at different location thanks to a set of X/Y translation table (Newport X Y linear stage).

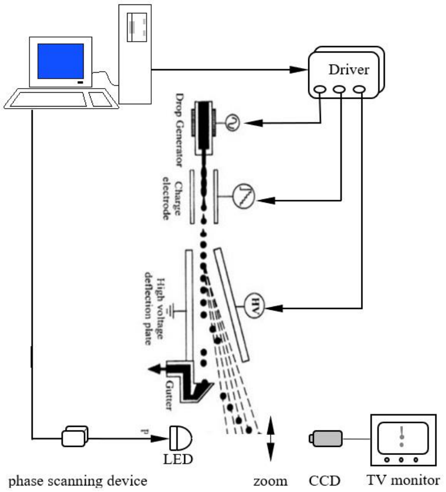

Figure 1: Schematic representation of the experimental set-up

Numerical model

Printer geometry is purposely simplified to feed COMSOL Multiphysics model by slicing the geometry consistently with 2D-geometry as described in figure 2.

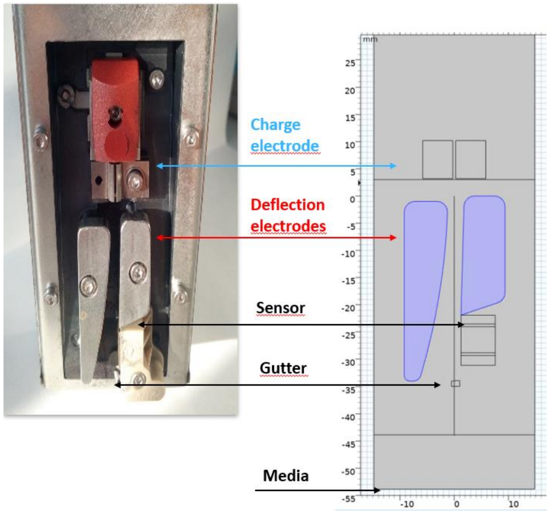

Figure 2: (left) Picture of the real device. (Right) 2D geometry taken into consideration in COMSOL Multiphysics.

To compute the electric field inside the print head, the following Maxwell equation is solved:

$$\nabla.[-\nabla V] = 0 \qquad \textit{Eq. 1}$$

where V reads the electric potential. Moreover, the electric field $\boldsymbol{E}$ is equal to $-\nabla V$.

The boundary conditions are summarized within the following figure:

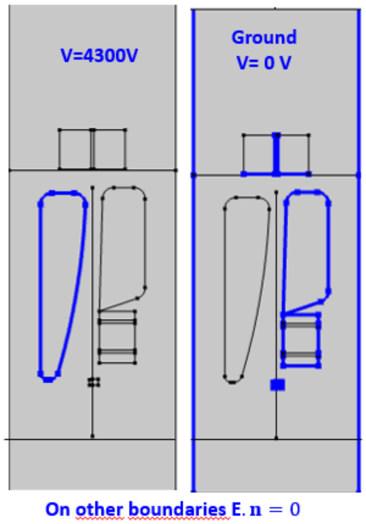

Figure 3: Boundary conditions for the electric potential.

To compute trajectories of charged droplets in field through the electric field, the fundamental principle of dynamics is applied to each particle thanks to the Particle Tracing COMSOL module:

$$\mathrm{M} * \mathbf{a} = \boldsymbol{F_d} + \boldsymbol{F_g} + \boldsymbol{F_l} + \boldsymbol{F_c} \qquad \text{Eq. 2}$$

where M is the mass of the particle, a its acceleration, F_d the drag force, F_g the force of gravity, F_l the Lorentz force and F_c the Coulomb force.

In our configuration, the force of gravity can be neglected when compared to others. The drag force is not considered in this study, but it will be studied specifically in upcoming papers. The two remaining forces reads:

$$\boldsymbol{F_l} = q\boldsymbol{E}\,, \qquad \boldsymbol{F_c} = \frac{e^2}{4\pi\varepsilon_0}\sum_{i=1}^{N-1} z * z_j * \frac{r - r_i}{|r - r_i|^3} \qquad \text{Eq. 3}$$

where q is the electrical charge of the droplet, e the elementary electrical charge of an electron, z the number of charges of the considered particle, z_i the number of charges of other particles, and r and r_i are respectively positions of the bunch of particles including the considered one.

Electrical charge captured by a droplet is estimated by the following equation, assuming an electrostatic full coupling within a cylindrical capacitor geometry like [5].

$$Q = \frac{2\pi v_{jet}\epsilon_0}{f_0 * ln\left(\frac{D_{electrode}}{D_{droplet}}\right)} V \qquad \text{Eq. 4}$$

where V is the charging electrode potential, $D_{electrode}$ the distance between the two charge electrodes, $D_{droplet}$ the droplet diameter, v_{jet} the jet velocity and f_0 the droplets production frequency.

It could be worth noting that, if N particle are taken into consideration, the charged particle/particle interaction leads to approximatively $(N-1)^2$ forces, leading to a rapid complexification of the computation.

Linear triangular elements are used for meshing. A refined mesh, shown in Figure *1*, is used in areas where the electric field gradient is high (mainly to manage electrostatic tip effects). A sensitivity study dealing with mesh properties has been performed to ensure no-dependency of the solution on the mesh refinement.

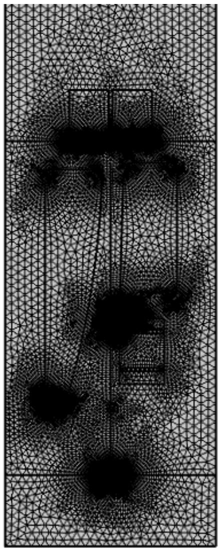

Figure 1: Triangular mesh

Concerning the solver properties, two steps are used to compute the problem (weak coupling):

- First, the electric field is computed at the stationary state with the PARDISO solver
- Then, the time dependent evolution of particles is computed with the temporal solver Gen-a, based on the results for the electric field of the first step, with the iterative solver GMRES.

The numerical parameters used in simulations are the default ones.

Simulation Results

Electric Results

The norm of the electric field and the electric potential are plotted in Figure 4, respectively. Some peak effects can be observed in the electric field distribution but far away from the droplets flight trajectories. It appears that due to the geometry of the left side deflection electrode, the electrostatic field is not homogenous between the two deflection electrodes.

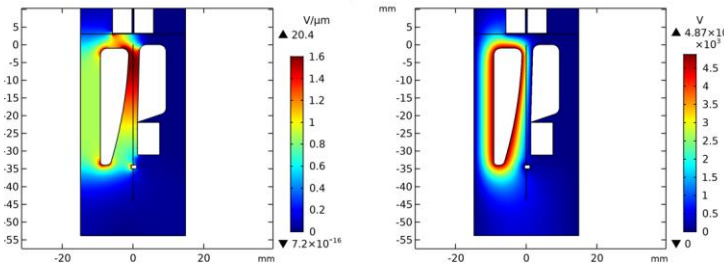

Figure 4: (left) Norm of the Electric Field. (Right) Electric potential.

Droplet Trajectory

First, the model has been validated according some analytical results obtained by integrating twice the *eq. 2* for one single droplet (momentum conservation law). The following figure describes the comparison of the x-component of the position of the particle from the numerical computation and the analytical formula. The curves are so close that they are overlapping.

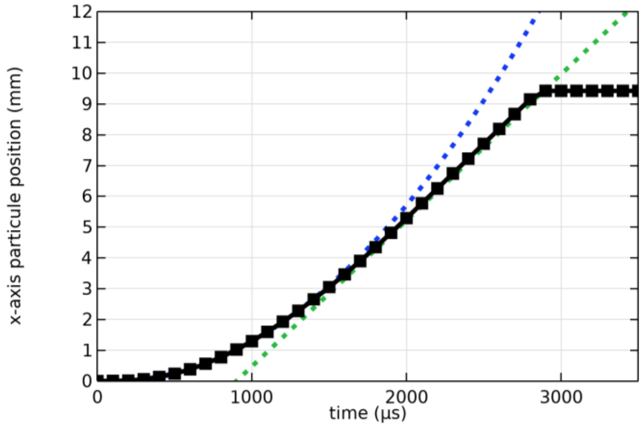

Figure 2: Comparison between numerical result and analytical ones. The blue dotted line fittes the droplet position when the droplet is inside the electrostatic field $x(t) = \frac{1}{2}\frac{qE}{m}t^2$. The green dotted line $x(t) = \frac{qEL_{elec}}{v_{jet}m}(\frac{1}{2}\frac{L_{elec}}{v_{jet}} + t)$ the droplet position when the droplet is out of the electrostatic field

The figure 5 shows the position of the less and the more deviated droplet of a raster.

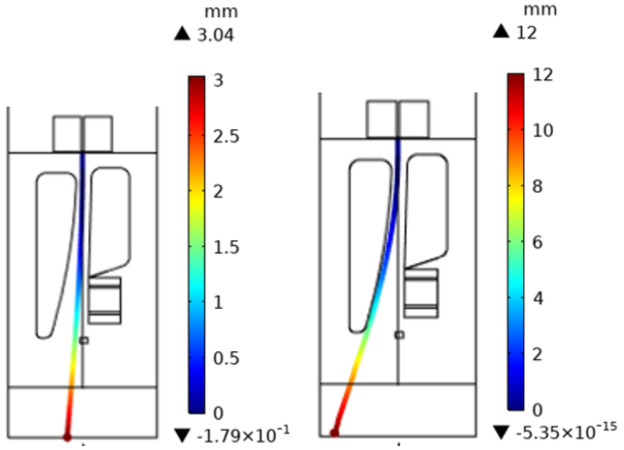

Figure 5: Influence of the charge of the droplet on the trajectory. (left) Charge=0.48pC. (Right) Charge=1.93pC

Comparison Num. vs Exp. Results

In the configuration shown in Figure, numerical results are compared to the experimental ones. Two indicators are studied: the deflection of the particle at media level, and the raster width.

Deflection (mm)	0,48 pC	1,93 pC	Frame width
Numerical Model	3,07	12,03	8,95
Experimental Result	2,59	10,76	8,18

Figure 6: Comparison between exp. and num. results

These results exhibit a consistent agreement between the numerical approach and the experimental data.

We then take in consideration a raster of 48-droplets issued from a stream of droplets. Droplets are individually charged at different level one by one. This consideration involves the coupling between COMSOL Multiphysics® and Matlab® thanks to the Livelink for Matlab® module. With a *.m* script, droplets are injected with the correct amount of electrical charge and at the right time inside the domain. By this way, the model allows to simulate the flight of a droplet raster as follows.

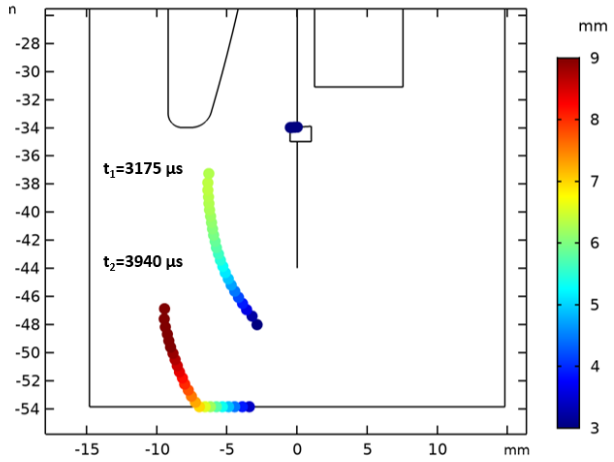

Figure 7: In-flight raster for the same frame at two different times.

At this point, the numerical model allows to predict the position of each droplet of the raster at the media level. A comparison between the numerical results and the experimental measurement are provided in Figure8.

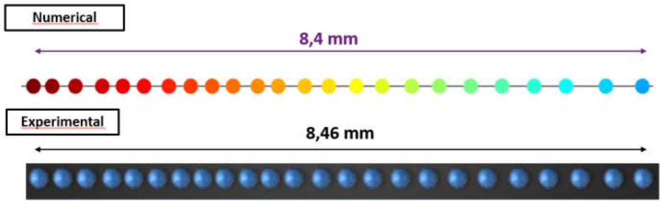

Figure 8: Comparison between exp. and num. results.

The numerical predictions give a correct order of magnitude of the raster deflection amplitude and the local gap between droplets follows the same trend (the more the droplets are deflected, the closer they are on the media). However, the droplets position between exp. and num. data are not exactly the same. We assumed this gap is due to the wake effect not considered so far.

Conclusions

A 2D model which simulates droplets trajectories in a print head has been built. This model computes the electrostatic field and then charged droplets position during their flight within the print head. Moreover, it considers coupled interactions between charged particles. Thus, this tool allows to predict the position at the first order of each raster's i.e. location of droplet in a row on the media. By comparing with the experimental data, it is worth adding air wake effects in order to predict more accurately the exact deviation of the droplets. The idea is to compute the air velocity distribution around droplets at each time step by solving Navier-Stokes equation, and then, to estimate the drag force undergone by droplets which is proportional to the droplet velocity.

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