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Inertial microfluidic based particle sorting device

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Abstract

More and more functional inks are developed to enlarge the applications of inkjet printing. Yet, the stability of the inks is often challenging. For example, particles might agglomerate and clog the printhead, eventually compromising the whole printing process. Having a reliable filtering system is therefore key for complex inks. Here, we present a novel passive filtering system based on the inertial microfluidic concept that can potentially be used to filter inkjet inks in a continuous manner. The system has been first optimized thanks to numerical simulations and then characterized experimentally.

Introduction

Inertial focusing is a well-known phenomenon in the world of microfluidics, in particular thanks to the significant contributions of Dino Di Carlo at UCLA, who demonstrated that when inertial effects are considered, particles occupy well defined equilibrium positions in microchannels. The first observation of this phenomena goes back to seminal work of Segre and Silberberg [1] who noticed that randomly distributed millimeter-sized particles in a tube migrate laterally to focus on an annulus with radius 0.6 times the radius of a one-centimeter-diameter pipe [2].

In fact, when inertial effects are considered, the particles experience two inertial lift forces. The wall-induced lift force pushes the particle away from the wall, while the shear gradient induced lift force directs the particle away from the channel center (in the direction of highest shear), as shown in Figure 1. As a result, equilibrium positions exist away from the channel center.

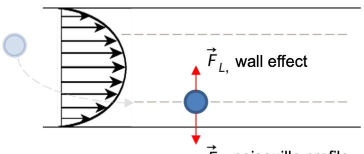

Figure 1. *Illustration of inertial lift forces induced by the wall and by the shear gradient.*

Depending on the geometry of the channel cross-section (round, square, rectangular, triangular, etc.) several equilibrium positions exist (see for instance Figure 2 for the case of a square duct), which can be either stable (along the longest side of the channel) or unstable (along the shortest side of the channel), in the case of a rectangular channel.

The equilibrium positions shift towards the walls for increasing Reynolds numbers Re, while for larger particles, the equilibrium position shifts toward the channel center [2].

When a channel is curved, a secondary flow appears. This so-called *Dean flow* is also induced by inertial effects. Fluid parcels near the center of the channel flow faster and have a larger inertia directed outward compared to the fluid parcels near the walls. Due to mass conservation, the fluid near the top and bottom walls moves inwards [2], resulting in *Dean vortices* (see Figure 3). The magnitude of the secondary flow depends on the

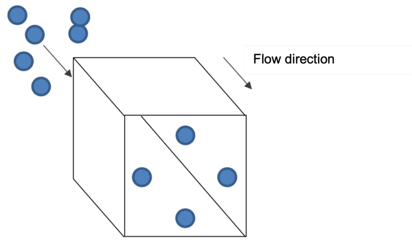

Figure 2. *Illustration of possible equilibrium positions for a square channel with initially randomly distributed particles.*

Dean number, $De = Re\sqrt{D_H/D}$, where D_H the hydraulic diameter of the channel and $D = 2R$ the double of the curvature radius R of the channel.

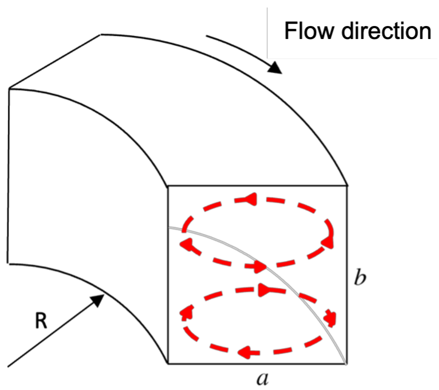

Figure 3. *Illustration of Dean vortices in a channel of curvature radius R.*

Particles in the flow experience some drag induced by the Dean vortices and as a result, unique stable equilibrium positions can be identified in the channel. In fact, the drag force follows the underlaying secondary velocity field, while the shear induced lift force (which dominates the wall lift force) pushes the particle away from the centerline. Hence, only particles which are close to the inner channel wall (with respect to the channel curvature) experience an equilibrium between drag and inertial lift forces (see Figure 4). The equilibrium position does not only depend on the Reynolds number and particle diameter, but also on the Dean number.

In spite of the numerous researches done on this subject, industrial applications have been mainly focused on biomedical application as for instance the sorting of cells (e.g. CTCs), where the particle concentration is low. Strikingly, the same phenomena can also be used to sort micron-sized particles of inkjet inks. Yet, two main challenges have to be solved. First, the solid content of inkjet ink can reach much higher concentrations than the ones typically used in inertial focusing applications, where the particles are sufficiently spaced to avoid hydrodynamic particle-particle interactions. Second, the inkjet inks rheology is often

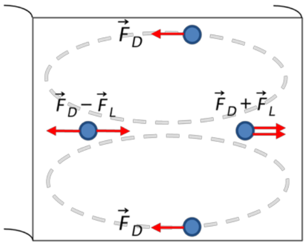

Figure 4. Representation of drag (F_D) and lift (F_L) forces on the particles at different locations. It can clearly be seen that a single equilibrium position close to the channel inner wall exists.

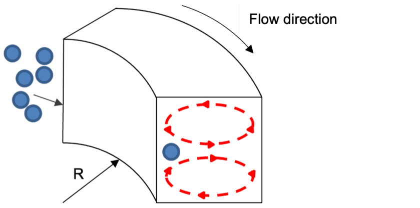

Figure 5. Equilibrium position of a particle in a curved channel.

non-Newtonian. Unfortunately, only few studies have focused on these two challenges, which are key for inkjet applications. It has been observed that particle interactions play a role when the distance between two particles is less than 10x their diameter, and as a result, multiple streams of particles are observed, since some particles are pushed away from the equilibrium position [2]. For non-Newtonian fluids, it has been shown that particles migrate in the direction of decreasing absolute shear rate [2].

The aim of this study is to develop a demonstrator showing the possibility of filtering micron-sized particles of inkjet inks, leveraging on inertial microfluidics phenomenon.

Materials and methods

This work combines numerical simulations and experimental tests. A first particle sorting device has been designed based on existing theoretical models of inertial microfluidics. Numerical simulations in COMSOL Multiphysics have been then performed to optimize the device geometry and flow parameters. The flow field has been first computed and the particle trajectory has been then obtained thanks to the Particle Tracing Module.

The final design of the particle sorting device developed is shown in Figures 6 and 7. The entire experimental setup consisting in the microfluidic chip (6), the ink supply system with reservoirs (8,9), the pressure regulator (11) with positive and negative air pressures (2,3), the particle injection device (10), the high speed camera (4) with a LED (7) and its power supply unit (5) and the computer for the control (1) is shown in Figure 8.

For this first experimental setup, a scale-up is done and a similar system at the millimetric scale has been developed, while keeping all dimensionless numbers identical as at the micrometric scale. A mix between water and glycerin has been used as a fluid. The ratio between the two has been adapted to have the desired Reynolds number. Two types of particles have been used (see Figure 9). Small PMMA particles having a diameter from 1 to 75 microns have been combined with large PE particles with a diameter between 125 and 150 microns. The former mimic the small particles that inkjet inks contain, while the latter correspond to their agglomerations that have to be filtered out. Particles are dispersed in the fluid and then injected in the circulating ink system with a syringe (see Figure 10).

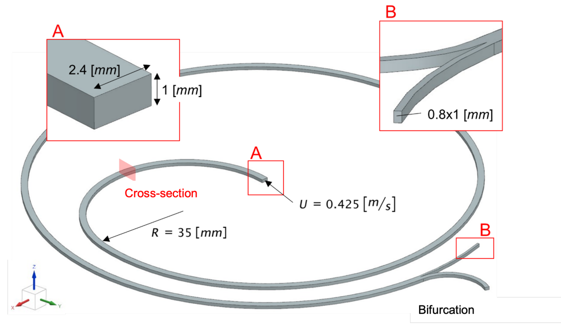

Figure 6. Design of the particle sorting device realized.

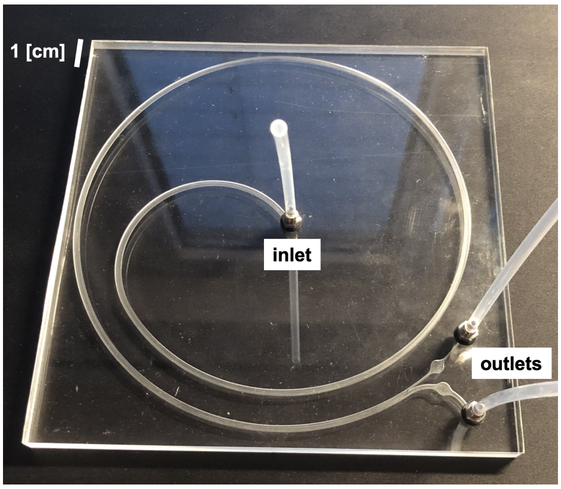

Figure 7. Image of the particle sorting device realized.

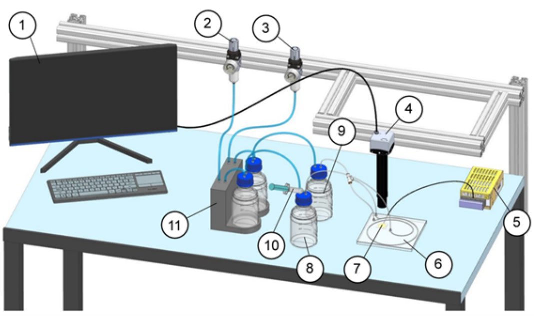

Figure 8. Experimental setup.

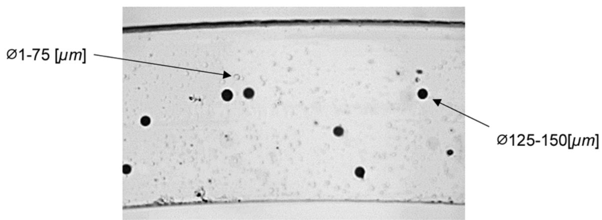

Figure 9. Particle used.

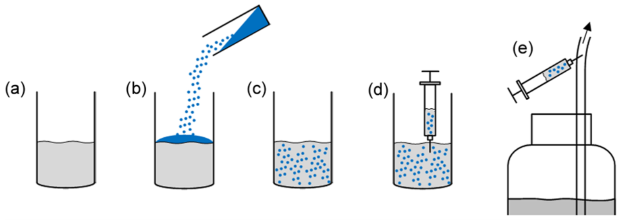

Figure 10. Procedure to inject the particles into the circulating ink.

The device has been then realized and the filtering efficiency characterized in the laboratory.

Results

The performed numerical simulation confirms the formation of Dean vortices, whose magnitude has been optimized by tuning the channel geometry and flow parameters. The maximal Dean velocity, U_{Dean} for a rectangular duct has been compared to the literature model which holds for a square duct, $U_{Dean} = 1.8 \cdot 10^{-4} De^{1.63}$(m/s) (see Figure 12).

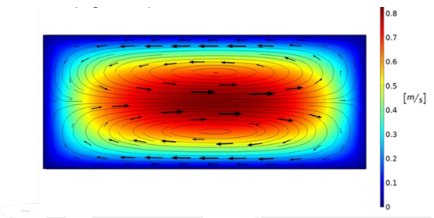

Figure 11. Flow field showing the Dean vortices.

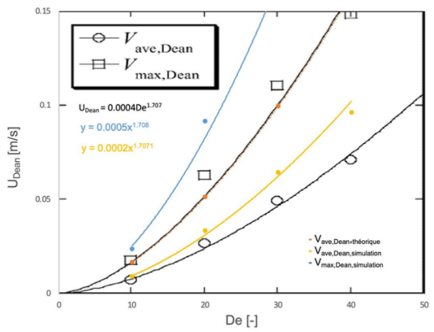

Figure 12. Dean velocity as a function of Dean number and comparison with Ref. [3]

The optimized microfluidic circuit has been then employed to simulate the trajectory of particles having different sizes (see Figure 13). It can be clearly seen, that big particles focus close to the inner wall, and can be therefore filtered out by defining a correct bifurcation in the channel. The position of the bifurcation must be adjusted to collect all the particles to be filtered, while maintaining a suitable flow of filtered ink to the printhead.

An example of experimental result is shown in Figure 14. Initially randomly distributed particles eventually focuses at different locations. The big particles can be collected by the outlet channel closer to the inner wall. The flow field in the bifurcation has been compared between numerical simulations and experimental measurements. The agreement is only qualitative since for the experimental measurement it has not been possible to only

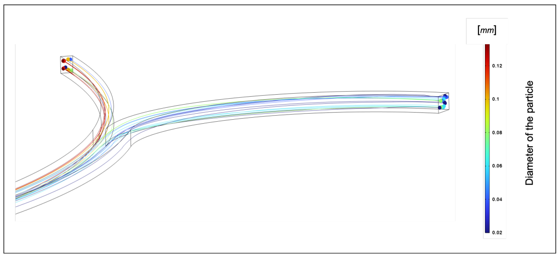

Figure 13. Numerical particles trajectories based on their size

visualize the particles in the mid plane, meaning that the Particle Image Velocimetry (PIV) result is an integral measurement over the entire height.

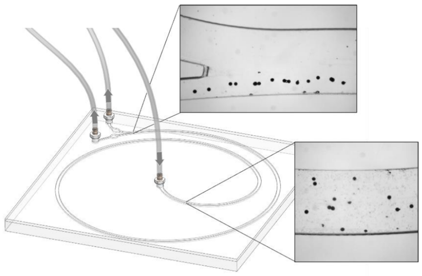

Figure 14. Initial and final particles positions illustrating a successful filtration.

The filtering efficiency has been studied in terms of Dean and Reynolds numbers. For sufficiently high Reynolds and Dean numbers, the filtering efficiency is higher than 95%. It has also been observed that the particle concentration plays a key role in the filtering efficiency. For high particle loads, typically 20 %vol, the particle interaction hinders their focusing at the equilibrium position. Additional strategies to focus the particles are foreseen and will be investigated in future studies.

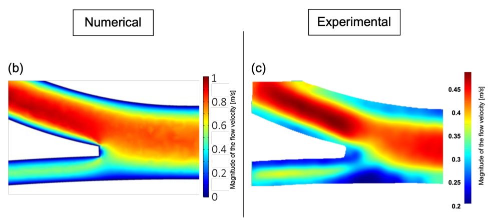

Figure 15. Comparison between numerical and experimental flow fields at the exit bifurcation.

Conclusions

To the best of our knowledge, it is the first time that inertial microfluidics is employed in the context of inkjet ink filtration. In addition to the potential for filtering, inertial microfluidics could also play a role to stream the particles at particular positions in printheads microchannels and prevent channels obstruction. In this work, it has been possible to numerically design and experimentally validate a millimetric particle filtering system. For time reasons, only reduced particle concentrations in a Newtonian fluid have been considered. The next step consists in the

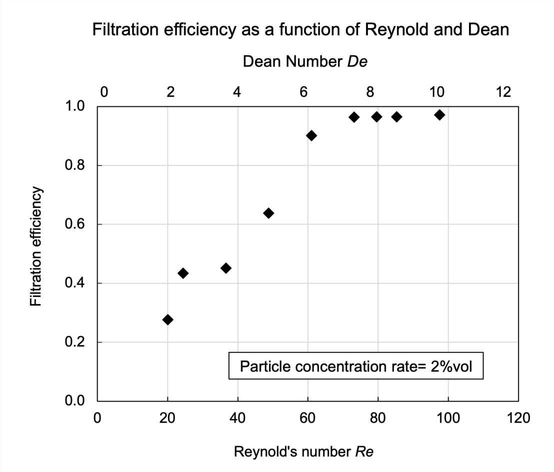

Figure 16. *Filtration efficiency of the experimental device as a function of Re and De.*

miniaturization of the system and in the consideration of higher concentration of potentially non-Newtonian inkjet inks.

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Author Biography

Thibault Maillard received his Bachelor degree in Mechanical Engineering from the School of Engineering and Architecture of Fribourg in 2023 and is currently pursuing a Master's degree at the University of Bern.

Gioele Balestra holds a Master degree in Mechanical Engineering from ETH Zurich and a PhD from EPFL. He joined iPrint in 2019 to develop new digital deposition techniques and since July 2020 he is in charge of the applied research and educational activities of the institute and competence center.