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Intensified microfluidic separations under magnetic field

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1. Introduction

Microfluidic magnetophoretic separators have found increasing use in a diverse range of fields because of their inherent benefits. Firstly, their reduced dimensions lead to an enhancement of the mass and heat transfer rates and to the development of laminar flow conditions inside these devices, which allows the coflowing of miscible fluids without mixing. These microfluidic systems are also characterized by their low sample consumption, which reduces the risk and the cost involved in handling hazardous and expensive materials, and by its functionality, that arise from the possibility of integrate multiple steps onto one device (known as lab-on-a-chip, LOC). On the other hand, functionalized magnetic beads can selectively separate and sort target molecules by the application of an external magentic field, due to its outstanding properties, such as, high specific surface area, chemical stability, high loading capacity, etc [1, 2]

In the biomedical area, magnetophoretic-microseparators are conceived as potential tools to be employed in extracorporeal blood detoxification processes, such as sepsis, since the removal of the disease-causing pathogen is considered the most direct treatment. Thereby, at an initial stage, blood is incubated with magnetic particles, which results in the attachment of the pathogen into the bead surface. Then, the pathogen-bead complexes are recovered in a second stage by exerting a magnetic force on the particles. [2, 3] Nevertheless, while these systems prove notably beneficial, the recovery of the magnetic beads at relatively high blood flow rates remains challenging.

2. Methods

Herein, we address the optimization of multiphase continuous-flow Y-Y shape microseparators by assessing the influence of the channel geometry (i.e. cross section and length). Therefore, we tested three channel length (2, 5 and 10 mm) and two cross sectional shapes (rectangular and U-shape), which are the ones derived from the most widely used chip fabrication methods. For that purpose, a customized Computational Fluid Dynamics (CFD) software, Flow-3D, linked to a Fortran Code was employed, in order to combine the magnetic and fluidic analysis, and thus to accurately describe the bead trajectories. Two dimensionless design numbers were developed and introduced in order to efficiently compare across all geometries. Once the channel design was optimized, we carried out the system parallelization to fulfil the flow rates requirements of typical blood detoxification processes. In this regard, the number of channels that should be arranged in parallel, as well as the number of magnets and their position and orientation were determined. To optimize the magnetic force distribution in parallel channels when a magnet array is considered, so as to the magnetic force in the channels is sufficient for capturing the beads at high flow rates, a custom MatLab code was used.

3. Results and discussion

The performance of all the geometrical designs considered in this study was evaluated by calculating the percentage of particle recovery, which is a measurement of the number of beads that are successfully deflected by the magnet. In Figure 1, the influence of the blood flow rate on the capture efficiency is illustrated. The results suggest that when the channel length is increased by 5 times, the particle recovery is enhanced of about 65% for rectangular and 44% for U-shaped cross section channels. On the other hand, for attaining comparable recoveries, the treated flow rate in U-shaped channels must be at lest one order of magnitude reduced in comparison to rectangular ones.

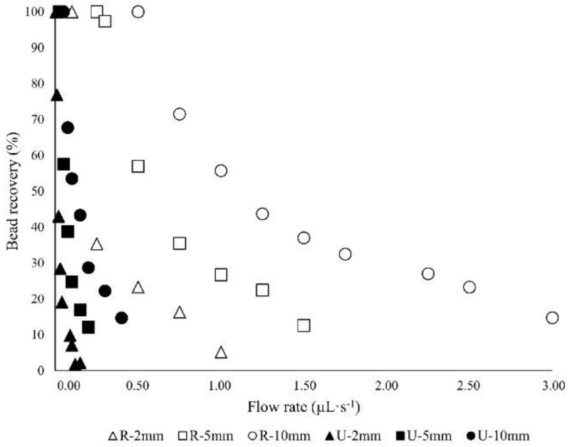

Figure 1. Influence of blood flow rate on bead recovery.

Additionally, to compare and characterize the geometries under study we made use of two dimensionless numbers: the J parameter, which accounts for the ratio of magnetic and fluidic forces exerted on the particles, and the θ parameter which relates the J parameter with the length-width aspect ratio. The relatively high flow rates analysed in this study lead to J values lower than 1 (being in the range 0.01-0.08), which demonstrates that by optimizing the channel geometry, complete bead captures can be obtained with fluidic forces considerably larger than magnetic ones. Regarding the overall influence of the channel geometry and the exerted forces (θ parameter), we found that independently from the length, rectangular sections allow to entirely recover the beads with lower θ values than U-shaped channels, which in turn means that higher blood flow rates can be treated when rectangular channels are used.

4. Conclusions

The computational guidelines described in this study prove extremely useful as a decision-making tool regarding the channel length and cross-sectional shape prior to chip fabrication. Besides, they can be applied and adapted to any microfluidic magnetophoretic-based separation beyond the biomedical field.

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