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Theoretical and experimental consideration regarding magnetic separation in microfluidic device

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ABSTRACT

The paper describes the implementation of the high gradient magnetic separation principle at the microscale on a microfluidic device under continuous flow for the separation of magnetic cells from diluted sanguine plasma.

If a uniform external magnetic field, H, is applied normal to the axis of a ferromagnetic wire, it is deformed near the ferromagnetic wire and generates a force experienced by the magnetic particles moving around the wire.

2D simulations of different passive magnetic microsystem activated via application of a bias field that magnetizes ferromagnetic elements were performed on Maxwell SV. Once magnetized, the elements produce a non-uniform magnetic field distribution which gives rise to a force on magnetic cells as they pass trough the microsystem. The force direction and intensity depends on the type of cell subjected to it and on the different structure of the ferromagnetic material. To analyze the influence of a permanent magnetic flux applied on a ferromagnetic structure and the resulting magnetization in the device different structures have been drawn and tests have been performed in case of two different substrate materials, silicon and glass.

The magnetic field has different intensities and different peaks according to the dimensions and the shape of the ferromagnetic structures. The results show how the field is concentrated at the edges of the structures, while it almost disappears on the top. As the cells pass through the microsystem, the magnetic field gives rise to a force on magnetic cells which can be simply calculated using the “effective” dipole moment approach which is given by the following formula:

$$F_m = \mu_0 V_c (\chi_c - \chi_f)(B \bullet \nabla) B$$

where χc and Vc are the susceptibility and volume of the cell, χf is the susceptibility of the transport fluid, which is plasma, B is the applied magnetic flux density and μ0 = 4π x 10-7 H/m is the permeability of the free space.

In this paper we calculated the magnetic force applied on red and white cells, therefore the magnetic properties of white and red blood cells were taken into account to complete the mathematical model. The magnetic field gradient is calculated by the software program and directly used in the magnetic force calculation.

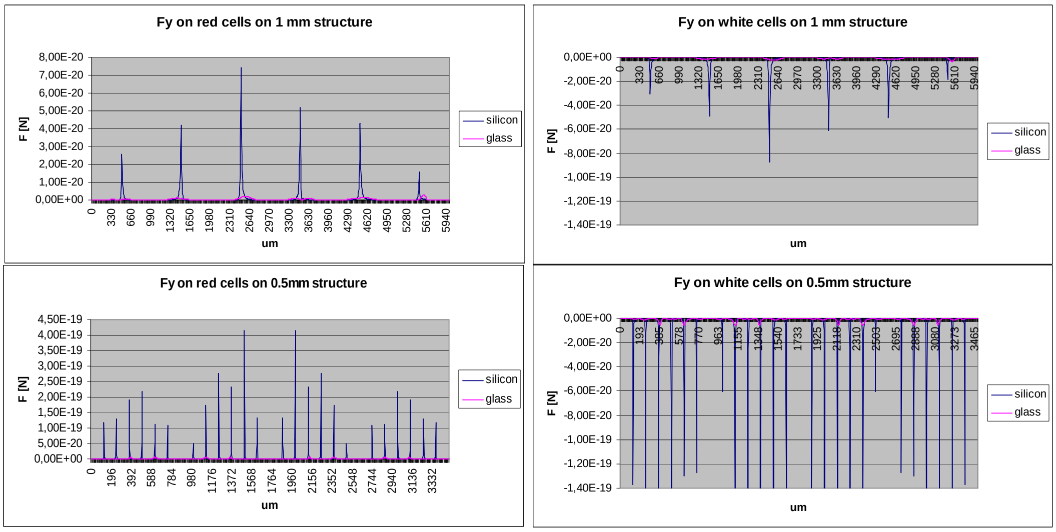

Figure 1: Force components on red cells in 1 mm and 0.5 mm magnetic structure

When a ferromagnetic structure is surrounded by a permanent magnetic field, it drives the magnetic flux components according to the dimensions and the shape of the magnetic layer. In the case of a thin magnetic layer deposited on a silicon or glass base the magnetic flux exhibits a specific behaviour. The magnetic intensity is higher near the edges of the structure while it decreases in the middle. Decreasing the dimensions of the magnetic components and the distance among them, the magnetic flux increases in the number of peaks, because of the superimposition of the effect, maintaining almost the same intensity.

As consequence the force applied on a magnetic particle subjected to the magnetic flux shows a similar behavior respect to the magnetic flux; its intensity has the higher value in correspondence of the edges of the structure and it is almost zero at the structure mid point. Moreover the force can be separated in two components, Fx and Fy, which act, respectively, in the flow direction and perpendicular to the flow, being responsible for cell separation. Red and white blood cells, having an opposite susceptibility, are subjected to an opposite force due to the magnetic field, but they show similar behaviour in the structure. We can observe that a red or white blood cell, in a fluid medium, injected in this type of structure, while it is subject to a positive or negative acceleration it is, at the same time, attracted or repulsed, respectively, near the edges of the structure, allowing magnetic separation. The material used as base for the ferromagnetic structure has an evident influence on the magnetic flux and on the force; in fact, in the case of a macrometric dimensions glass structure, the force on a particle has slightly less intensity than in the case of a silicon structure.

The method was then implemented at the microscale and fabricated using a microfluidic system that consists of an array of integrated ferromagnetic elements embedded beneath a microfluidic channel.

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