COMSOL Conference 2017, Singapore

Red Blood Cell Separation Using Magnetophoresis Force

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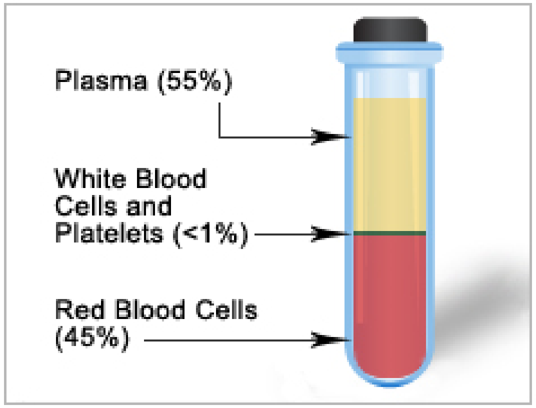
Motivation

Blood component



Separation → Red blood cells

Magnetophoresis force

$$\vec{F}_m = 2\pi\mu_0\mu_f R^3\left(\frac{\mu_p - \mu_f}{\mu_p + 2\mu_f}\right)\nabla\left|\vec{H}\right|^2$$

where $\mu_f = 1$

Oxygenated RBCs: $\mu_p = \mu_f + 3.8 \times 10^{-6}$

Deoxygenated RBCs: $\mu_p = \mu_f - 1.52 \times 10^{-6}$

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COMSOL BLOG

Red Blood Cell Separation from a Flow Channel

Fanny Littmarck   January 3, 2014

Before conducting certain blood sample analyses, researchers need to separate the red blood cell particles from the blood plasma. Using lab-on-a-chip (LOC) technology, red blood cell separation can be achieved via *magnetophoresis* (i.e., motion induced by magnetic fields). Since the magnetic permeability of the particles is different from the blood plasma, their trajectory can be controlled within the flow channel of the LOC device and then separated out from the fluid.

Blood Plasma and Red Blood Cells

Whole blood consists of red and white blood cells, as well as platelets suspended in a liquid referred to as *blood plasma*. According to the American Red Cross, plasma is 92% water and makes up 55% of blood volume. The permeability of blood plasma is equal to 1.

Red blood cells make up slightly lower blood volume than blood plasma — about 45% of whole blood. As you probably already know, these types of blood cells contain hemoglobin, which in turn consists of iron that helps transport oxygen throughout the body. The permeability of red blood cells is slightly less than 1 (1 – 3.9e-6). Or to put it in words, red blood cell particles are *diamagnetic*.

Red Blood Cell Separation via Magnetophoresis in LOCs

Lab-on-a-chip devices (LOCs) are very small (picture an area in the millimeter-centimeter range) microfluidic devices consisting of flow channels that perform one or more lab functions on a

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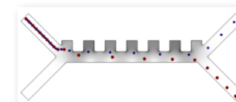
APPLICATION GALLERY

Red Blood Cell Separation

Application ID: 17013



Dielectrophoresis (DEP) occurs when a force is exerted on a dielectric particle as it is subjected to a nonuniform electric field. DEP has many applications in the field of biomedical devices used for biosensors, diagnostics, particle manipulation and filtration (sorting), particle assembly, and more.

The DEP force is sensitive to the size, shape, and dielectric properties of the particles. This allows DEP to be used to separate different kinds of particles, such as various kinds of cells from a mixture. The Red Blood Cell Separation application shows how red blood cells can be selectively filtered from a blood sample in order to isolate red blood cells from platelets.

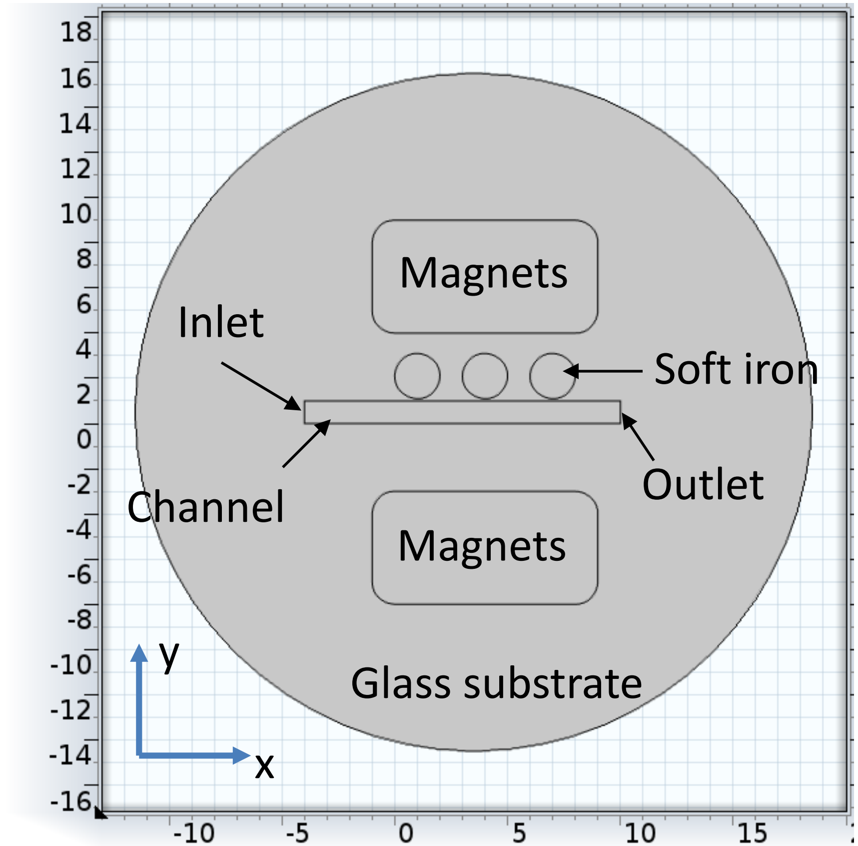
In the DEP filter device, the red blood cells, which are larger than the platelets, feel a larger force and are thereby deflected more. The two outlets are arranged so that the top outlet catches undeflected particles and only particles that have been deflected can exit from the lower outlet.

The app allows you to vary characteristics of the red blood cells and platelets, as well as the electric field.

Used modules:

AC/DC,
Microfluidics
Particle Tracing modules

Computational domain



- ❑Unit: mm
- ❑Inlet: v_{fa}=0.2[mm/s], C=1
- ❑Applied magnetization: M=8x10^6[A/m]
- ❑Channel: w=1[mm], L=14[mm]
- ❑Diffusion coefficient of RBCs: D=3x10^{-7}[cm^2/s]
- ❑Other parameters: use the real RBCs properties
- ❑Multiphysics in COMSOL:

1. Convection and diffusion
2. Stokes flow
3. Magnetic field

- Simulation in steady state
- Less time cost in 3D

Governing equations and boundary conditions

Stokes' flow

$$\eta\nabla^2\mathbf{v}_f - \nabla p = 0$$

$$\nabla\cdot\mathbf{v}_f = 0$$

BCs
- Inlet: $\mathbf{v}_f$=0.2[mm/s]
- Outlet: p=0
- Channel wall: No slip

Maxwell equation

$$B = \mu(H+M)$$

$$\nabla\times H = 0$$

$$B = \nabla\times A$$

BCs
- M=8x10^6 A/m on magnets
- Magnetic insulation on other boundaries

Particle motion equation (steady state)

$$\vec{F}_m + \vec{F}_f + \vec{F}_g = 0$$

$$\vec{\mathbf{v}}_p = \frac{1}{6\pi\eta R}\left(\vec{F}_m + \vec{F}_g\right) + \vec{\mathbf{v}}_f$$

where

$$\vec{F}_m = 2\pi\mu_0\mu_f R^3\left(\frac{\mu_p-\mu_f}{\mu_p+2\mu_f}\right)\nabla\left|\vec{H}\right|^2$$

$$\vec{F}_f = 6\pi\eta R\left(\vec{\mathbf{v}}_f - \vec{\mathbf{v}}_p\right)$$

$$\vec{F}_g = gV_p\left(\rho_p-\rho_f\right)\left(-\vec{e}_y\right)$$

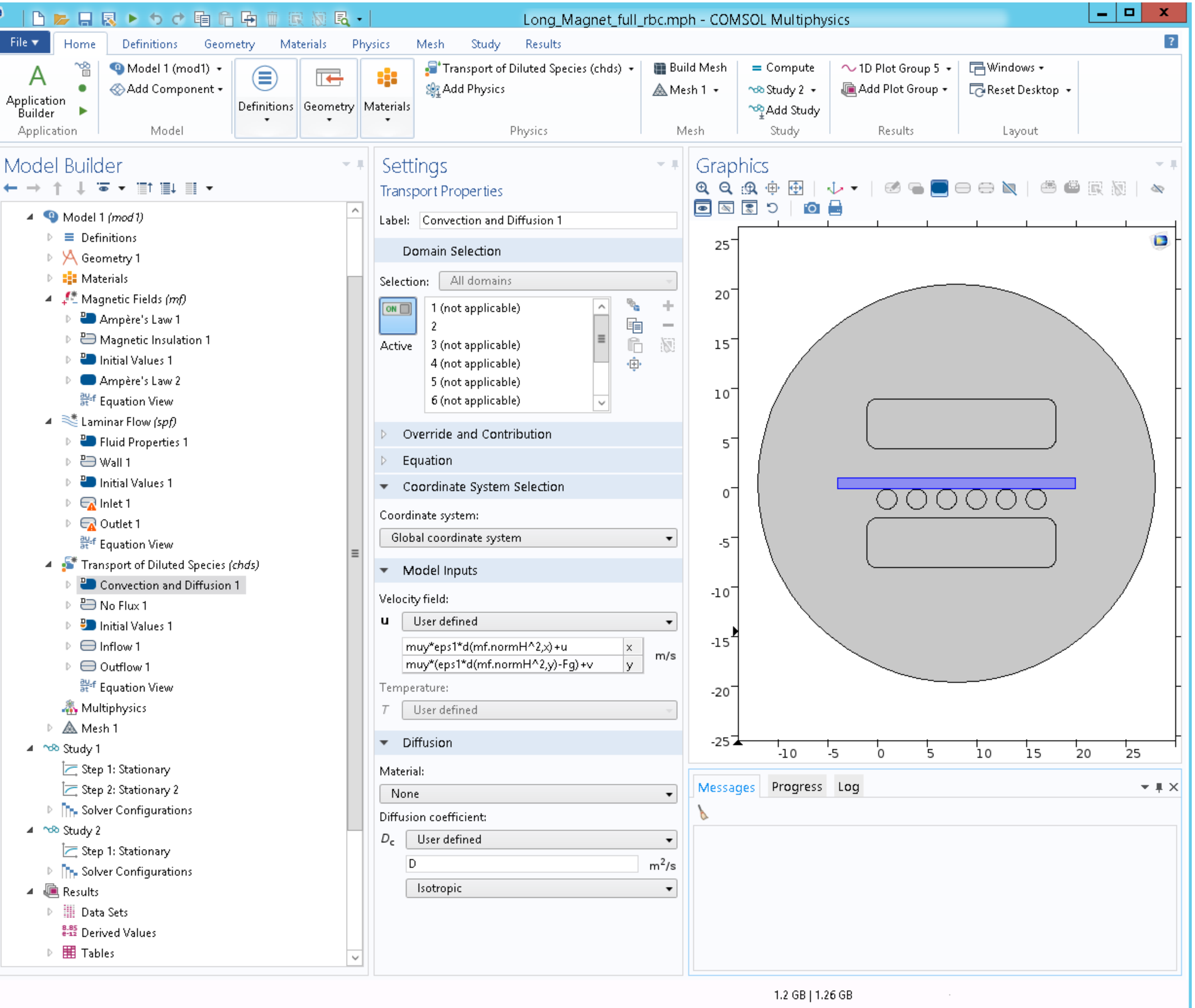
Diffusion and convection

$$D\nabla^2 c - \mathbf{v}_p\cdot\nabla c = 0$$

BCs
- Inlet: c=1
- Outlet: $\nabla c = 0$
- Channel wall: No flux

η: dynamic viscosity
μ: magnetic permeability
ρ_f: plasma mass density
ρ_p:RBCs mass density
R: RBC radius
g: acceleration of gravity
p: plasma pressure
$\mathbf{v}_f$: plasma velocity
$\mathbf{v}_p$: RBCs velocity
μ_f: relative magnetic permeability of plasma
μ_p: relative magnetic permeability of RBCs
μ_0: magnetic reference permeability
V_p: RBCs volume
H: magnetic field
B: magnetic flux density
M: magnetization
A: magnetic vector potential
F_m: Magnetic force
F_f: Drag force
F_g: Gravity force
D: diffusion coefficient of RBCs
c: RBCs concentration

COMSOL V5.2 interface



$$D\nabla^2 c - \mathbf{v_p}\cdot\nabla c = 0$$

$$\vec{\mathbf{v}}_p = \frac{1}{6\pi\eta R}\left(\vec{F}_m + \vec{F}_g\right) + \vec{\mathbf{v}}_f$$

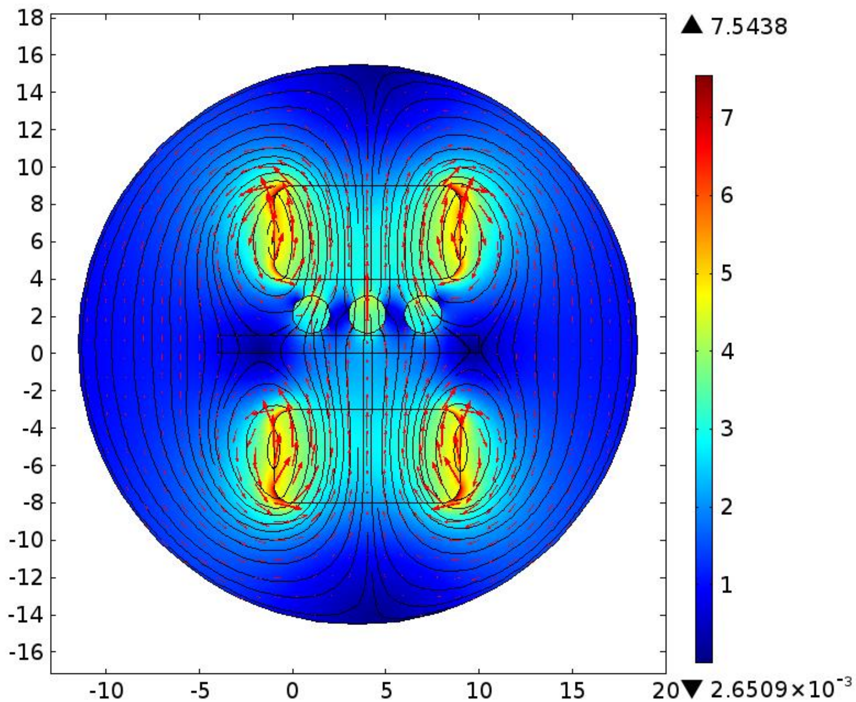
muy

$$\vec{F}_m = 2\pi\mu_0\mu_f R^3\left(\frac{\mu_p-\mu_f}{\mu_p+2\mu_f}\right)\nabla|\vec{H}|^2$$

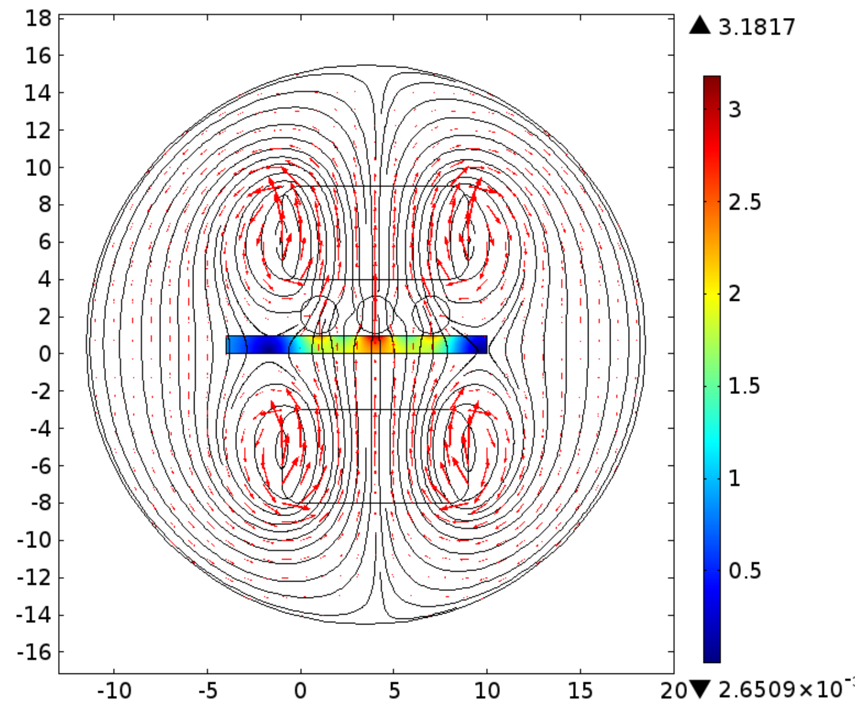
eps1

RESULTS

Magnetic flux density (B)



Magnetic field (T) in the **whole domain**, the streamline and magnetic flux arrow



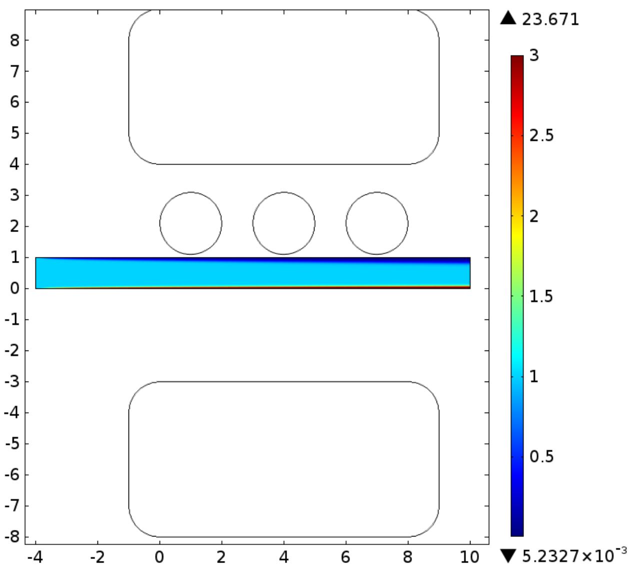
Magnetic field (T) in the **channel**, the streamline and magnetic flux arrow

Effect of gravity and magnets on oxygenated and deoxygenated RBCs

Concentration of red blood cell (Steady state)

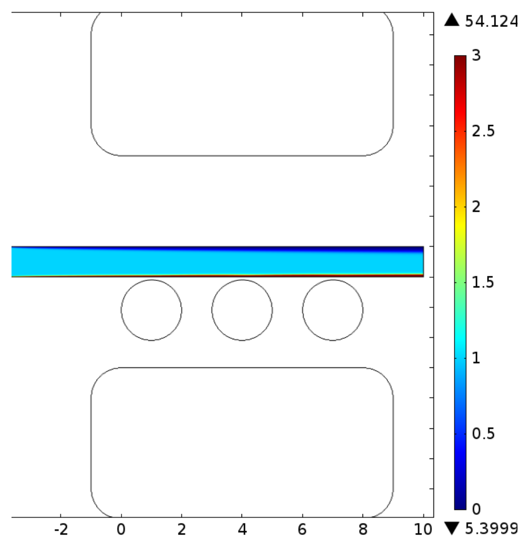
- Length unit: mm
- Concentration unit: C=1 is equal to RBCs concentration of normal blood

Gravity only



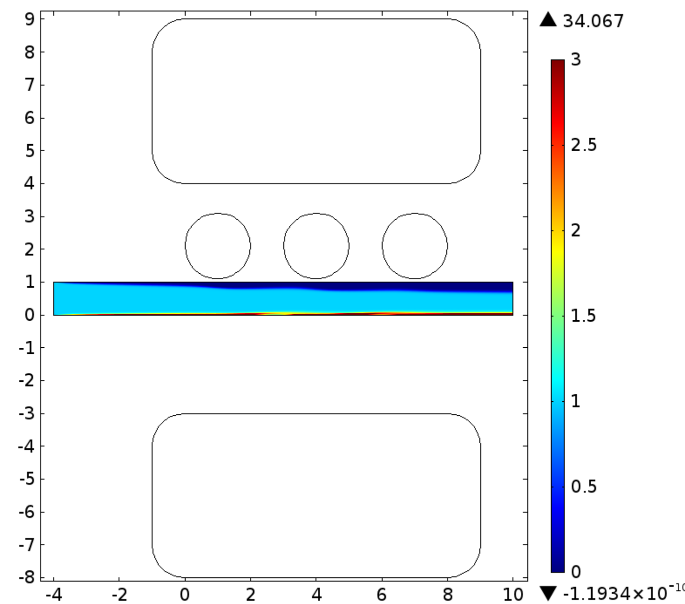
M=0

Magnets+gravity
RBC (deoxygenated)
PULL



$M=10^6$ A/m

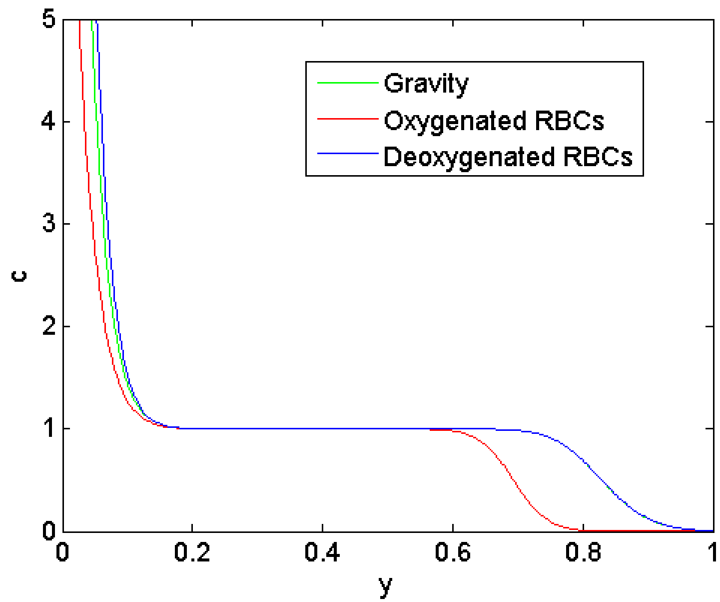
Magnets+gravity
RBC (oxygenated)
PUSH



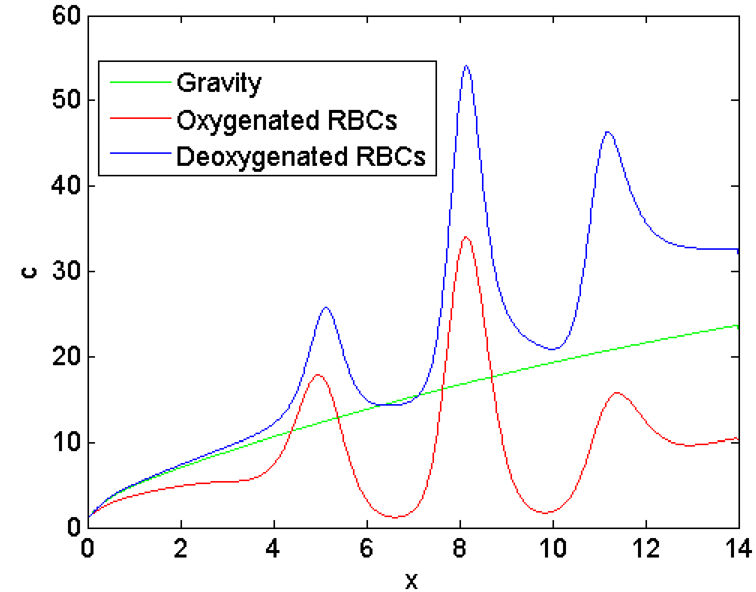
$M=8x10^6$ A/m

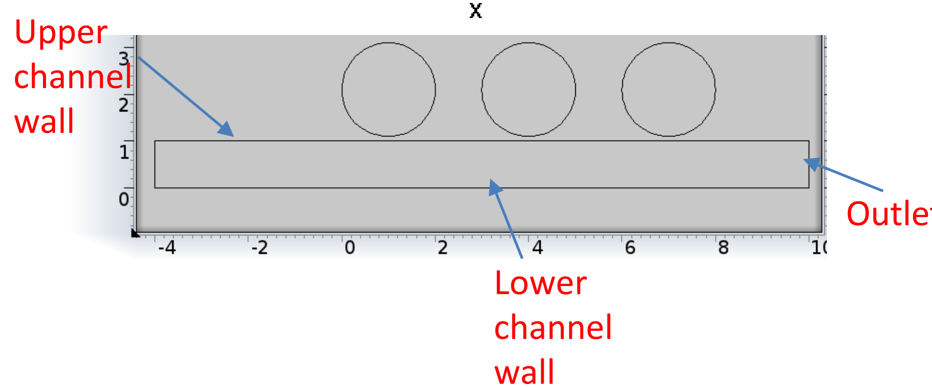
Note: deoxygenated RBC is pulled by soft iron coils, therefore the coils are set up at the lower channel side

RBCs concentration at the channel outlet



RBCs concentration at the lower channel wall

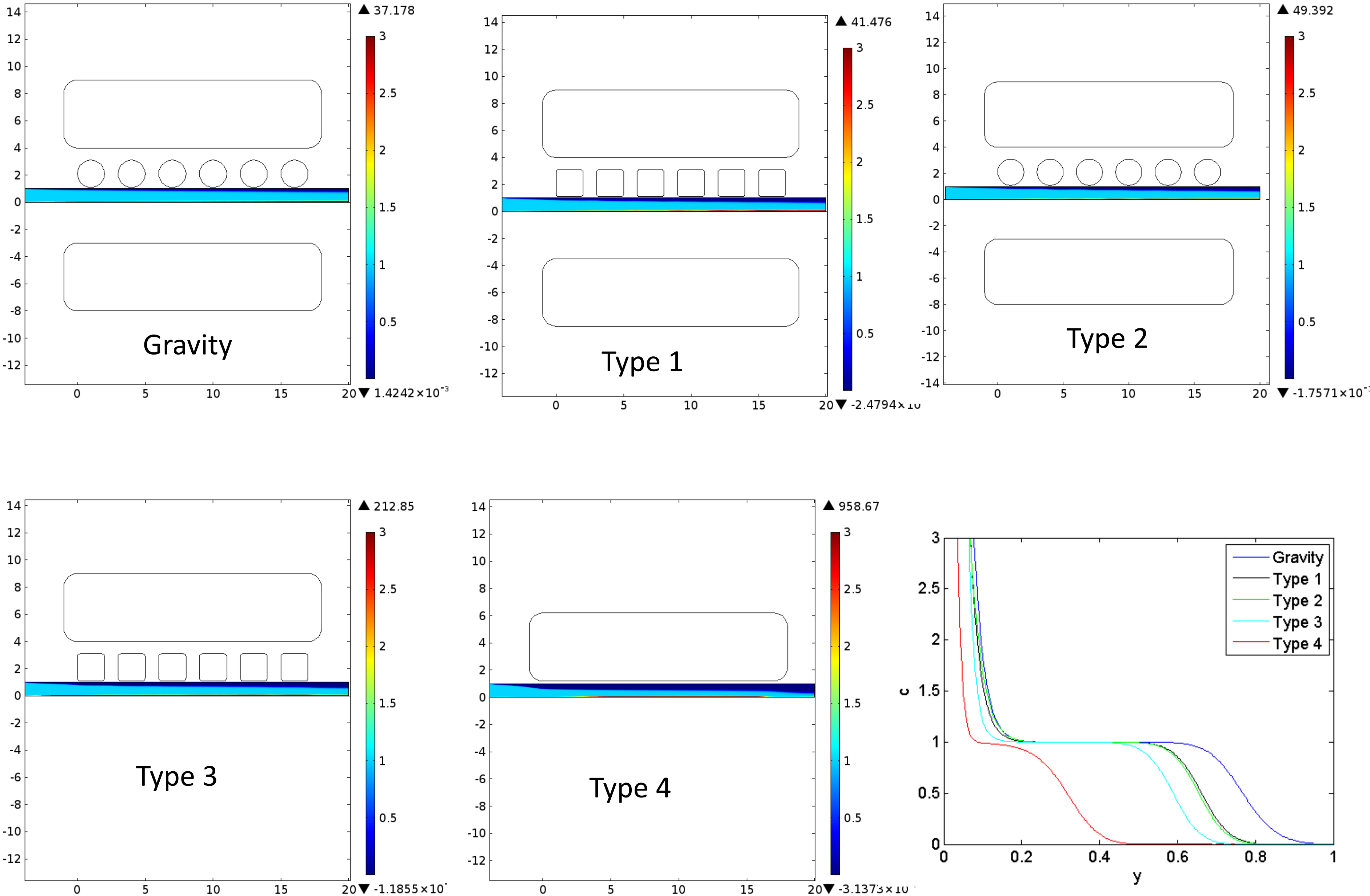




Other designs

Push one side

(Oxygenated RBCs)

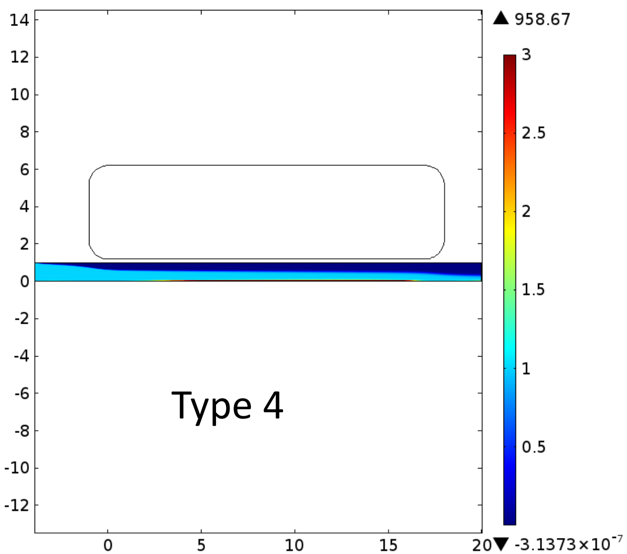


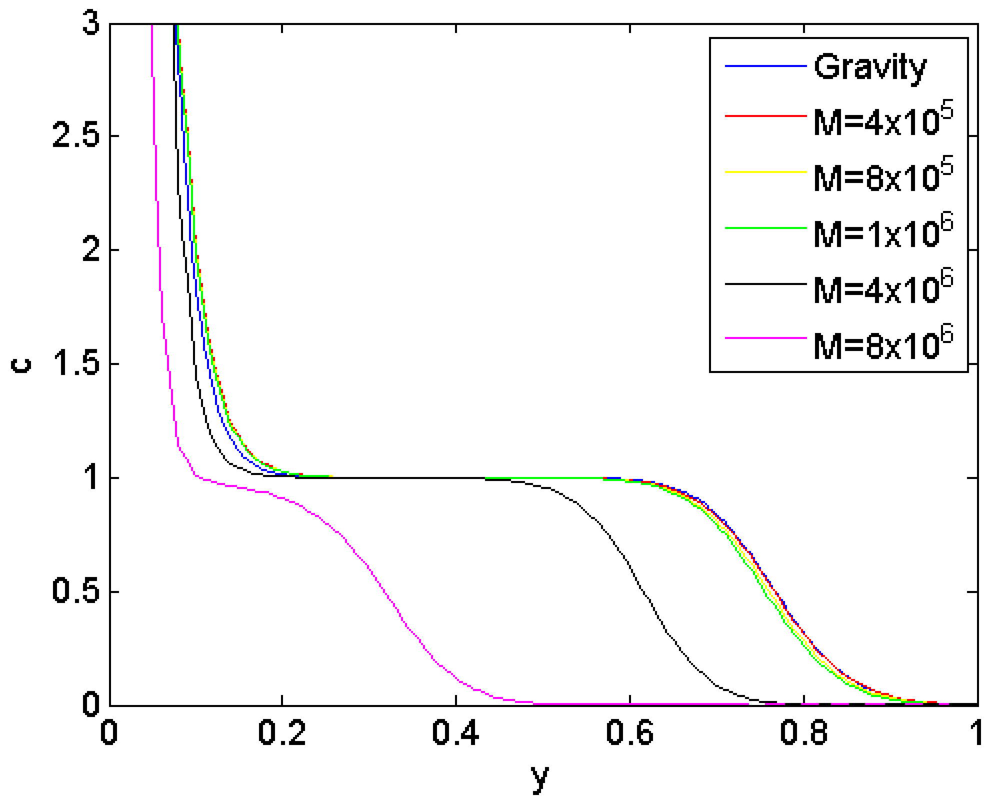
Concentration of RBCs in the channel

$M = 8 \times 10^6$ A/m

RBCs concentration at the channel outlet

Effect of magnetization on outlet RBC concentration of type 4

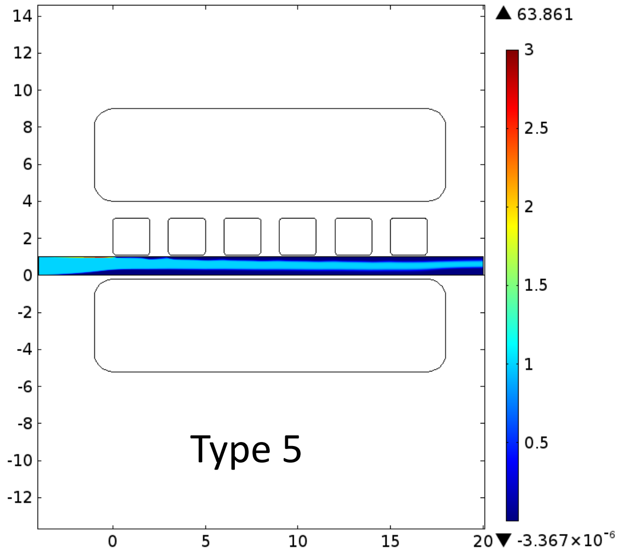


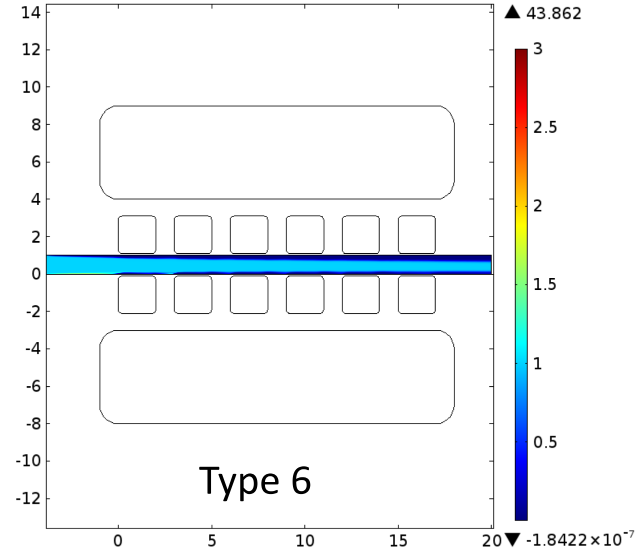


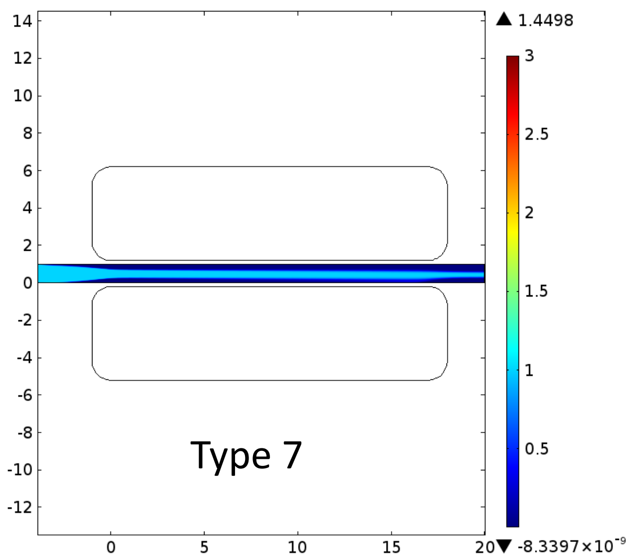
Unit M: A/m^2

Push two sides

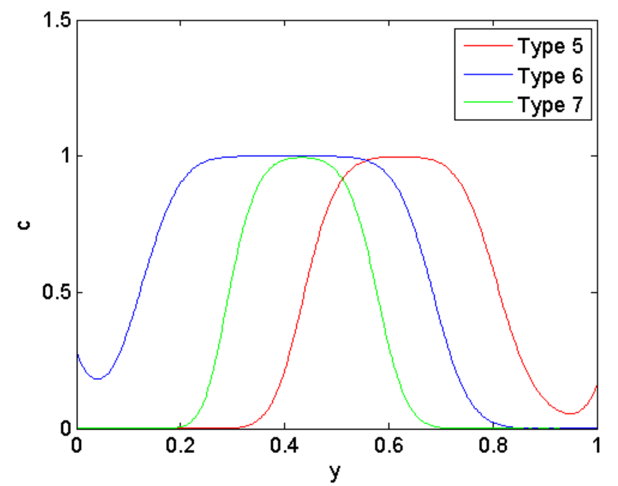
(Oxygenated RBCs)







Concentration of RBCs in the channel



RBCs concentration at the channel outlet

Conclusions

1. Magnets pushes the oxygenated RBCs and shows an efficiency on RBCs separation

2. Magnets pulls the deoxygenated RBCs and shows less efficiency on RBCs separation

3. The Type 4 (no soft iron coils) shows a high efficiency on RBCs separation (push RBCs to one side of the channel)

4. The Type 7 (no soft iron coils) shows a high efficiency on RBCs separation (push RBCs to the center of the channel)

Parameters

η:	0.001[kg/(m.s)]	Dynamic viscosity
R_p:	3.84[μm]	Hydrodynamic radius of RBCs
μ:	$1/(6\pi\eta R_p)$	Mobility of the particle
v_{fa}:	0.2[mm/s]	Inlet fluid velocity
ρ_f:	1000[kg/m^3]	Plasma density
ρ_p:	1100[kg/m^3]	RBCs density
g:	9.8[m/s^2]	Gravity acceleration
F_g:	$(\rho_p - \rho_f)V_p g$	Gravity force
V_p:	88.4[μm^3]	RBCs volume
ε:	$2\pi\mu_0\mu_m R_p^3 (\mu_{wbc} - \mu_m)/(\mu_{wbc}+2\mu_m)$	Magnetophoresis force coefficient
X_{wbc}:	-9.22e-6	Susceptibility of oxygenated RBCs
X_m:	-7.7e-6	Susceptibility of plasma
X_{rbc}:	-3.9e-6	Susceptibility of RBCs
μ_0:	$4\pi 10^{-7}$[N/A^2]	Reference permeability
μ_m:	1+X_m	Plasma permeability
μ_{wbc}:	1+X_wbc	Oxygenated RBCs permeability
μ_{rbc}:	1+X_rbc	RBCs permeability
D:	3e-7[cm^2/s]	Diffusion coefficient

1mm^3 blood (1 drop) =3.5-5 million RBCs