Magnetic Fields for Cell Cultures Suspended in a Perturbed Diamagnetic Medium

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Introduction: Effects of static magnetic fields (SMF) on living matter is a promising research field. Efforts have been given to understand underlying mechanisms. We study cell cultures subjected to SMF in the lab and with COMSOL Multiphysics ®.

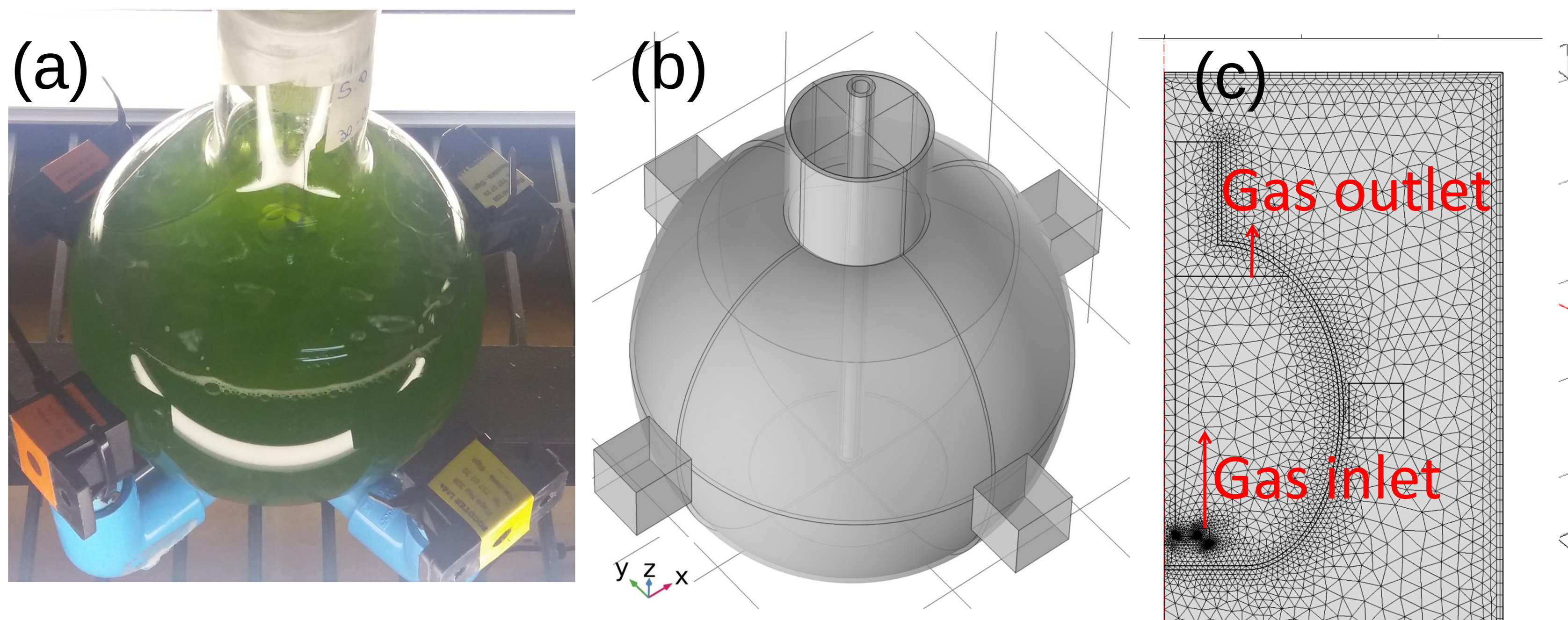

Fig. 1. (a) Ring of magnets surrounding a glass flask with a medium for cell cultures. (b) 3D geometry model. (c) 2D axis symmetric model from 3D geometry.

Computational methods

Step 1: stationary study of *Maxwell* equations applied to magnetostatics to solve ***B*** for an array of magnets [1].

Step 2: time-dependent study of *Navier-Stokes* equations applied to a multiphase bubbly flow to solve velocity and pressure fields of liquid and gas phase, coupled with ***B*** [2,3].

Step 3: time-dependent study of *Newton*'s law for fluid particle tracing (cells), coupled with the velocity field [4].

Maxwell equations

Faraday's law $\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$

Gauss' law (magnetism) $\nabla \cdot \boldsymbol{B} = 0$

Constitutive relations

Magnets $\boldsymbol{B} = \mu_m(\boldsymbol{H} + \boldsymbol{M})$

Medium $\boldsymbol{B} = \mu_i \boldsymbol{H}$

μ_m and μ_i permeability of magnet and medium i

Navier-Stokes equations

Continuity $\frac{\partial}{\partial t}(\Phi_l \rho_l + \Phi_g \rho_g) + \nabla \cdot (\Phi_l \rho_l \boldsymbol{u_l} + \Phi_g \rho_g \boldsymbol{u_g}) = 0$

Momentum $\Phi_l \rho_l \frac{\partial}{\partial t} \boldsymbol{u_l} + \rho(\boldsymbol{u_l} \cdot \nabla)\boldsymbol{u_l} = \nabla \cdot [-p\boldsymbol{I} + \boldsymbol{\tau}] + \rho \boldsymbol{g} + \boldsymbol{f_m}$

$\boldsymbol{\tau}$: viscous stress tensor (see [3])

Magnetic gradient force $\boldsymbol{f_m} = -\chi_v \frac{(\boldsymbol{B} \cdot \nabla)\boldsymbol{B}}{\mu_0}$

χ_v : volumetric susceptibility $\mu_r = \frac{\mu_i}{\mu_0} = \chi_v + 1$

Particle tracing for cells

Newton's law $\frac{d}{dt}(m_p \boldsymbol{v_{cell}}) = \boldsymbol{F_{drag}} + \boldsymbol{F_g} + F_m$

Solution strategy

Reynolds $Re = \frac{\rho_l U L}{\mu_w} > 10000$ → Turbulent flow

Magnetic *Re* $Re_m = \frac{UL}{\lambda} \ll 1$, magnetic diffusivity $\lambda = \frac{1}{\mu_0 \sigma_i}$

B **will tend to relax towards diffusive state, determined by BC, not fluid flow ⇒ One way coupling**

Results: The solution for the magnetic flux density is shown in Fig. 2-6, whereas the gas volume fraction as well as the velocity field are visualized in Fig. 7-9. Finally, the cell tracing is depicted in Fig. 10.

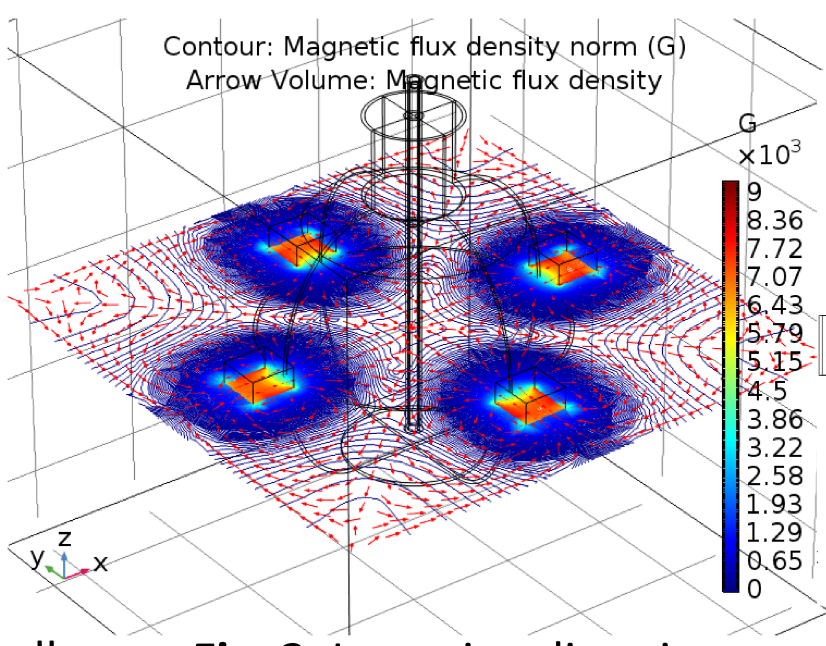

Fig. 2. Intensity, direction and shape of ***B***.

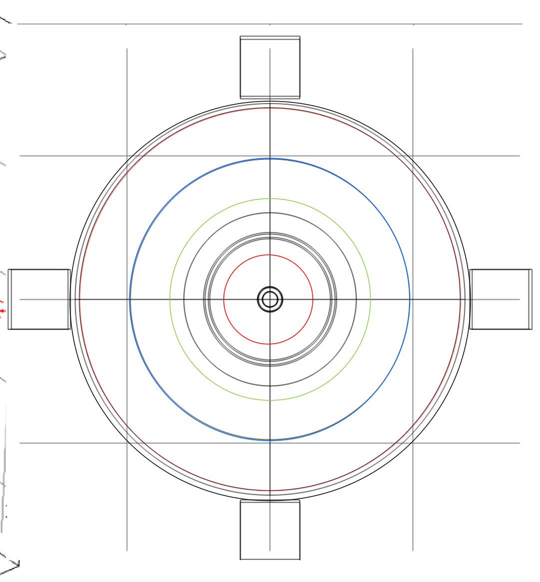

Fig. 3. Curves to specify norm ***B*** of Fig. 5.

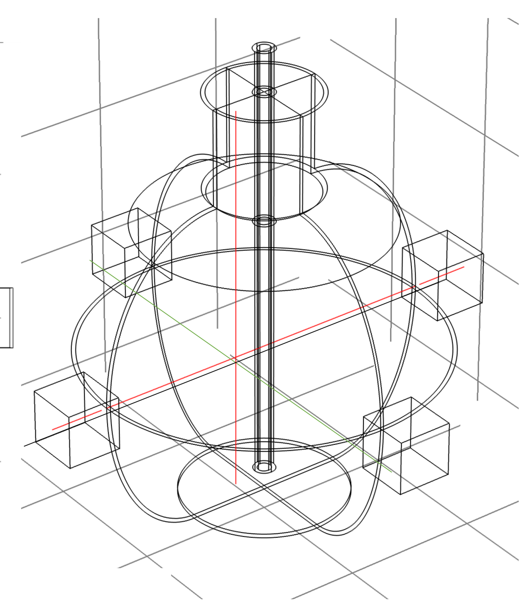

Fig. 4. Lines to specify norm ***B*** of Fig. 6.

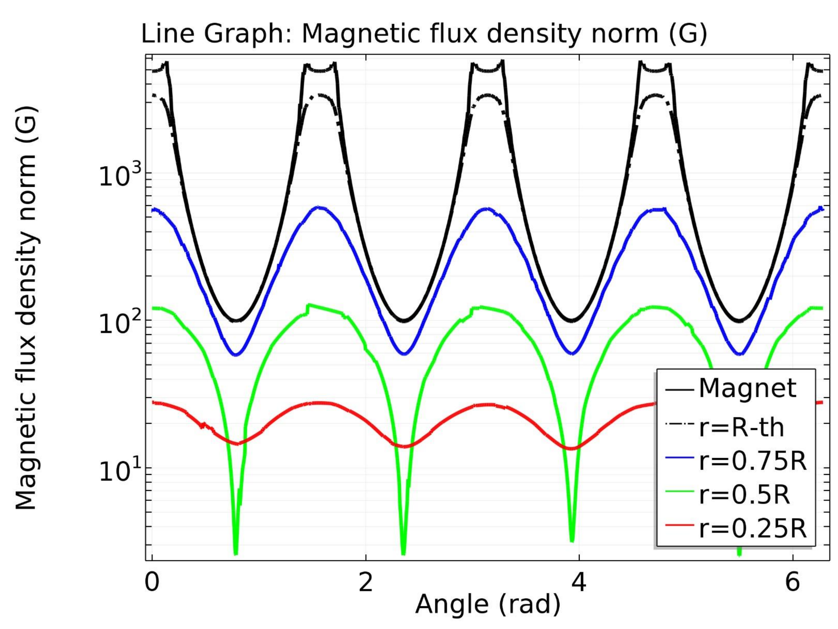

Fig. 5. norm ***B*** along curves.

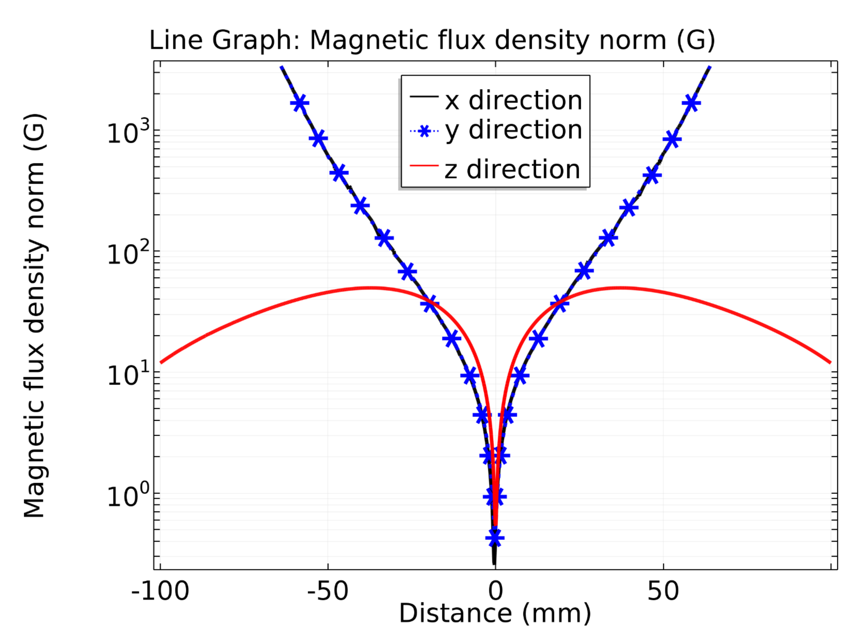

Fig. 6. norm ***B*** along lines.

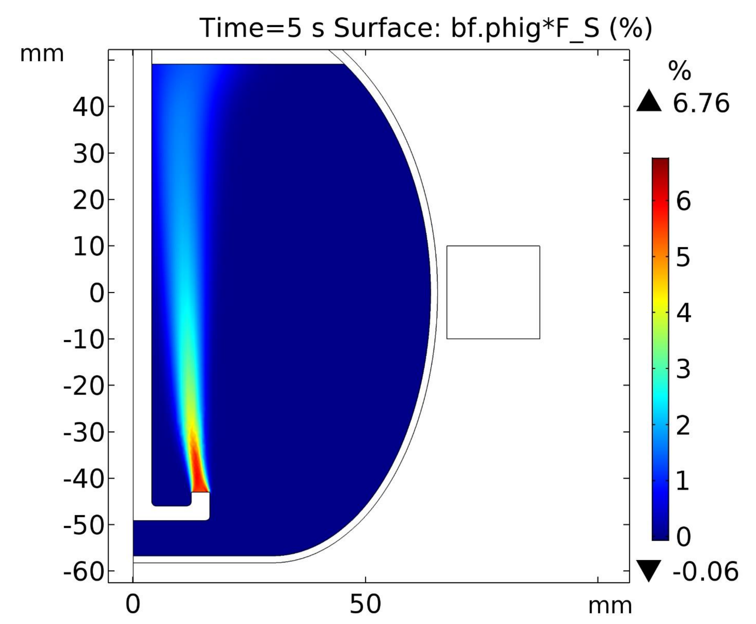

Fig. 7. Gas volume fraction.

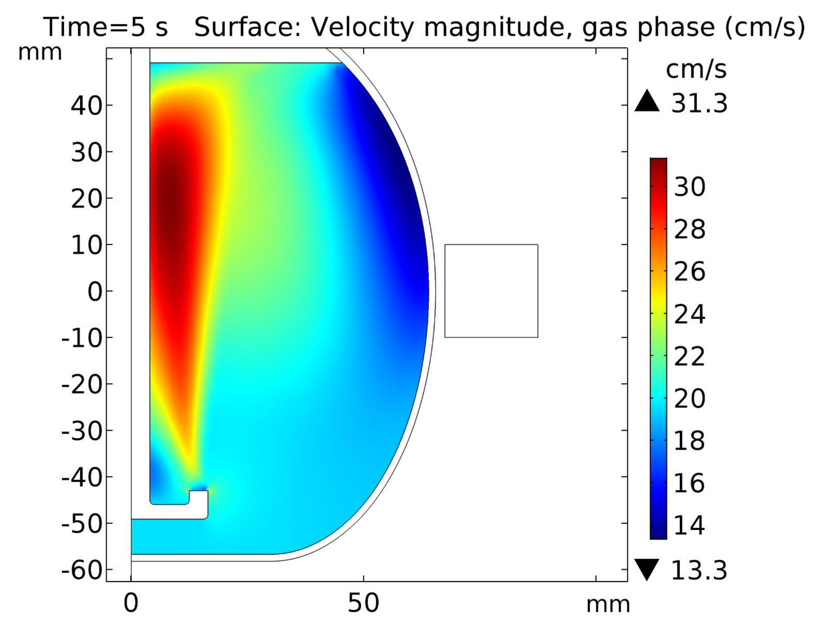

Fig. 8. Gas phase velocity.

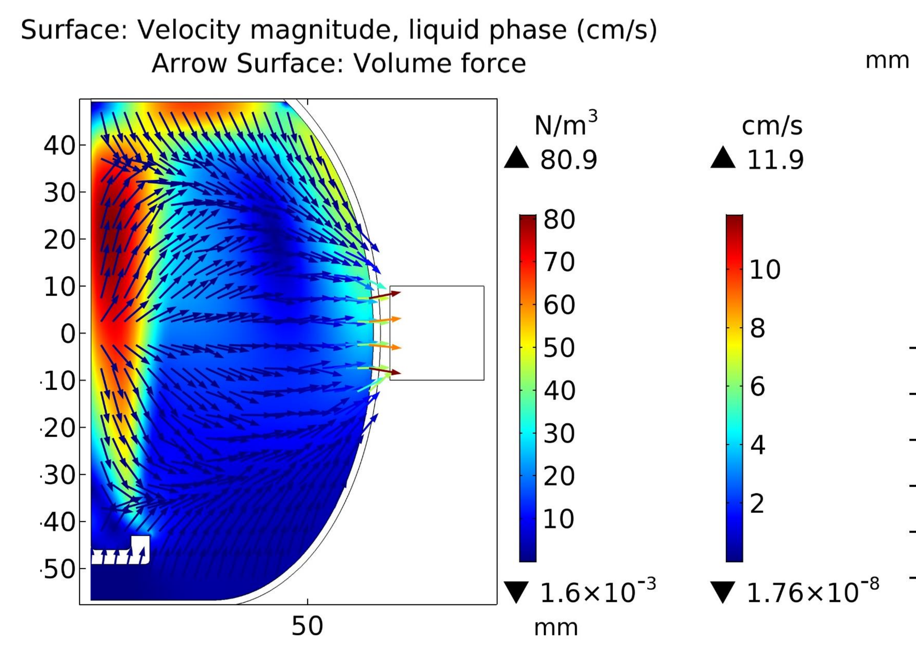

Fig. 9. Liquid phase velocity.

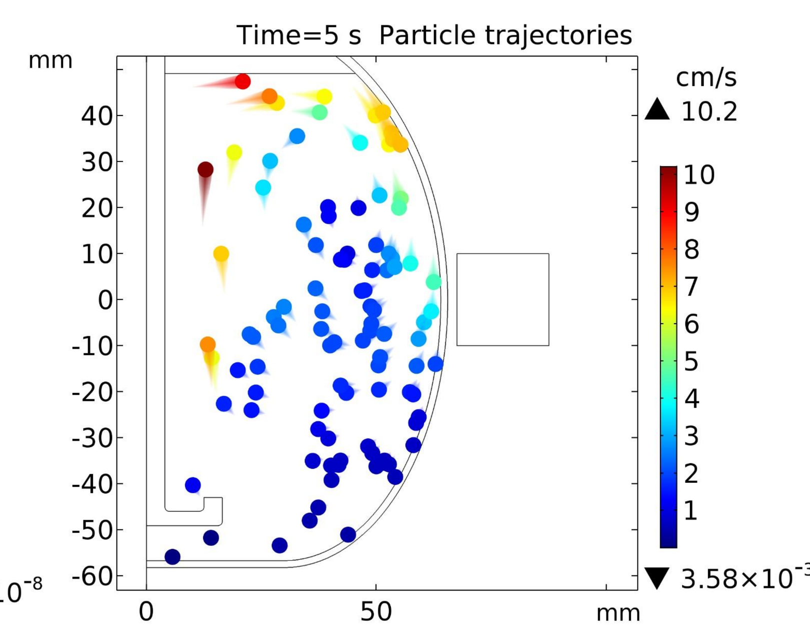

Fig. 10. Particle (cell) tracing.

Summary

Cell cultures in a perturbed medium subjected to SMF were studied with magnetic field no currents, bubbly flow, particle tracing. One-way coupling was used based on Re numbers.

References:

1. Xiao-fan. Analytic Expression of Magnetic Field Distribution of Rectangular Permanent Magnets. Appl Math Mech 25, 297 (2004).
2. C. Crowe, M. Sommerfeld, Y. Tsuji, Multiphase Flows with Droplets and Particles, CRC Press, 1998.
3. CFD Module User's Guide, COMSOL v5.3a
4. Particle Tracing Module User's Guide, COMSOL v5.3a0