High Gradient Magnetic Separation as a Means of Water Purification

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In Bangladesh, like many developing nations, the drinking water is unsafe. Traditionally, the population acquired its water from ponds and reservoirs laden with a myriad of unpleasant contaminants including cholera, botulism, typhoid, hepatitis A, dysentery, and polio. In an attempt to remedy this problem, Bangladeshis drilled shallow wells but soon found the water to be contaminated with high levels of naturally occurring arsenic. The level present in some aquifers is several hundred micrograms per liter (μg/L). The World Health Organization currently sets the allowable concentration at .05 μg/L. The effects of chronic arsenic exposure include cancer of the skin, lungs, urinary bladder, and kidney as well as other skin disorders. With an estimated 25% of the population chronically exposed to unsafe levels of arsenic and 200,000-270,000 deaths related to arsenic poisoning, the situation has captured the attention of the National Academy of Engineering which offered the Grainger Challenge Prize to encourage research and foster a viable solution to this massive public health problem.[1]

An article in *Science*, "Low-Field Magnetic Separation of Monodisperse Fe3O4 Nanocrystals," (Yavuz, *et al.*, 2006) was highlighted in a C&E News article, "Cleaning Water with 'Nanorust,'" (Halford, 2006). This method of magnetic separation to remove arsenic (As) from water caught the attention of Dr. Finlayson, who is interested in ferrofluids. The method centers around mixing a ferrofluid with contaminated water where As binds to ferromagnetic particles (magnetite - Fe_3O_4) and can be then extracted

[1] http://www.nae.edu/NAE/grainger.nsf/weblinks/NAEW-68HUZT?OpenDocument

using a high-gradient magnetic field. The research that Dr. Finlayson and I conducted sought to utilize a wire mesh or “steel wool” to create high local gradients in an otherwise homogenous field to collect the As-magnetite particles in a cycle that would alternate between the separation of the particles and cleaning the filtration device. This process is somewhat common in industrial operations like mining and certain metal manufacturing as well as biological and medical research. Industrial high-gradient magnetic separators (HGMS) are typically on the order of several meters in all three dimensions and when possible are designed for continuous operation in which an annular filter rotates through an electromagnet for the separation phase and then through a cleaning device.

Our goal is to establish a very preliminary design of a system to separate As from contaminated water by means of HGMS. To do this we have assembled information on various steel wool configurations and their respective magnetic and fluid dynamics properties. COMSOL Multiphysics was used to solve the differential equations and boundary value problems of four mock configurations. The equations are appropriate for steady, 2D, non-conducting fluid.

$$\nabla \bullet \mathbf{B} = 0, \ \nabla \times \mathbf{H} = 0, \ \mathbf{B} = \mu_0(\mathbf{M} + \mathbf{H})$$

In this case the magnetic flux density can be represented by a magnetic potential.

$$\mathbf{B} = \nabla \times (A_z \mathbf{e}_z)$$

The magnetic potential was taken as 1-y, which corresponds to an applied magnetic flux density of 1 T. The designs include an array of squares holes representing a fine mesh of perpendicularly intersecting cylindrical wires, an array of circular holes in a plane similar to a colander, an array that models an exact solution for cylinders arranged parallel to the flow direction and also serves as an approximate two-dimensional model for closely packed spheres, and finally an array of "ninja-stars" whose sharp corners are designed to take advantage of the high gradients produced at sharp corners.

The method for evaluating the effectiveness of each design is to determine the average force with respect to the surface area of each grid. The force is $\mu_0 \mathbf{B} \bullet \nabla \mathbf{H}$, and averages of it are calculated over the surface area through which the ferrofluid flows. To do this we evaluate the expression, called criterion

$$\int \sqrt{\left(B_x \frac{\partial H_x}{\partial x} \hat{e}_x + B_y \frac{\partial H_y}{\partial x} \hat{e}_y + B_y \frac{\partial H_x}{\partial y} \hat{e}_x + B_y \frac{\partial H_y}{\partial y} \hat{e}_y \right) \bullet \left(B_x \frac{\partial H_x}{\partial x} \hat{e}_x + B_y \frac{\partial H_y}{\partial x} \hat{e}_y + B_y \frac{\partial H_x}{\partial y} \hat{e}_x + B_y \frac{\partial H_y}{\partial y} \hat{e}_y \right)} dA$$

and divide it by the surface area of the material through which the ferrofluid flows. The average force is then $\dfrac{\mu_0 \bullet criterion}{\int dA}$. The units of **B** are tesla (T), the units of **H** are A/m, and $\mu_0 = 4\pi \, 10^{-7} \; Wb / A\, m$. Thus the units of $\mu_0 \mathbf{B} \bullet \nabla \mathbf{H}$ are T^2/m, which is also N/m^3.

It is assumed that this material would be steel because of its high relative permeability, but this need not necessarily be the case. The magnetic field goes from right to left in the solution-plots below.

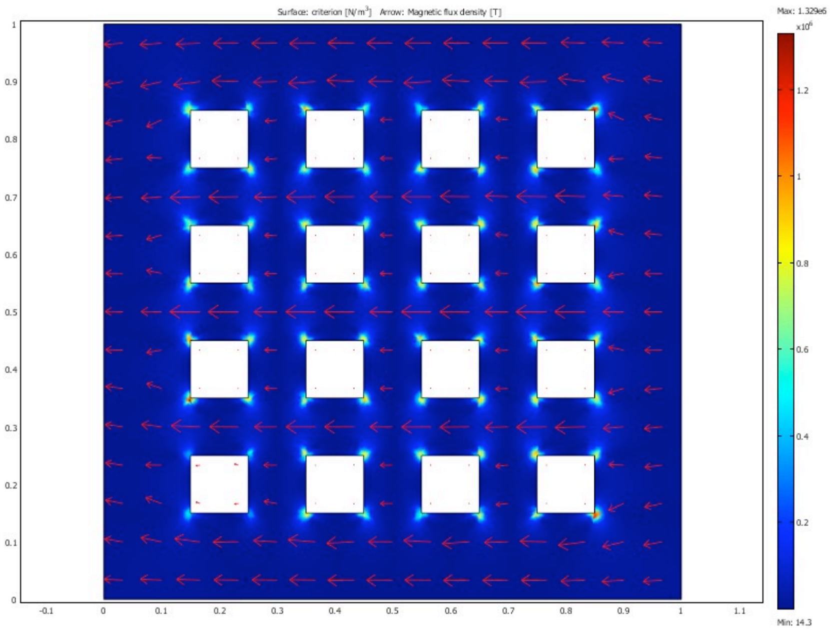
Square Holes:

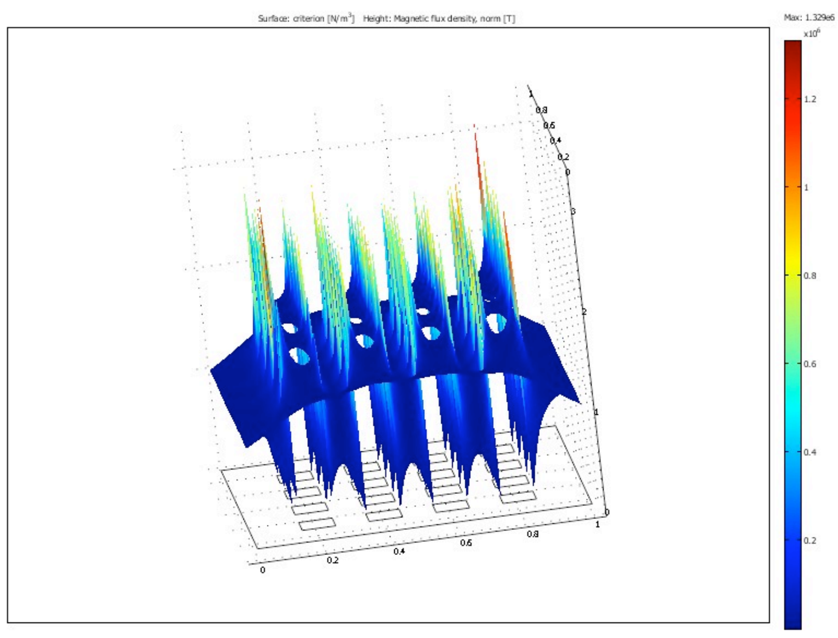
$\text{criterion} \cdot 4\pi \cdot 10^{-7} = 0.042833 \text{ N/m}$

$\text{criterion}_{\max} \cdot 4\pi \cdot 10^{-7} = 1.6700 \text{N/m}$

$\text{criterion} \cdot 4\pi \cdot 10^{-7} / (\text{surface area of grid}) = 0.50992 \text{ N/m}^3$

$\text{criterion} \cdot 4\pi \cdot 10^{-7} / (\text{surface area of entire square}) = 0.042833 \text{ N/m}^3$





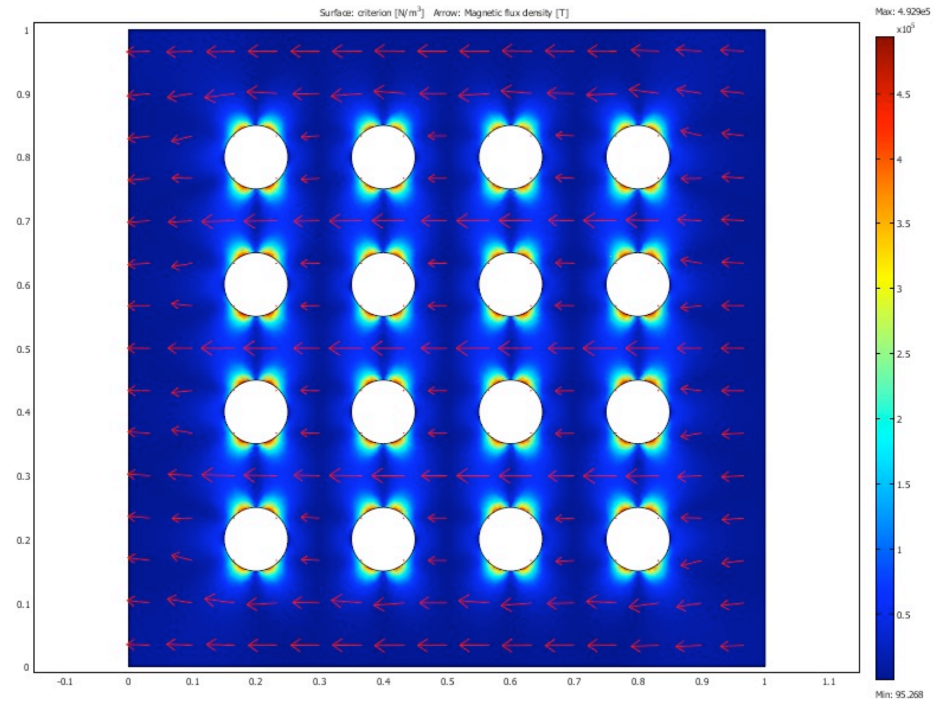
Circular Holes:

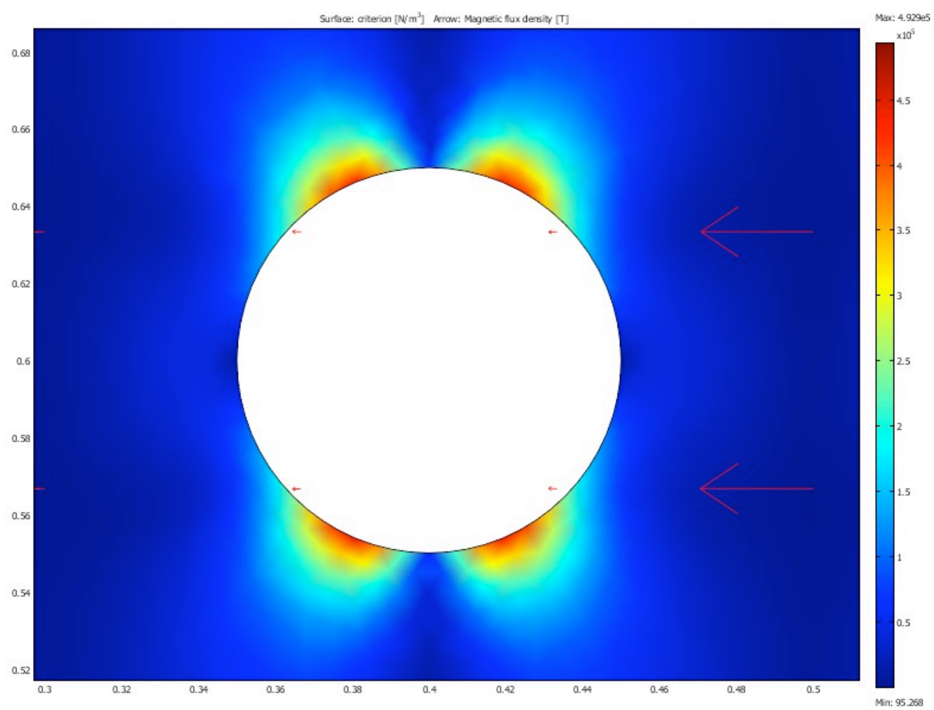
$\text{criterion} \cdot 4\pi \cdot 10^{-7} = 0.039351$ N/m

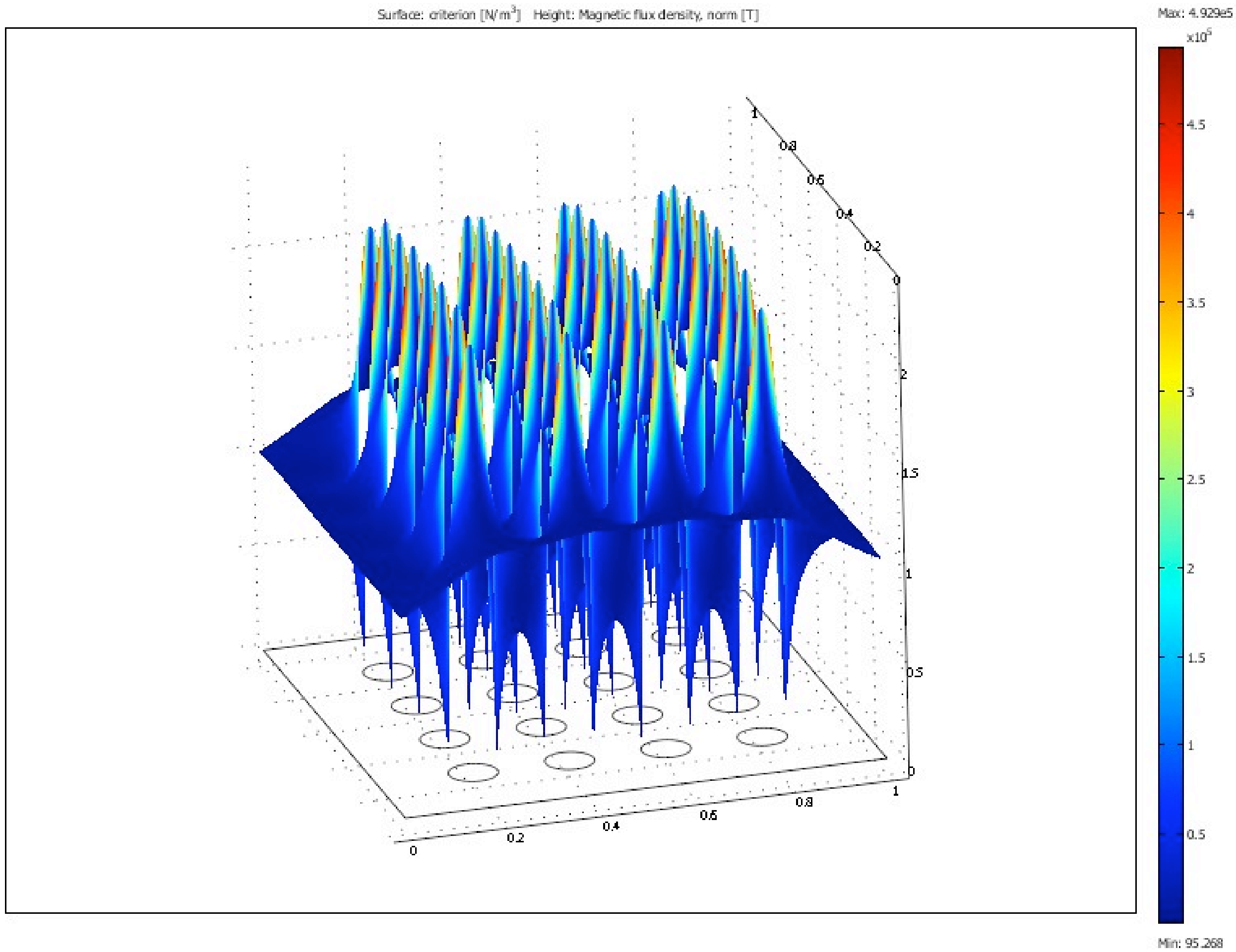
$\text{criterion}_{max} \cdot 4\pi \cdot 10^{-7} = 0.61939$ N/m

$\text{criterion} \cdot 4\pi \cdot 10^{-7}$ /(surface area of grid) = 0.045006 N/m^3

$\text{criterion} \cdot 4\pi \cdot 10^{-7}$ /(surface area of entire square) = 0.039351 N/m^3







Note the high gradients' distribution around the perimeter of each circle. Perhaps as much as a quarter of the circle's perimeter has a very respectable gradient.

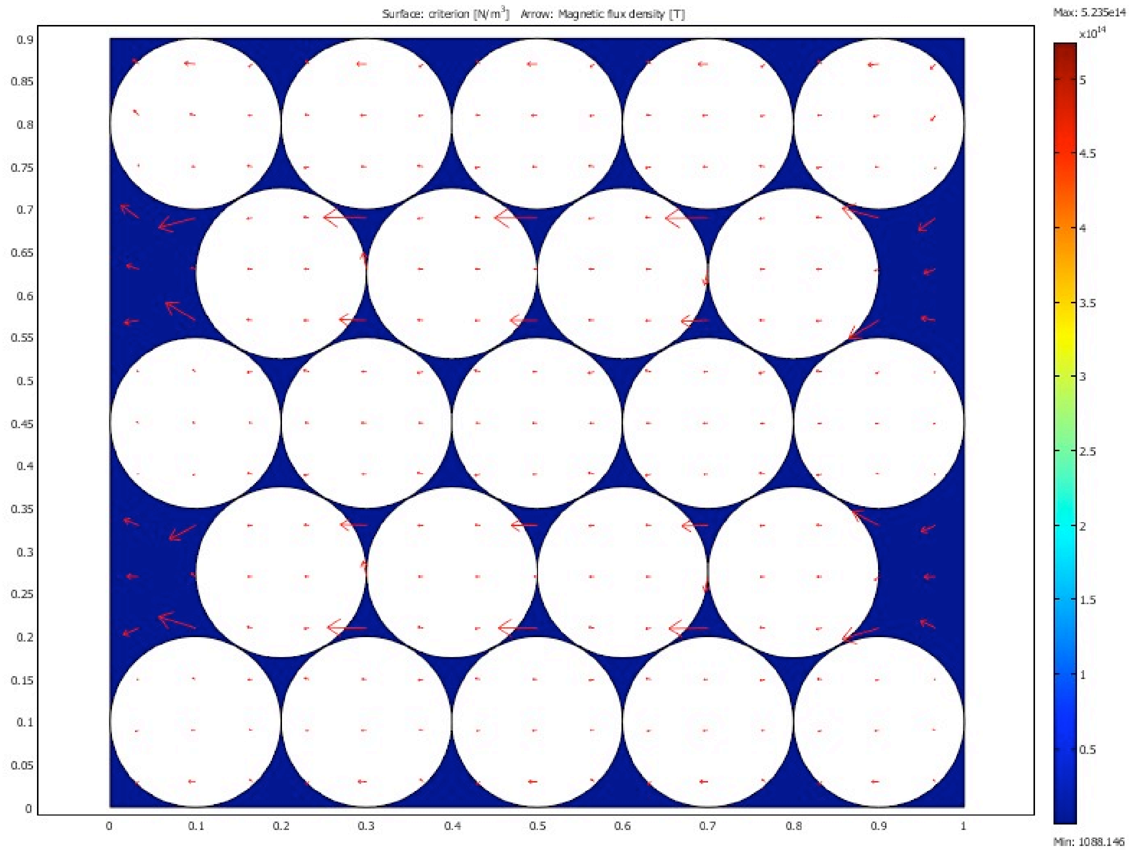
Cylinders/ close-packed spheres approximation:

$\text{criterion} \cdot 4\pi \cdot 10^{-7} = 1.553597$ N/m

$\text{criterion}_{\max} \cdot 4\pi \cdot 10^{-7} = 6.6 \cdot 10^{8}$ N/m

$\text{criterion} \cdot 4\pi \cdot 10^{-7}$ /(surface area of grid) = 2.15001 N/m^3

$\text{criterion} \cdot 4\pi \cdot 10^{-7}$ /(surface area of entire square) = 1.726219 N/m^3



Note that the average gradient value is rather high, yet the plot does not show any area of even moderately high gradient. The high average value may simply be due to a fairly uniform distribution of modest gradients. A three dimensional plot was not included because it fails to reveal any significant indicator of high gradients.

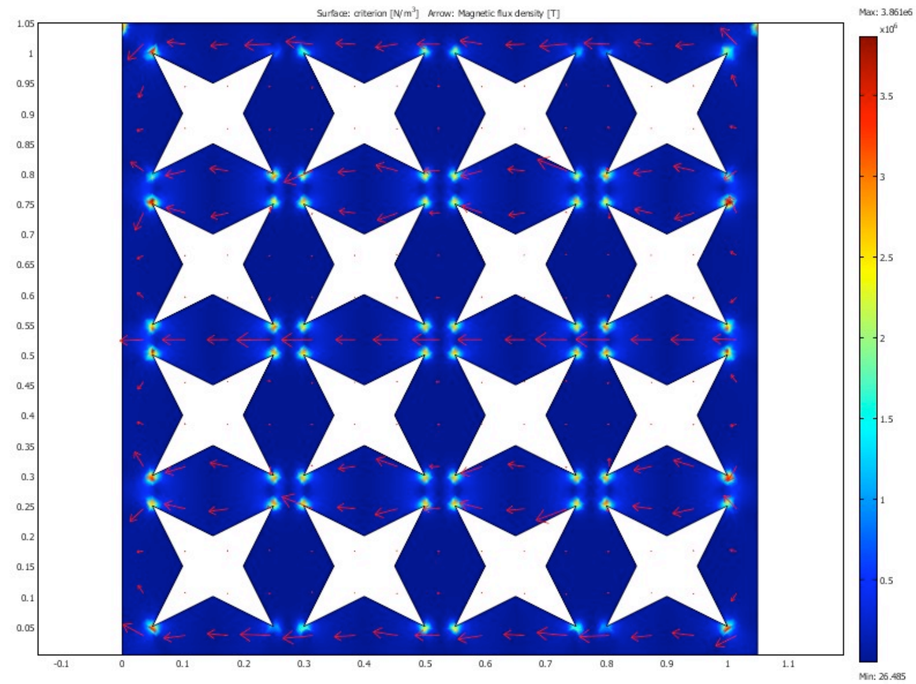
Ninja Stars:

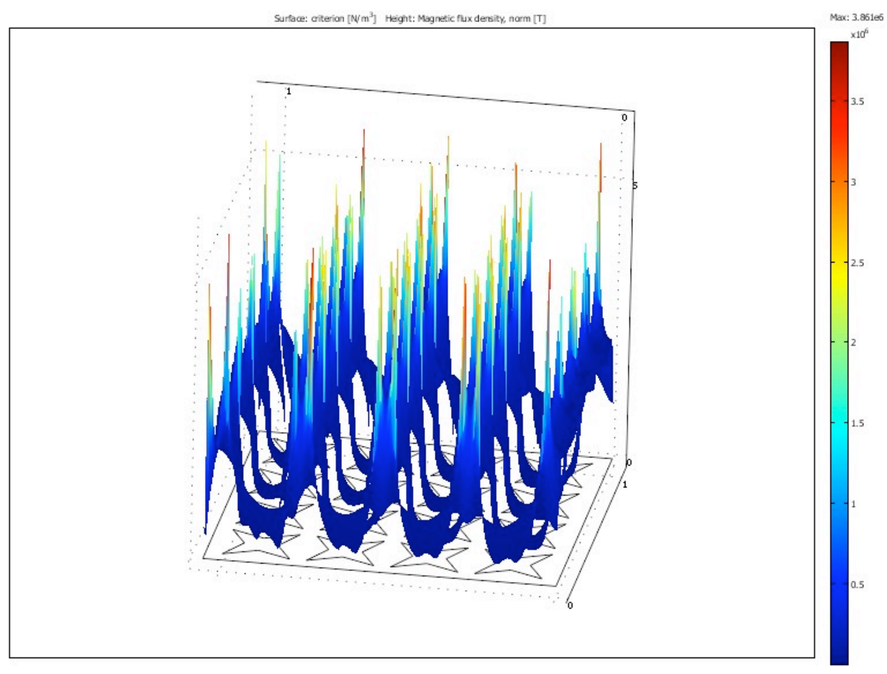
$\text{criterion} \cdot 4\pi \cdot 10^{-7} = 0.119596 \text{ N/m}$

$\text{criterion}_{\max} \cdot 4\pi \cdot 10^{-7} = 4.8581 \text{ N/m}$

$\text{criterion} \cdot 4\pi \cdot 10^{-7} / (\text{surface area of grid}) = 0.152838 \text{ N/m}^3$

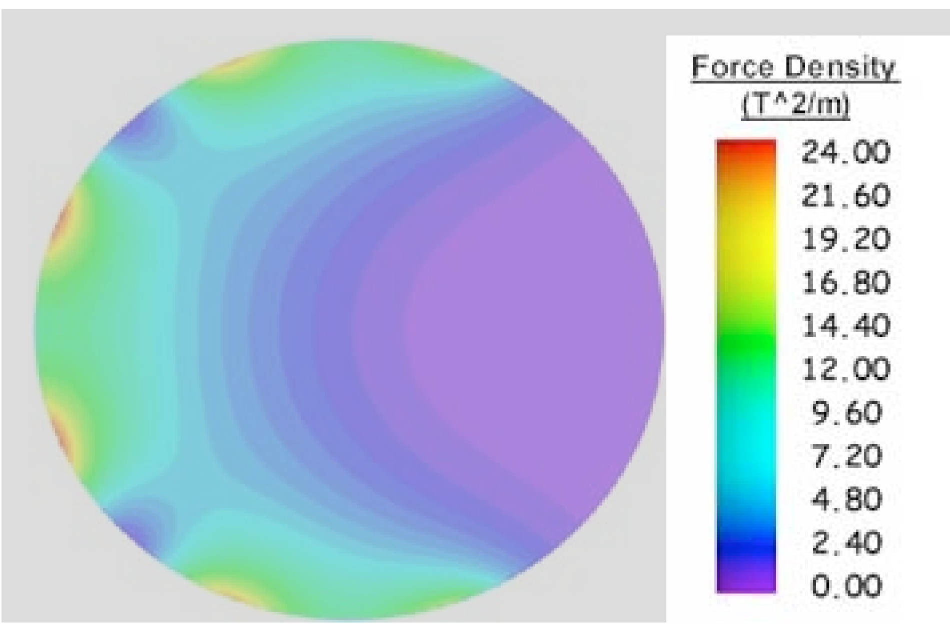
$\text{criterion} \cdot 4\pi \cdot 10^{-7} / (\text{surface area of entire square}) = 0.108477 \text{ N/m}^3$





From these data one can see that sharp corners produce high local gradients, but the average gradient is maximized by increasing the cross sectional area through which the fluid flows. From here one might infer that a promising design would be one that captures both of these features. Such a design could be similar to the cylinders-grid but with the additional feature of a saw-tooth pattern surrounding the surface of the cylinder or sphere.

These results should be compared with two experimental situations. The first is a device made by Dexter for biological magnetic particle separation. The diagram of the force density is shown below, and reaches a peak of 24 T^2/m in small regions.[2] Professor S. Adler in the Chemical Engineering Department at the University of Washington has a magnetic setup which goes as high as 32 24 T^2/m. Thus, reaching a peak value of about 5 T^2/m is within the range of experimental devices..



Another curious feature that arose is the relationship between the relative permeabilities of the steel wool and the ferrofluid. Since HGMS is based on creating a

[2] http://www.dextermag.com/LifeSep-50SX-Performance-Data.aspx?, accessed Feb. 2, 2007.

gradient where the magnetic field encounters a change in permeability, one would expect that the average gradient would increase with the ratio $R = \mu_{\text{steel wool}} / \mu_{\text{ferrofluid}}$, however, there appears to be a maximum average gradient when R = 5. I discovered this by first setting the permeability of the steel wool to a very high value and noticed that it had almost no effect on the value of criterion. Next I set the permeability of the steel wool very close to the value of the ferrofluid and from here went about testing other values in search of a permeability that maximizes the value of criterion.

With a viable steel wool configuration and relative permeability ratio, we now turn our attention to the design of the separator itself. Bethany Halford in a *Chemical & Engineering News* article, “Cleaning Water with ‘Nanorust’” states that it may be possible to use strong permanent magnets for HGMS rather than electromagnets that consume large amounts of electricity, limiting their practicality for this application. With cost-efficiency in mind, it would also be preferable to feed the HGMS by gravity rather than electric pump. To see if this is possible we now examine fluid flow through a packed bed.

<u>Flow through packed beds</u>

Formula for pressure drop:

$$\left(\frac{\Delta p \rho}{G_0^{\,2}}\right)\frac{D_p}{L}\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = 150\left(\frac{(1-\varepsilon)\mu}{D_p G_0}\right) + \frac{7}{4}$$

Δp = pressure drop in Pascals
ρ = density = 1000 kg/m^3
_ = viscosity = 10^{-3} Pa·s
G_0 = mass flux in $\frac{kg}{m^2 s} = \rho u = \frac{\rho Q}{A}$

u = velocity in $\frac{m}{s}$
D_p = diameter of spherical packing
L = length of packed bed
ε = void fraction = .37 (est. for small $\frac{D_p}{D_t}$)
D_t = diameter of cylinder
$A = \frac{\pi}{4} D_t^{\,2}$
Q = volumetric flow rate
R_e = Reynolds number $\equiv \frac{D_p G_0}{\mu(1-\varepsilon)}$

Here we use

$D_p = 0.3\text{mm} = 3 \cdot 10^{-4}\,\text{m}$
$D_t = .02\text{m}$
$\Delta p = 30{,}000$ Pa $= 3 \cdot 10^4$ Pa (the pressure given by about 10ft of head)
L = length of packed bed = .05m

When the Reynolds number is small ($R_e < 10$), one can ignore the additive constant, 7/4, and $G_0 \propto \Delta p$. In such a case, $Q = \frac{D_p^2 \Delta p \frac{\pi}{4} D_t^2 \varepsilon^3}{150(1-\varepsilon)^2 \mu L} = 1.443 \cdot 10^{-5} \frac{m^3}{s}$. Including the 7/4 term gives

$$\frac{7}{4} G_0^{\,2} + 150\left(\frac{(1-\varepsilon)\mu}{D_p G_0}\right) G_0 + \Delta p \rho \frac{D_p}{L}\left(\frac{\varepsilon^3}{1-\varepsilon}\right) = 0$$ and solving with the above parameters,

$G_0 = 37.94 \frac{kg \cdot s}{m^2}$ which in turn gives a Reynolds number

$Re \equiv \frac{D_p G_0}{\mu(1-\varepsilon)} = 18.07 > 10$ and

$Q = G_0 \cdot \frac{A}{\rho} = G_0 \cdot \frac{\frac{\pi}{4} D_t^2}{\rho} = 1.192 \cdot 10^{-5} \frac{m^3}{s} = 1.030 \cdot 10^3 \frac{L}{day}$, a rate of water purification that would supply 62 Bangladeshis per day if each consumes 16.5 L/day. Note that this figure does not account for the cycling time when the filter becomes saturated with contaminant and must be cleaned.

Given that the device could be functional without electricity and due to its modest dimensions, would be easily transportable, HGMS is a potentially viable solution to the arsenic contamination problem in Bangladesh. Only more involved research and experimental data can resolve some of the lingering questions like those regarding the causes of the gradient-maximizing permeability ratio and cleaning-cycle time, but, if nothing else, this application of HGMS is a promising start.

References

Halford, Bethany. "Cleaning Water with 'Nanorust.'" *Chemical & Engineering News,* **84(46),** p.12, November 13, 2006

Yavuz, C. T., *et al*. "Low-Field Magnetic Separation of Monodisperse Fe3O4 Nanocrystals," *Science* **314** 964-967 (2006).