Pull Force of a Refrigerator Magnet

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1 Problem

Estimate the pull force of a refrigerator magnet when attached to a plane of high permeability, such as the steel door of a refrigerator.

2 Solution

We consider a magnet with surface area A in contact with the permeable surface, and suppose the the magnetic field in the contact region is uniform with strength B.[1]

2.1 Via the Magnetic Field Energy

Our first estimate is based on the magnetic-field-energy density, $u = B^2/\mu_0$ in SI units, such that the total field energy is approximately

$$U \approx \frac{B^2 A x}{\mu_0} + \text{constant}, \tag{1}$$

when the gap between the magnet and the permeable surface has thickness x, and we suppose the field energy outside the gap (of volume Ax) in independent of x for small x. Then, the pull force is

$$F = -\frac{\partial U}{\partial x} \approx -\frac{AB^2}{\mu_0}\,\text{newtons}, \tag{2}$$

where the minus sign indicates that the magnet is attracted to the permeable surface.

Sometimes the pull force is expressed in kg as the mass m whose weight mg equals the pull force. In this convention, the pull "force" is $AB^2/\mu_0 g$ (in kg).

Online calculators of the pull force based on the approximation (2) are available at
https://www.kjmagnetics.com/magnet-strength-calculator.asp?
https://supermagnetman.com/pages/pull-force-calculator?

2.2 Via Effective Magnetic Poles

Wayne Saslow (private communication) prefers a derivation of the pull force based on the concept of effective magnetic poles. See, for example, Appendix A of
https://kirkmcd.princeton.edu/examples/poynting.pdf.

[1] This is not a very good approximation, and the pull force achieved is practice is only about 1/3 of the estimate in this note.

In this approach we suppose that the refrigerator magnet has uniform magnetization density $\mathbf{M}$ pointing toward the permeable surface, The magnetic field inside the magnet, and in the gap between the magnet and the permeable surface, is $\mathbf{B} \approx \mu_0 \mathbf{M}$ (for a refrigerator magnet that is sufficiently thick). The magnetization can be thought of as leading to a surface density of effective magnetic poles/charges,[2] related by

$$\sigma = \mathbf{M} \cdot \hat{\mathbf{n}} = M = \frac{B}{\mu_0}\,, \tag{3}$$

where $\hat{\mathbf{n}}$ is the unit vector normal to the surface of the magnet facing the permeable surface. The areal force density on the effective magnetic poles is $\mathbf{f} = \sigma \mathbf{B}$, so the total pull force is given by

$$F = Af \approx A\sigma B = \frac{AB^2}{\mu_0} \text{ newtons}, \tag{4}$$

in agreement with the estimate of eq. (2).

[2]The effective magnetic poles are not physical, but rather a convenient tool for computation. True magnetic poles do not exist in Nature as far as we know.