The Effect of Magnetic Field on Oil Based Ferrofluid in Field Reversible Thermal Connector Interface

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Citation


Abstract

The usage of wet contact methods can reduce the overall thermal resistance between two surfaces. Yousif et al. [1] suggested a new method for reducing generated heat in an avionics chassis by using a field reversible thermal connector that utilizes ferrofluid as interface wet material. However, in order to maintain the ferrofluid in place and avoid spilling, strong neodymium magnets were introduced in grooves parallel to the card so that the ferrofluid is hold in place. Although magnets have shown positive results by maintaining the ferrofluid in place, the effect of the magnetic field on the electronic components is concerned. Therefore, the size, place and strength of the magnets are to be identified to avoid unnecessary interference. In this paper, the magnetic analysis for this type of thermal connectors is discussed to estimate the effect of magnetic field on electronic components.

1. Introduction

There are many kinds of permanent magnets that are different in their properties and chemical compound. Modern permanent magnets are listed below:

a) Ceramic Magnets:
   One of the best known types of magnets. A ceramic or ferrite magnet is mainly of Iron Oxide and Barium Carbonate (BaCO\textsubscript{3}) or strontium Carbonate (SrCO\textsubscript{3}). This type of magnets is cheap and easy to manufacture. However, it is brittle and difficult to shape. [2]

b) Alnico Magnets:
   Alnico is an abbreviation of the basic contents of this magnet: Aluminum, Nickel and Cobalt [3]. They are the second strongest magnets after rare-earth magnets.

c) Samarium-Cobalt Magnets:
   Abbreviated as (SmCo), these magnets have more desirable properties than Alnico and Ceramic magnets. These magnets can resist heat up to 300°C. [4]

d) Neodymium magnets:
   Neodymium magnets are one of the earth’s strongest magnets [5]. The development of such magnets took place in the sixties of the last century and the first production of neodymium magnets was by Sumitomo Special Metals in Japan in 1983 [6]. The basic chemical formula for a neodymium magnet is Nd\textsubscript{2}Fe\textsubscript{14}B. The general reaction that produce this kind of magnets is [7].
The reaction takes place in vacuum induction furnace and yields in higher ratio of the formula, this can happen since the final product contains nonmagnetic forms of Nd and B together with magnetic Nd$_2$Fe$_{14}$B.

Afterwards, the resulting material is jet milled into very small particles (3 micrometer) and pressed in a die-upsetting technique, which converts the powder into a solid with the preferred magnetization direction at a temperature about 725°C. The next step is to place the solid in a second die to compress it to a wider shape about half of the original height in order to align the preferred direction of magnetization parallel to the pressing direction. Then, the solids are sintered at high temperatures around 1080°C so that the particles adhere to each other. The sintered magnets are then machined to the required shape and electroplated with three layers: Nickel, Copper, and Nickel in order to protect the magnets from the loss of magnetization due to corrosion. Finally, magnets are ready to be magnetized. Although they have a preferred magnetic direction, they are not magnetized yet. The process is to expose the magnets to very strong magnetic field for short period of time. The magnetizing device uses banks of capacitors and huge voltage to supply strong current for short period [8, 9]. These magnets are used in this research due to their distinct properties.

2. Mathematical Analysis

In this analysis, one side of the cooling block will be studied since the other side is identical. One side includes magnets and ferrofluid that is being attached to the Aluminum wall.

From the material safety and data sheet for the EFH1 ferrofluid provided by Ferrotech [10], the density of the ferrofluid is (1210 kg/m$^3$). From experiments, it was shown that one cubic centimeter of ferrofluid is enough for each side of the cooling block. By simple calculations, we find that the weight of this ferrofluid is:

$$m_f = 1210 \times 1 \times 10^{-6} \text{ kg}$$

$$m_f = 1.21 \times 10^{-3} \text{ kg}$$

The figure below shows mechanical analysis for the system:

![Figure 1. Forces Acting upon Ferrofluid.](image)

The ferrofluid is lifted up due to both the magnetic force component and the surface tension force.

The equation below puts the description above into mathematical equation:

$$m_f \times g = F_{ST} + F \sin \theta$$

Where $F_{ST}$ is the force of the surface tension. Franklin [11] used a tensiometer to measure the surface tension of the EFH1 oil based ferrofluid and found it to be 0.0258 N/m.

Matsch [12] explain a method to calculate the magnetic force (F) with respect to the field density. The equation that Matsch had found is:

$$F = \frac{AB^2}{2 \mu_0}$$
Where,
A is the cross sectional area that the magnetic lines pass through.
B is the magnetic field intensity, measured in Tesla
\(\mu_0\) is the permeability of vacuum, which is \((4\pi \times 10^{-7})\) h / m.

Reorganizing the aforementioned equations together, \(B = 5.38 \times 10^{-3}\) Tesla, the least required magnetic field density to hold the ferrofluid in place.

Since

\[ H = \frac{B}{\mu_0\mu_r} \]  

Then \(H = 4285.95\) A/m

This means that at any field strength larger than 4285.95 A/m the ferrofluid will be pulled upward against gravity. The H field can be increased or decreased, depending on the magnets being used. The following data shows the effect of using different kinds of magnets of the same shape and dimensions mentioned earlier in chapter two but with different H field strengths:

<table>
<thead>
<tr>
<th>H Field (A/m)</th>
<th>B Field (Tesla)</th>
<th>Magnetic Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8000</td>
<td>0.01</td>
<td>0.096</td>
</tr>
<tr>
<td>7000</td>
<td>0.0087</td>
<td>0.074</td>
</tr>
<tr>
<td>6000</td>
<td>0.0075</td>
<td>0.054</td>
</tr>
<tr>
<td>5000</td>
<td>0.0062</td>
<td>0.037</td>
</tr>
<tr>
<td>4285.95</td>
<td>0.0053</td>
<td>0.027</td>
</tr>
<tr>
<td>3000</td>
<td>0.0037</td>
<td>0.013</td>
</tr>
<tr>
<td>2000</td>
<td>0.0025</td>
<td>0.006</td>
</tr>
<tr>
<td>1000</td>
<td>0.0012</td>
<td>0.001</td>
</tr>
<tr>
<td>100</td>
<td>0.0001</td>
<td>1.51 \times 10^{-5}</td>
</tr>
<tr>
<td>50</td>
<td>6.2E-5</td>
<td>3.7 \times 10^{-5}</td>
</tr>
</tbody>
</table>

The table above was generated by picking different values for the magnetic force and finding the corresponding B field and H field from equations 29 and 30. Below is the graph for these results:

![Figure 2. H-Field versus B-Field. Any Value to the right of the vertical line can pull the ferrofluid upward.](image2)

![Figure 3. H-Field versus the Magnetic Force. Again, the values to the right of the vertical line can pull the ferrofluid upward.](image3)
3. Numerical Analysis

The numerical analysis can be useful to show the magnetic density distribution, the direction of the magnetic field, and to calculate the coercive force ($H_c$) property for the magnet necessary to hold the ferrofluid in place. The magnets that had been used in the experimental analysis were purchased from K&J Magnetics. The seller lists in its website that the coercive force for N52 neodymium magnet is larger than 11.2 KOe or 900 A/m. Thus, it is unclear what value should the coercive force be in order to hold the ferrofluid; however, the numerical analysis might provide an estimation for this magnetic property.

In this research, Finite Element Method Magnetics (FEMM) was used to carry out the analysis because of its ability of solving magnetics problems. The figure below shows the main screen for FEMM:

![Finite Elements Method Magnetics (FEMM) Main Screen.](image)

3.1. Modeling

In order to model the device, two rows of magnets are required to model so that it matches the experimental setup. The following model was generated:
3.2. Results and Post Processing

After meshing and solving the system, the results for different coercive forces were collected and shown below starting with the minimum coercive force anticipated by the supplier:

<table>
<thead>
<tr>
<th>Trial No.</th>
<th>Coercive Force (A/m)</th>
<th>Magnetic Flux Density at Ferrofluid Location (T)</th>
<th>Percentage difference from analytical solution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>900</td>
<td>$1.7 \times 10^{-4}$</td>
<td>96.8401487</td>
</tr>
<tr>
<td>2</td>
<td>1200</td>
<td>$2.4 \times 10^{-4}$</td>
<td>95.53903346</td>
</tr>
<tr>
<td>3</td>
<td>3000</td>
<td>$5.9 \times 10^{-4}$</td>
<td>89.03345725</td>
</tr>
<tr>
<td>4</td>
<td>10000</td>
<td>$2.0 \times 10^{-3}$</td>
<td>62.82527881</td>
</tr>
<tr>
<td>5</td>
<td>11000</td>
<td>$2.2 \times 10^{-3}$</td>
<td>59.10780669</td>
</tr>
<tr>
<td>6</td>
<td>15000</td>
<td>$3.0 \times 10^{-3}$</td>
<td>44.23791822</td>
</tr>
<tr>
<td>7</td>
<td>19000</td>
<td>$3.7 \times 10^{-3}$</td>
<td>31.2267658</td>
</tr>
<tr>
<td>8</td>
<td>24000</td>
<td>$4.7 \times 10^{-3}$</td>
<td>12.6394052</td>
</tr>
<tr>
<td>9</td>
<td>25000</td>
<td>$5.0 \times 10^{-3}$</td>
<td>7.063197026</td>
</tr>
<tr>
<td>10</td>
<td>26000</td>
<td>$5.31 \times 10^{-3}$</td>
<td>1.30115242</td>
</tr>
<tr>
<td>11</td>
<td>26500</td>
<td>$5.44 \times 10^{-3}$</td>
<td>1.15241636</td>
</tr>
<tr>
<td>12</td>
<td>27000</td>
<td>$5.6 \times 10^{-3}$</td>
<td>4.089219331</td>
</tr>
<tr>
<td>13</td>
<td>30000</td>
<td>$6.0 \times 10^{-3}$</td>
<td>11.52416357</td>
</tr>
</tbody>
</table>

It is clear that trial eleven has the lowest error percentage and the best match to the analytical values. We will pick trial eleven as the numerical value for the least coercive force required to produce a B-field strong enough to equalize the surface tension and weight of ferrofluid. The relation between the coercive force and the flux density is shown below:

From figure 7 above, the relation looks linear and proportional between the coercive force and the magnetic flux density. The intersection of the vertical and horizontal lines with coordinates represents the least coercive force and its B field required to equalize the ferrofluid forces. The coercive force is important since it is one of the properties of the magnets and represents how strong the magnets are.

The figures below show the magnetic flux density distribution and direction for a coercive force of 26500 A/m...
Figure 8. Magnetic Flux Density Distribution.

Figure 9. Vector representation for the Flux Density, showing its direction.
4. Conclusion

Figures 10 and 11 show that the magnetic force drops considerably soon after leaving the magnets. This behavior is preferred since the magnetic field will have negligible effect on electronic components of the card. Figure 9 and 8 shows the direction of the flux density, explaining why the magnetic force drops since most of the field is horizontal.

In this research, the magnetic intensity and location were optimized. However, the shape and size of the magnets were not studied. Different shapes of magnets may have different effect on the magnetic field direction. Also, different sizes of magnets with different length may affect the magnetic field distribution, too.

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References


