Simulation of Thermal Distribution on a Ferrofluid Bimetallic Overload Relay

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Abstract—This article discusses a thermal model of overload relay which uses magnetic fluids, or commonly called as ferrofluid, in its bimetallic strip construction. The use of ferrofluid aims to improve the performance of bimetallic thermal strip. It is purposed to produce more accurate and faster response. Cases study has been undertaken by using various heating times of the relay. Observation on the resulted thermal distribution has been carried out using finite-element theory-based simulation software. The study was conducted by comparing bimetallic strip using ferrofluid as thermal conductor to that using air as thermal conductor from the heat sources. It was confirmed that the bimetallic strip using ferrofluid as thermal conductor indicated a better thermal response than that using air due to more even thermal distribution.

Keywords— bimetallic strip, ferrofluid, FEMM, thermal overload relay

I. INTRODUCTION

Relay is an electric switch, containing a part responsible for producing the control signal and another part dealing with the contact. Various types of relay are widely used in industry. An electromechanical relay is a device consisting of 2 main parts, namely electromagnetic coil and mechanical switch. It uses electromagnetic principles to move the switch contacts so that a small electric current of low power can conduct higher-voltage electricity, such as overload relays [1].

Many designs of thermal overload relays use a strip of bimetal as the heat-responsive element, which is deflected by heat. One of the overload relay problem is the slow response to heat of the bimetal strip under certain conditions. Consequently, the bimetal strip circuit will act too late in breaking an electrical circuit, causing an undesired large amount of current to continue to flow in the circuit. The current will result in overheating of component in the circuit and may damage the insulation, produce fire, or even harm the users [2], [3].

This paper discusses the heating phenomenon in a relay, in order to develop a relay with high reliability, low cost and low energy consumption. An observation is to be made on a smart relay containing magnet of liquid property, called as ferrofluid. Ferrofluid material can moves through very small place and adapts to any geometry [4]-[6]. Various heating times are considered in observing the resulted thermal distribution using finite-element theory-based simulation software.

II. DESIGN AND SIMULATION METHOD

A. Thermal Overload Relay

Overload is an electrical phenomenon that occurs due to a very large current which may damage an electric equipment or components in an electrical circuit [7]. There some protection devices being dedicated to clear different types of overload, including overload relay. Overload relays may be in a form of thermal overload relay or magnetic overload relay.

Thermal overload relay is a switching equipment that is sensitive to temperature. It will open or close the contactors when the temperature exceeds the specified limit determined in an electrical control equipment. It serves to protect the electrical circuit or electrical components from damage because of overload [8], [9].

B. Bimetallic Strip

Bimetallic strip is a part of the thermal overload relay that serves to convert a temperature change into mechanical energy. This bimetallic strip consists of 2 metals with different values of expansion coefficient [10]. Fig. 1 explains the working principle of a bimetallic strip when exposed to thermal expansion.

![Fig. 1. Bimetallic Strip Structure](image)
C. Ferrofluid

Ferrofluid, being also known as ferromagnetic fluid, is a liquid which becomes strongly magnetized in the presence of a magnetic field, as shown in Fig. 2. It is a thick liquid consisting of magnetite (Fe₃O₄) flakes of nanometer size. It is dissolved in liquid, and consequently it will be active when being exposed to a magnetic field. Ferrofluid indicates its ferromagnetic properties when the ambient temperature is in normal conditions and eliminates the ferromagnetic properties when experiencing excessive temperature expansion. It is characterized with high magnetization saturation with no remanence [5], [11]. A volume of a ferrofluid usually consists of 5% magnetic solid, 10% surfactant, and 85% carrier liquid with permeability $\mu_r = 5$ [12].

D. Relay Specifications

The ferrofluid relay to be used in simulation was specified to have a high sensitivity to represent quick response to temperature change. The dimension of the bimetallic strip relay was 123 mm, 45 mm, and 66 mm. The coefficient of length expansion of each metal involved in the relay is given in Table I.

Considering the advantage provided by numerical methods, the Finite Element Method Magnetics (FEMM) software was used to simulate the bimetallic strip overload relay and to observe the thermal distribution being caused by various heating treatments. Input voltage and current variables were determined adapting to conditions.

E. Design of the Bimetallic Strip

Two cases of bimetallic strip design were considered. The first one was bimetallic strip construction without ferrofluid, whereas the second one contains ferrofluid. In the bimetallic strip using ferrofluid, as shown in Fig. 3.a, the ferrofluid was placed at the end of the bimetallic strip near to the heat source, which was the iron part directly joined to the electrical connection. In practice, it can be done by dipping the two metal ends of bimetallic strips into the ferrofluid. When the ferrofluid gets heated, it will fill up the empty space between the bimetallic strip and the iron to take the role of thermal conductor.

TABLE I. LENGTH EXPANSION COEFFICIENT OF BIMETALLIC STRIP

<table>
<thead>
<tr>
<th>Metal</th>
<th>Coefficient of Length Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.0000167/°C</td>
</tr>
<tr>
<td>Steel</td>
<td>0.000011/°C</td>
</tr>
</tbody>
</table>

Fig. 3. a. Bimetallic Strip Construction with Ferrofluid, b. Bimetallic Strip Construction without Ferrofluid

The bimetallic strip design without ferrofluid was similar to the bimetallic strip in common overload relays. The air acts as a conductor of heat to the two metals of bimetallic strip conductors which are directly joined to the electrical connection, as shown in Fig. 3.b. The top view of both the bimetallic strips with and without ferrofluid is given in Fig. 4.a and 4.b.

F. Simulation Method

Simulation of thermal distribution on the bimetallic strip relay were to be carried out using the FEMM 4.2 software. Two types of metal, which were copper and steel, have been considered. The value of heat charge $Q$ was obtained through the calculation of power being produced using an electrical circuit with a voltage source $V$ of 12V and a current $I$ of 8A. The generated power represents the heat charge contained in the electrical circuit, as shown using (1).

$$Q = V \times I$$

Calculation of the ferrofluid conductivity $k$ was done using (2).

$$k = \frac{Q \times L}{A \times \Delta T}$$
where $A$ is the surface area of bimetallic strip, $L$ is the thickness, whereas $\Delta T$ represents the temperature change in kelvin unit.

In order to observe the thermal distribution after 300s of heating, calculations were performed using (3) to (6) to determine the value of $T_2$ (final temperature) and $h$ (coefficient of heat transfer) to be used as input values in simulation.

\[
T_2 = \Delta T + T_1 \tag{3}
\]

\[
\Delta T = \frac{q}{m \times c} \tag{4}
\]

\[
T_2 = \Delta T + T_1 \tag{5}
\]

\[
h = \frac{q}{A \times \Delta T} \tag{6}
\]

Calculation of copper and steel masses were determined using their related values of density ($\rho$), volume ($V$), mass ($m$), and specific heat ($c$).

III. RESULTS AND DISCUSSION

A. Comparison of Thermal Distribution on Copper Bimetallic Strip with Ferrofluid and without Ferrofluid

The first simulation case considered was to compare the thermal distribution on copper bimetallic strip using ferrofluid and without using ferrofluid under the heating treatment during 300s, 360s, 420s, 480s, 540s, and 600s. At room temperature $T_1$ of 298.15°K or 25°C, the air thermal conductivity value of 0.023 W/(m.°K) and a ferrofluid thermal conductivity of 0.6501 W/(m.°K) were considered.

The simulation results of thermal distribution on the copper bimetallic strip with and without ferrofluid are given in Fig. 5.a and 5.b. Fig. 5a indicates an increasing temperature on the ferrofluid part. The calculation results of final temperature $T_2$ and coefficient of heat transfer $h$, after other heating durations are presented in Table II.

![Fig. 5. Thermal Distribution of Copper bimetallic strip (a) with, and (b) without Ferrofluid, using FEMM 4.2 after 300s of heating](image)

**TABLE II.** $T_2$ AND $h$ VALUES IN THERMAL DISTRIBUTION OF COPPER

<table>
<thead>
<tr>
<th>time (s)</th>
<th>$T_2$ (°K)</th>
<th>$h$ (W/(m²K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>320.86</td>
<td>17586.7122</td>
</tr>
<tr>
<td>360</td>
<td>325.40</td>
<td>20785.4694</td>
</tr>
<tr>
<td>420</td>
<td>329.94</td>
<td>23889.0863</td>
</tr>
<tr>
<td>480</td>
<td>334.49</td>
<td>26900.1751</td>
</tr>
<tr>
<td>540</td>
<td>339.03</td>
<td>29825.6717</td>
</tr>
<tr>
<td>600</td>
<td>343.57</td>
<td>32666.0239</td>
</tr>
</tbody>
</table>

Simulation results of thermal distribution on a copper bimetallic strip with and without ferrofluid after various heating durations considered are displayed in Fig. 6.a to Fig. 6.f.
Fig. 6. Comparison of thermal distribution on a copper bimetallic strip with and without ferrofluid after the heating duration of a. 300s, b. 360s, c. 420s, d. 480s, e. 540s, and f. 600s.

As can be observed from Fig. 5 and Fig. 6, there is a difference in the resulted final temperature both between the relay with and without ferrofluid, as well as among different heating durations. The temperature values were taken every distance step of 10mm on the metal bar, starting from the heat source. As seen, the temperature on the metal with ferrofluid is higher than that without ferrofluid. Farther the distance, lower also the final temperature.

B. Comparison of Thermal Distribution on Steel Bimetallic Strip with Ferrofluid and without Ferrofluid

The second case of simulation was conducted using steel bimetallic strip. The simulation results of thermal distribution on the steel bimetallic strip with and without ferrofluid after 300s of heating are given in Fig. 7.a and 7.b. The calculation results of final temperature $T_2$ and coefficient of heat transfer $h$, after other heating durations of the steel bimetallic strip relay are presented in Table III. Simulation results of thermal distribution on a steel bimetallic strip with and without ferrofluid after various heating durations considered are displayed in Fig. 8.a to Fig. 8.f.

Fig. 7. Thermal Distribution of steel (a) with, and (b) without Ferrofluid, using FEMM 4.2 after 300s of heating.

<table>
<thead>
<tr>
<th>time (s)</th>
<th>$T_2$ (°K)</th>
<th>$h$ (W/(m²K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>320.61</td>
<td>17601.7601</td>
</tr>
<tr>
<td>360</td>
<td>325.40</td>
<td>20806.7429</td>
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<tr>
<td>420</td>
<td>329.59</td>
<td>23916.0092</td>
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<tr>
<td>480</td>
<td>334.08</td>
<td>26941.0664</td>
</tr>
<tr>
<td>540</td>
<td>338.57</td>
<td>29858.6333</td>
</tr>
<tr>
<td>600</td>
<td>343.07</td>
<td>32717.9778</td>
</tr>
</tbody>
</table>
Like what have been observed during the simulation using copper, as can be observed from Fig. 7 and Fig. 8, there is also a difference in the resulted final temperature both between the relay with and without ferrofluid, as well as among different heating durations. The temperature values were taken every distance step of 10mm on the metal bar, starting from the heat source. As seen, the temperature on the metal with ferrofluid is also higher than that without ferrofluid. Farther the distance, lower also the final temperature.

C. Comparison of Thermal Distribution on Copper and Steel Bimetallic Strip with and without Ferrofluid

The comparison of thermal distribution on the copper and steel bimetallic strips with and without ferrofluid after heating duration of 600s is presented in Fig. 9. As seen, longer the heating time, higher the final temperature will be. The use of steel will result in higher temperature than copper. The use of ferrofluid will also result in higher temperature. It confirms that steel is better thermal conductor than copper. The use of ferrofluid also increase the thermal conductivity in the bimetallic strip, making it preferable for relay application.

IV. CONCLUSIONS

The analysis on the simulation results of thermal distribution on bimetallic strips brought to some conclusions that longer the exposure to heat source, higher the final temperature in bimetallic strip to reach. Different types of metal used in bimetallic strip behave differently in propagate temperature. The use of ferrofluid facilitates the propagation of temperature on the bimetallic strip, enabling quicker thermal response being useful in relay application.

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