Introduction

Liquid (e.g., silicone oil, mineral oil)-based fluids mixed up with surfactants and magnetic particles having dimensions ranging between 0.1 and 100 µm are known as fluids or magnetorheological suspensions (MRS). An MRS can be obtained by various means [1-10].

A remarkable property of an MRS is that its fluidity can be modified from the value of the intensity of an external magnetic field [11]. This property finds utilization in various applications [12-14].

An MRS mixed up with graphite micro-particles exhibits a modified conductivity function of the intensity and direction of the magnetic field intensity vector. Based on this phenomenon, property sensors with destinations specified in Refs. [15,16] have been achieved in MRS.

It has been shown [17] that the thickness of the oil layer between the magnetic dipoles, oriented according to the magnetic field lines, defines the value of the MRS electric conductivity. In what follows, we set ourselves to show that the thermal conductivity of an MRS is influenced by the intensity of the external magnetic field, for well-defined values of the thermal field.

Magnetorheological Suspension

Production of an MRS is achieved by means of an experimental installation and a method, both of which are described in Ref. [3].

A mixture consisting of:

- Fe₃(CO)₉ powder (granulation: 4.5 ~ 2 µm; quantity: 0.082 kg ± 5%)
- Aneron/Merck-type mineral oil (quantity: 0.025 kg ± 5%);
- Stearic acid (quantity: 0.002 kg ± 2%).

The mixture so formed is homogenized and treated thermally for 1800 s at a temperature of 510 K ± 10 %.

A mineral oil-based MRS and iron micro-particles were obtained (Figure 1).

The diameter of the particles from Figure 1 was measured using a laser granule-meter (Analysette 22, type). The diameters of the micro-particles ranged between 1.8 and 3.8 µm (Figure 2).

MRS saturation magnetization is 475 kA/m for intensities of magnetic field H ≥ 00 kA/m (Figure 3). In magnetic fields with intensities of up to H = 100 kA/m (Figure 3), the relative permeability of the MRS is \( \mu_r = 3 \).
Thermal Conductivity of a Magnetoreheological Suspension Based on Mineral Oil and Iron Micro-Particles

**Figure 1.** Iron micro-particles in mineral oil (dilution 1:10).

**Figure 2.** The cumulative frequency $v$ plotted as a function of the diameter $d$ of the iron micro-particles ($\overline{d}$ - mean diameter; $\sigma$ - standard deviation).

**Figure 3.** MRS magnetization $M$ plotted as a function of the intensity $H$ of the external magnetic field (measuring apparatus: magnetometer with vibrating probe, VSM 880-type).

**Experimental Device**

The overall configuration of the experimental device meant for the study of heat propagation in MRS, is shown in Figure 4. It includes:

- the electromagnet 1 with the power source $S_1$ and the ampermeter $A_1$;
- the measurement cell 2 with the power source $S_2$, the ampermeter $A_2$ and the digital thermometers $T_1$, $T_2$, and $T_3$, respectively
- the gauss meter $G$ with the Hall sonde 3.

Between the poles of the electromagnet 1, the intensity $H$ of the magnetic field can be varied continuously between 5 kA/m ± 1 % and 110 kA/m ± 1 %, for $0.02 \leq 1 (A_{dc}) \leq 0.75$. The measurement cell 2 has the heat propagation axis Ox (Figure 4). Overall, the configuration of the cell is that presented in Figure 5.

The cylindrical body of the cell is made of polyamide. The bases of the cylinder are the lid 2 (made of polyamide) and the radiator 3 (made of copper). Inside the cell are fixed, along the direction of the Ox axis as against
Experimental Results and Discussion

The study of heat propagation in MRS is performed by means of the experiment device in Figure 4. In the measurement cell, the quantity of the MRS was 0.012 kg ± 10%.

The MRS is obtained through thermal decomposition in mineral oil with stearic acid using a method described previously [3].

The time after the MRS had become a sediment was ca. about 2000 s. To avoid sedimentation of the MRS, the measurements were obtained in a time range of up to 100 s. The magnetization characteristics of the MRS are those displayed in Figure 3. The power dissipated by the resistance R is 7.5 W ± 1.2%. The temperatures displayed by the digital thermometers were recorded every 5 s. Their variation with respect to time is shown in Figures 6 and 7.

We observe in Figure 6 that heat propagation in the MRS occurs in a non-stationary manner. In Figures 6 and 7, for x=0.014 m ± 10%, there results $T_i = T_0 = 296$ K ± 3% and equal to that of the surrounding medium. Thus, the MRS can be assimilated to a semi-infinite medium.

The thermal conductivity $\lambda$, the specific heat at constant pressure $C_p$ and the density $\rho$ of MRS are considered constant along the direction of the axis at temperature $T_i$ and fixed times $t_i$.

Following these considerations, the equation of thermal conductivity of the MRS along the direction of the axis Ox, is

$$\alpha \frac{\partial^2 T_i}{\partial x^2} = -\frac{\partial T_i}{\partial t}, \text{ for } 0 \leq x \leq \infty$$

(1)

where $\alpha$ is the thermal diffusiveness coefficient. The value $\alpha$ is obtained from the formula

$$\alpha = \frac{\lambda}{\rho C_p}$$

(2)

where the notations used are the known ones. The initial and limit conditions that characterize the semi-infinite media are

$$T_i = T_0 \text{ at } t_i = 0 \text{ and } x > 0$$

$$T_i = T_{1i} \text{ at } t_i > 0 \text{ and } x = 0$$

$$T_i = T_0 \text{ at } t_i > 0 \text{ and } x \to \infty$$

(3)

The condition

$T_i = T_0 \text{ at } t_i = 0 \text{ and } x > 0$ indicates that, for semi-infinite media after a certain time and a great distance from the heated surface, the temperature stays practically constant and at the initial value.

The thermal conductivity equation, under these conditions, will allow particular solutions of the form

$$T_i = A + B \cdot \text{erfc} \left( \frac{x}{2\sqrt{\alpha t_i}} \right)$$

(4)

where A and B are constants and $\text{erfc} \left( \frac{x}{2\sqrt{\alpha t_i}} \right)$ is the error function complementary.

From the first condition of the group (3) and Eq. (4), we obtain $A = T_0$; from the second condition of the group
Figure 8. The $\beta$ function of $t_i$ and $H$ as parameter.

Figure 9. The $\alpha$ function of $t_i$ and $H$ as parameter.

(3) and Eq. (4), it is obtained.

Then, the solution of the Eq. (1) becomes:

$$T_i = T_0 + (T_{i0} - T_0) \cdot e^{\psi c \left( \frac{x}{2\sqrt{a_{t_i}}} \right)}$$

For $x = x_2$, from Eq. (5), the function is

$$\beta = \frac{T_{2i} - T_0}{T_{i0} - T_0} = e^{\psi c \left( \frac{x}{2\sqrt{a_{t_i}}} \right)}$$

The temperatures $T_{i0}$, $T_{2i}$, and $T_0$, corresponding to $H$ and $t_i$ (Figures 6 and 7), are introduced in the first equality in (6) and we obtain the $\beta$ function of $t_i$ and $H$ as parameter, as shown in Figure 8.

For values of $\beta$ in Figure 8 and $x_2 = 0.010$ m, from the argument of the function, $\alpha$ is obtained. The variation of $\alpha$ by $t_i$ for $H$ as parameter is shown in Figure 9.

It is observed from Figure 9 that the values of $\alpha$, of the MRS, increase considerably in the first 12.5 s since the application of $H$, as compared to the values of MRS in the absence of the magnetic field. No net differences are observed, however, between $\alpha$ at $H = 50$ kA/m and $H = 100$ kA/m.

At thermal balance, the relation $\eta P_{t_i} = m C_p \Delta T_i$ takes place, wherefrom

$$C_p = \frac{\eta P_{t_i}}{m \cdot \Delta T_i}$$

Figure 10. The $\Delta T_i$ function of $t_i$ and $H$ as parameter.

For $\eta \approx 0.9$, $P = 7.5$ W, $m = 0.012$ kg, and $\Delta T_i$ in Figure 10, from Eq. (7) the variation of $C_p$ by $t_i$ results from Figures 6 and 7, and is presented in Figure 10.

Figure 11. The $C_p$ function of $t_i$ and $H$ as parameter.

The formula for the calculation of thermal conductivity results from the relation (2), and is of the form

$$\lambda = \alpha \cdot \rho \cdot C_p$$

where the notations used are the known ones.
The values of $\alpha$ in Figure 9 and, respectively, the values of $C_p$ in Figure 11 are introduced in Eq. (8), and a function of $t_i$ and $H$ as parameter (Figure 12) are obtained.

We notice that, on the application of the magnetic field, the temperature drop, $\Delta T_j$, on the MRS cylinder ($\phi \times 10 \times 10$ mm) diminishes by the application of the external magnetic field. The diminution of $\Delta T_j$ is considerably influenced by $H$ (Figure 12). The specific heat $C_p$ (Figure 11) in the presence of the magnetic field increases considerably with the increase of the value of $H$; thus:

- $C_p = 1.75$ J/Kg K at $t_i = 60$ s and $H = 0$ kA/m;
- $C_p = 3.25$ J/Kg K at $t_i = 7.5$ s and $H = 50$ kA/m;
- $C_p = 5.20$ J/Kg K at $t_i = 12.5$ s and $H = 100$ kA/m.

The MRS in a magnetic field transforms into a Bingham solid. Through heating, due to thermal agitation and to thermal convection currents, solid-liquid phase transformations take place, depending on $H$ and $t_i$.

It is observed from Figure 11 that the phase transformations occur at

- $t_i = 7.5$ s for $H = 50$ kA/m and, respectively, at
- $t_i = 12.5$ s for $H = 100$ kA/m.

For $t_i = 60$ s and $50 \leq (kA/m) \leq 100$, it results from Figure 11 that $C_p$ converges toward the same value (close to the value of $C_p$ MRS, at $H = 0$ kA/m).

The thermal conductivity of the MRS is influenced considerably by the intensity of the magnetic field $H$ and the time $t_i$ of MRS heating (Figure 12). Net differentiations of the values of $\lambda$ at $H = 50$ kA/m and of the values of $\lambda$ at $H = 100$ kA/m are noticed for MRS heating times of up to $t_i = 12.5$ s.

For $t_i \geq 0$ s, however, $\lambda$ is independent of $H$ and has values identical with those of MRS in the absence of the external magnetic field.

If the condition is set that the difference between the temperatures $T_{1i}$ in the presence and absence of the magnetic field should be at least 2.5 K, then, from Figures 6 and 7, it is obtained that the mean temperature

$T = 0.5 \left( T_{1i} + T_{2i} \right)$ in the MRS is, at most, 316 K. For $T = 316$ K, the results from Figures 6 and 7 suggest a heating time of the MRS of up to $t_i = 60$ s.

Corresponding to the pairs of values $(T, t_i)$, from Figures 9, 11, and 12 there results:

- the variation of $\alpha$ by $T$ and $H$ as parameter, in Figure 13;
- the variation of $C_p$ by $T$ and $H$ as parameter, in Figure 14 and
- the variation of $\lambda$ by $T$ and $H$ as parameter, in Figure 15.

From Figures 13, 14, and 15 we observe that $\alpha$, $C_p$, and $\lambda$ have a slow variation by $t$ for $H = 0$ kA/m. For $296 \leq T (K) \leq 302$, and $50 \leq (kA/m) \leq 100$, the values of $\alpha$, $C_p$, and $\lambda$ are considerably increased, relative to the corresponding ones of MRS for the case $H = 0$ kA/m.

For $H \neq 0$, but fixed, however, beginning with $T = 303$ K, the values of $\alpha$, $C_p$, and $\lambda$ decrease by $T$ and become equal to those of the MRS for $H = 0$ kA/m and $T > 316$ K.

The temperature drop ($\Delta T_i$) over the distance $x_2 = 0.010$ m, creates, in the MRS, perpendicular thermal gradients on the magnetic field lines.

The value of the thermal gradient, $\Delta T_i/x_2$ (Figure 10),
for $x_2 = 0.010$ m, ranges between

- 200 and $3250 \text{ K/m}$ at $H = 50 \text{ kA/m}$ and, respectively,
- 250 and $2750 \text{ K/m}$ at $H = 100 \text{ kA/m}$.

With the increase of the temperature $T$, an intense Brownian movement is generated in the MRS, and phenomena of diffusion of the magnetic dipoles [17,18] occur.

On the other hand, the existence of the thermal gradients leads to the appearance of thermal convection in the MRS. We consider that, following thermal convection, a transport of the substance takes place, in the sense of the axis Ox in Figure 4.

The thermal conductivity of the MRS is caused by both components: the carrier liquids and the iron micro-particles. In a magnetic field, the forming of magnetic dipole chains shunts the thermal conductivity of the carrier liquids. Thus, applying the magnetic field leads to an increase in the thermal conductivity of the MRS. The increasing of the temperature of the MRS increases the thermal agitation of the dipoles. The distance between the magnetic dipoles increases [18] and, by default, $\lambda$ decreases at $H = ct$ (Figure 15).

**Conclusions**

1) The experimental device in Figure 4 allows the study of the heat propagation in the MRS as a semi-infinite medium (Figures 6 and 7);
2) The temperature drop $\Delta T_i$ in the MRS (Figure 10) is influenced considerably by the intensity of the external magnetic field;
3) The thermal conductivity of the MRS (Figures 12 and 15) is influenced considerably by the intensity of the external magnetic field and by the temperature $T$, for their well-defined values.

**Acknowledgments**

The author thanks Professor Papp Erhardt, Professor Constantin Cheverean, and Victor Cuiteau from West University of Timisoara for fruitful discussions on the topic and language used. Also, the author thanks Oana Marinica from “Politehnica” University of Timisoara for the magneto-metric measurements and Farkas Attila from INCDEMC-Timisoara for the granulometric measurements.

**References**