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INVESTIGATIONS ON CHARACTERIZATION OF HONGE OIL BASED MAGNETORHEOLOGICAL FLUIDS

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ABSTRACT

Magnetorheological (MR) fluids belong to the class of smart materials which mainly consist of carrier liquid and suspensions. Flow characteristics of these fluids are an important aspect to determine their suitability for various applications. Mineral oils, silicon oil, synthetic oils etc. are commonly used carrier liquids. Some of these liquids are neither-biodegradable, nor environmental friendly and of high cost. In this work, four different bio-degradable vegetable oils are considered for their suitability as carrier liquid. After evaluating basic properties relevant for MR fluids for all oils, one among that was selected as carrier liquid and then stability analysis at higher temperature was carried out. In the second phase of experimentation, two combinations of MR fluids have been prepared indigenously from the selected carrier liquid for examining flow characteristics of the MR fluid using a capillary viscometer experimental setup. It was observed that, at low magnetic field, the flow rate was not changed, but as it increased the flow rate gradually decreased and finally completely stopped with further increase in magnetic field. At this condition the theoretical yield stress are also determined.

Keywords: *Magnetorheological Fluids, Biodegradable Carriers, Honge Oil, Flow Characteristics.*

1. Introduction

Magnetorheological (MR) fluid was first developed by Jacob Rabinow [1] and then was used in his magnetic clutch. MR fluid used by him consisted of 9 parts by weight of carbonyl iron as suspended particles and one part by weight of silicon oil, petroleum or kerosene as carrier fluids. In volume terms the proportions of carrier liquid used in MR fluid of recent days are ranging from 60 to 80%. Hence if MR fluid technology is used in large scale for various applications, the total quantity of carrier fluid needed will be quite large. It was estimated that the quantum of fluid's volume required just for the use in damper of an automotive platform model alone is in the order of 10^5 liters/year [2]. Depending on the percentage of suspensions, this amount corresponds to 2-4X 10^5 kg/year of MR fluid per day. Considering other applications of MR fluid like brakes, clutches, suspensions, civil structures, machining etc. the volume of carrier liquid needed multiplies.

Carbonyl iron particles have been used widely as suspension in MR fluid because of its high magnetic permeability, low remnant magnetization and common availability. These suspensions exhibit a fast and very strong response to the action of external magnetic fields, become polarized and aligned themselves like a chain in the direction of magnetic field. This abruptly transforms the MR fluid from fluid-like into solid-like state by showing changes in rheological properties such as yield stress and enhancement of viscosity. In addition to carrier liquid and suspension, a wide variety of additives similar to those found in commercial lubricants are also added into MR fluids [3]. Since the discovery of MR fluid, various types of these fluids have been developed using different carrier liquids.

2. Literature Review on Carrier Liquids and Viscometers

The basic function of carrier liquid is primarily to provide a medium for magnetically active particulates to remain suspended during the absence of magnetic field and to facilitate realignment once magnetic field is applied. But the type of carrier liquid used in the MR fluid may differ. In the literature, different carrier liquids have been considered in the preparation of MR fluid and some of them are detailed here.

They are Polyvinyl-n-butyl and naphthol-thickened kerosene [4] in passive damping system, water with a stabilizer in MR finishing of a workpiece [5] and water-in-oil emulsion with dispersions of magnetic particles [6]. Silicon oil has been used as a carrier liquid to study the rheological properties of a MR fluid [7] and also in statistical modeling of MR damper [8]. Three different combinations of carrier liquids and suspensions [9] are also used; such as magnetizable particles in synthetic oil, magnetizable particles in water and nickel ferrite particles in organic liquids, to study the behavior of MR fluid in squeeze mode. Use of white and light grade mineral oils [10] as carrier liquids with

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submicron particles of fumed silica was reported in reducing sedimentation. A viscoplastic media with paraffin liquid [11] as a carrier liquid and grease as the additive was used in super finishing of hard materials. In addition to that, semi-synthetic oil, lubricating oil, glycol etc, were also been used as carrier liquids. However mineral oils are very widely used as carrier liquids.

Being a principal element, carrier liquid should possess certain properties to act as a disperse media which in turn influences the properties of MR fluid. Among those desirable properties of carrier liquid, few are highlighted [12] here i.e. inactive with magnetic material present in the MR fluid as well as the component of the devices in which the fluid has been filled. Next the stability of carrier liquids at elevated temperature to obtain the overall thermal stability of MR fluid is also important. Apart from these, the other desirable properties of carrier liquid are listed in Table 1. Also some carrier liquids and their properties, and a few commercially available MR fluids [13, 14, 15, 16] are listed in Table 2 and 3 respectively. Commercial MR fluids satisfy major requirements, but are costly. However, selection of carrier liquid for a particular application is based on desirable properties of MR fluid. MR fluids have been used in different applications and they must possess several properties, which are greatly influenced by property of carrier liquids.

Table 1: Desirable Properties of Carrier Liquids

1. High flash point temperature.
2. High fire point temperature.
3. High boiling temperature.
4. Low freezing point temperature.
5. Low vapor pressure at elevated temperatures.
6. Low viscosity at room temperature.
7. Low variation of viscosity with temperature.
8. Preferable viscosity at operating temperature.
9. Minimum off-state viscosity.
10. Bio degradable.
11. Environmental friendly.
12. Abundantly available.

Hence prior knowledge of carrier liquid properties like flash point, fire point, pour point, cloud point temperatures, density, viscosity, stability etc, are important for use in different applications. For example, if these MR fluids are used in a damper of the landing gear of an aircraft, the operating temperature can be as high as 50°C at one geographical place and as low as 0°C or less at another. Flash and fire point are temperatures at which liquid produces smoke and catches fire respectively and give an idea about the maximum operating temperature for MR fluid. The pour point temperature is the minimum temperature of a carrier liquid after which on decreasing the temperature, the liquid ceases to flow whereas cloud point is the temperature at which a cloud or hazes of crystals appear in the carrier liquid. These give an idea about the minimum operating temperature of MR fluid and its use in selected applications. Next, density, which is a relative term, represents the heaviness of the liquid with respect to water. A denser carrier liquid is preferred to overcome the sedimentation due to density mismatch, of high density suspension present in the MR fluid. Then, the viscosity, which is highly temperature dependent, greatly influences the flowability of MR fluid. Viscosity of MR fluid also depends on the magnitude and direction of the applied magnetic field, and on shear rate.

Table 2: List of Commonly used Carrier Liquids and

Properties/ Carrier liquids	**Silicon oil**	**Mineral oil**	**Water**	**Polar organic liquids- Glycol (Ethylene glycol**	**Kerosene**
Flash point (°C)	>300	204	NA	111	37-65
Boiling point °C	>200	393	100	197.3	150-300
Vapor pressure (mm of Hg at 25°C)	<5	<0.5	24.3	*0.06	---
Viscosity (p-s) at 25°C	0.45	**<0.028	0.001	0.0161	0.002
Specific gravity (at 25°C)	0.963	0.855	***1.001	*1.1	0.82
Density (g/cm^3)	0.96-0.98	0.8	1	1.11	0.817
Environment Friendly	Toxic	Toxic	Non Toxic	Non Toxic	Harmful
Bio-degradable	No	No	Yes	No	No

and their Properties

*@20°C; **@40°C; ***@4°C

Carrier liquid present in the MR fluid influences rheological properties like shear stress, viscosity, yield stress etc, of MR fluid. Different rheological properties of MR fluid are measured using various combinations of viscometers/rheometer and electromagnetic circuits. Electromagnetic circuit provides controlled magnetic field and facilitates to vary the rheological properties of

MR fluid. In the following paragraphs different viscometers and electromagnetic circuits observed in the literature are discussed. Viscosity and normal stresses of MR fluid at high shear rates are measured using a parallel plate rheometer [17] consisting of a pair of circular parallel-plate fixtures and a small gap. This device is more suitable at low magnetic field, whereas rheological properties at high magnetic field (0.8 T) are measured using a strain rate controlled double Couette rheometer comprising of a cup and bob fixtures [7]. But this instrument is not useful for off-state (without magnetic field) and also for very low shear stresses encountered with low field even during on-state (with magnetic field) measurements.

Table 3: Lists of Some Commercially Available MR Fluids, Properties and Cost (Source: Lord Corporation, Technical Data, USA)

MR Fluid/Properties	Viscosity, Pa-s at 40°C (104°F)	Density g/cm^3	Flash point °C	Cost/lt ($)
Hydro carbon based MRF-122EG Magneto-Rheological Fluid	0.042±0.020	2.28-2.48	>150	750
Hydro carbon based MRF-132DG Magneto-Rheological Fluid	0.092±0.015	2.98-3.18	>150	750
Hydro carbon based MRF-140CG Magneto-Rheological Fluid	0.280±0.070	3.54-3.74	>150	750

A rotational rheometer [10] having provision for controlling coil current, and consequently magnetic field strength through software is also used. In this set up homogeneous magnetic field is perpendicular to the flow direction. A parallel-plate (20 mm diameter) measuring system made of non-magnetic metal was used to measure magnetic field. Capillary viscometer having a cylinder, capillary tube, top plate and base plate is used to measure various properties of Newtonian or non-Newtonian fluids under laminar flow conditions. MR fluid flows through a capillary tube having fixed radius, length and a pressure difference between ends of the capillary which is subjected to a magnetic field [11]. Capillary tube is designed such that the ratio of length of the capillary where magnetic field is applied to its radius is to be maintained more than 60. Electromagnetic circuit made of a pair of similar multilayered solenoid type electromagnetic coils generates uniform magnetic field. Each solenoid coil is made up of core, copper wire winding and pole plate. The core and pole plate are made up of cold rolled annealed steel.

Various other viscometer set up are also proposed for measuring magnetorheological properties of MR fluids; viscobalance based on a ball being drawn through a tube [18], a concentric-cylinder rotational viscometer [19], a hydraulic piston operated rheometer [20], a flexible bridge like distributor [21], a plate-plate geometry inserted into a coil [22], a rotational magnetic plate–plate viscometer [4], a double concentric cylinder type viscometer [23], an online measuring system for true flux density using plate–plate rheometer [24] etc.

Hence carrier liquid is an important constituent of MR fluid and plays a major role in obtaining properties of MR fluid for specific applications. Currently MR fluids have been prepared using mineral oil, synthetic oil, silicon oil etc. and have many limitations. Mineral oil is a petroleum product which is neither bio-degradable, nor environmentally friendly and likely to be depleted within few years. Synthetic oils made artificially from compounds other than crude oil, are used as a substitute for petroleum based lubricants. The cost of these oils is three times more than the cost of petroleum oils. Hence it is necessary to identify an alternative carrier liquid and establish its properties in the interest of MR applications. The characterization of this is important before using in the MR fluid.

3. The Present Study-Vegetable Oils as Carrier Liquid and Flow Nature Study of MR Fluid

In the first phase of the present work, four vegetable oils were chosen as alternative carrier liquids. They are renewable, non toxic, bio-degradable, environmentally friendly and abundantly available in nature at low cost. These oils are extracted from seeds which usually store much higher concentration of fatty oil than any other part of the plant. Oil extraction techniques from the seeds are relatively simple and may involve any one of the processes like, (i) pressing, (ii) cooking in water and (iii) solvent extraction. Among the oils chosen for study, two are edible oils; cottonseed and rice bran (Oryza sativa) oils and two are non-edible oils; Jatropha (Jatropha curcas) and Honge (pongamia pinnata). There is no evidence in the literature regarding the use of these oils as carrier liquids. After carrying out basic tests on these chosen carrier liquids, the best one was selected for further investigation on stability.

In the second phase, flow nature of MR fluid prepared from selected carrier liquid has been studied. In some of the MR fluid devices MR fluid is to be in flow condition (viscoplastic state) during working. But as the magnitude of applied magnetic field increases, viscosity increases. With further increase in the magnetic field, viscosity is so high that the fluid may not flow and in such cases it needs external force for the fluid flow. But this situation of non-flowing of MR fluid, due to higher applied magnetic field sometimes causes the working device, a non-performing one. Hence the user should have the knowledge regarding the level of magnetic field that could be applied for best performance of the device. This problem of ceasing of flow due to higher magnetic field was not addressed in the literature; hence there is a necessity to determine the quantum of magnetic field and corresponding yield stress (situation of maximum shear stress) which results in the flow to stop. In the following section the investigations carried out on various carrier liquid chosen and examination of the flow nature of indigenously prepared MR fluid are explained.

4. Methodologies

To select a best carrier liquid and then to evaluate the behavior of MR fluid prepared out of it, the methodology/steps given below .

(a) Evaluating basic characteristics of four chosen carrier liquids to select suitable one.
(b) Evaluating stability of selected carrier liquid with respect to temperature.
(c) Preparation of proposed MR fluid using selected carrier liquid.
(d) Examining the flow nature of MR fluid and to determine the corresponding yield stress.

5. Experiments and Results

5.1 Selection of carrier liquid

Initially all liquids chosen were tested to evaluate the properties namely; flash point, fire point, cloud point, pour point temperatures, density, and viscosity as per ASTM standards. Flash and fire point temperatures were evaluated using Cleveland apparatus (open cup) (ASTM D92). Cloud point and pour point temperatures were determined using controlled temperature ice bath (ASTM D97).

Density was estimated as the ratio of mass to volume by determining the mass and volume. Kinematic viscosity (ν) in Centistokes (cSt) was determined (ASTM D445) using Saybolt Universal Viscometer and corresponding Eq. 1 and Eq. 2 given below. The results are tabulated in Table 4 along with retail market cost of each liquid.

$$\nu=0.226SSU-195/SSU \text{ for } 32 \text{ sec}<SSU>100 \text{ sec} \qquad (1)$$

$$\nu=0.220SSU-135/SSU \text{ for } SSU>100 \text{ sec} \qquad (2)$$

Table 4: Basic Properties of Four Bio-Degradable Vegetable Oils

Name of carrier liquids	Honge oil	Jatro pha	Rice bran oil	Cotton seed oil
Viscosity# (cSt)	51.13	50.46	43.99	35.48
Flash point (°C)	230	255	285	335
Fire point (° C)	282	321	361	375
Specific gravity	0.927	0.918	0.927	*0.925
Density (g/cm^3)	0.932	0.911	0.925	0.896
Type of oil (E/NE)	NE	NE	E/NE	E/NE
Pour Point (°C)	-3	6	-2	-3
Cloud Point (° C)	1	8	1	2
Market cost ($/lt)	0.83	2.0	2.0	1.5

*@15^{0}C, #@40^{0}C Legend: E= Edible, NE= Non-edible

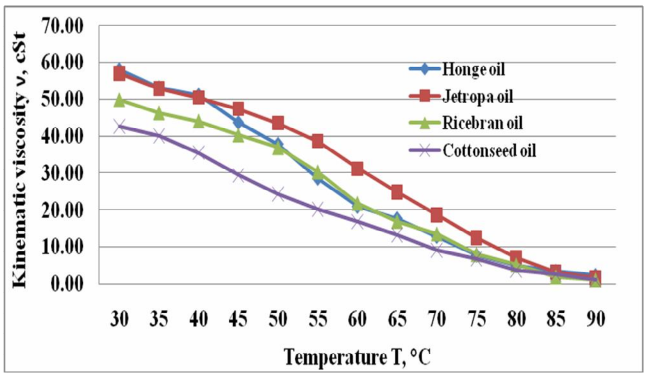


Fig1. Variation of Kinematic Viscosity with Temperature

Following inferences can be made from Table 4. Honge oil is having high viscosity, high density, low cloud and pour point temperatures and low cost as compared to other oils. High viscosity contributes to increased viscosity of MR fluid which in turn develops higher yield stress which is a desired property of MR fluid. Variation of viscosity with temperature for all four liquids from 30 to 90°C is plotted in Fig.1. The rate of decrease in viscosity of Honge oil is less with increase in temperature as compared to Cotton seed and Rice bran oils (Fig. 1). The high density of Honge oil may support the tendency to carry dense particles of suspensions without settling. This reduces one of the severe problems like sedimentation which arises in most of the MR fluids, during applications. Though Honge oil is having low cloud point, the user must be aware of possible effect under cold climatic conditions while considering it. Flash and fire point temperatures of Honge oil though slightly inferior, considering its merits in other properties, its cost and it being non edible oil, and its applications at higher temperature beyond this limit are few, and it is selected for use as a carrier liquid. Next the stability of Honge oil at higher temperatures is evaluated.

5.2 Experimental procedure for evaluating stability of honge oil against temperature

MR fluids are working in wide range of applications as in brakes, clutches, suspensions, civil structures, machining etc., and the working environment differs from case to case. In some applications like MR machining, the fluid may have to operate at higher temperature for longer period of time and hence performance of carrier liquid at these temperatures should be given due consideration, namely, carrier liquid present in the MR fluid must be stable at those working temperatures. In this context, the stability of Honge oil from 40 to 80°C temperatures was evaluated. During experiment, Honge oil was kept in an electric furnace maintained at various temperatures i.e. 40, 50, 60, 70 and 80°C for durations of 50 hrs. Viscosity of the oil was determined at intervals of 10, 20, 30, 40 and 50 hrs. The change in color and volume, presence of sedimentation, and formation of undesired layer were observed at regular intervals. Results of the variation of kinematic viscosity with different durations of heating at different temperatures are plotted in Fig.2 (a-e) and Fig. 3. The following observations can be made from the figure.

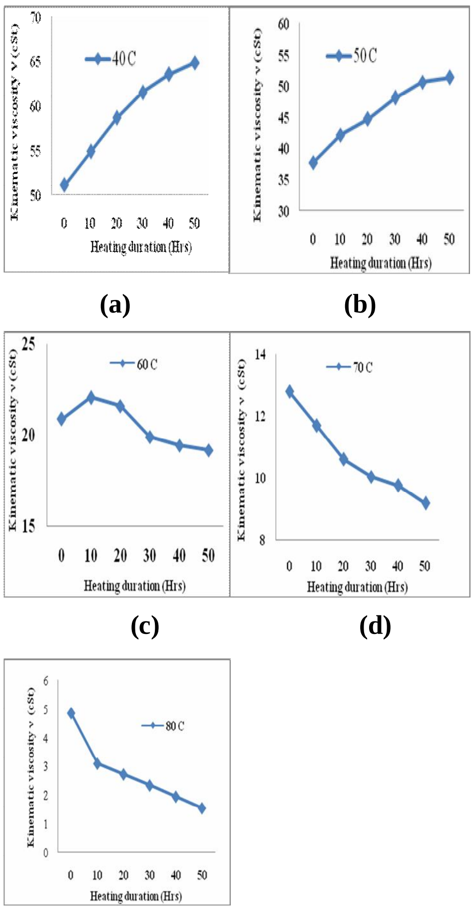
(i) At both 40° and 50°C, the kinematic viscosity increase in heating duration (Fig. 2a and 2b).

(ii) In case of 60°C, the kinematic viscosity slightly increased with 10 hrs of heating and then has shown a decreasing trend thereafter with increase in heating duration (Fig. 2c).

(iii) At 70° and 80°C, the kinematic viscosity decreases with increase in duration of heating (Fig. 2d and 2e).

(iv) Fig 3 compares the kinematic viscosity of Honge oil without heating and with heating for 50 hrs. The kinematic viscosity of this liquid increases when heated at 40° and 50°C as compared to the oil without heating. Thereafter kinematic viscosity of the liquid remains same for 60°C and decreased for both 70°C and 80°C, as compared to the liquid without heating.

In summary, the kinematic viscosity increases as the temperature is raised from 40° to 50°C (Fig. 2a and 2b), because at lower temperatures, with continuous heating the cohesive forces between the molecules predominates the molecular momentum transfer between the molecules, as the molecules are closely packed and hence a gradual increase in viscosity has been observed. But further increase in temperature, a decreasing trend of viscosity is observed with rise in temperature (Fig. 2c).



(a) **(b)**

(c) **(d)**

(e)

Fig.2 (a-e) Plot Representing Dependence of Viscosity with Heating Duration of Honge Oil

This decreasing trend in viscosity is increased with further rise in temperature (Fig. 2d and 2e). This may be due to the molecules of Honge oil break down as the duration of heating is increased. This reduces the cohesive forces between the molecules, and the forces of attraction between them reduce, which eventually reduces the viscosity of the liquid. Further, photographs of the Honge oil after each heating were taken and their colors compared with that of the liquid without heating 4 (a). Fig.4 (b) shows the color of the liquid after 50 hrs when heated at 80 °C. Then the quantity of liquid evaporated was evaluated by knowing the difference in volume of carrier liquid before and after heating. There were no observations indicating any evaporation, formation of layer and sedimentation, and change in color throughout the heating process except at 80 °C for 50 hrs (Fig. 4b).

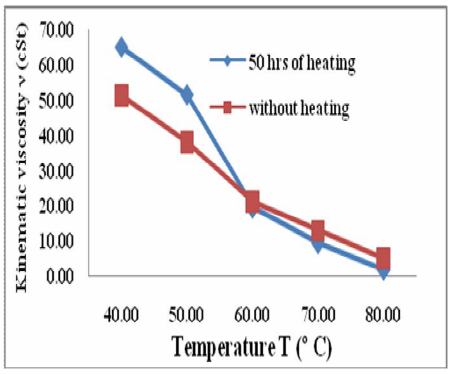
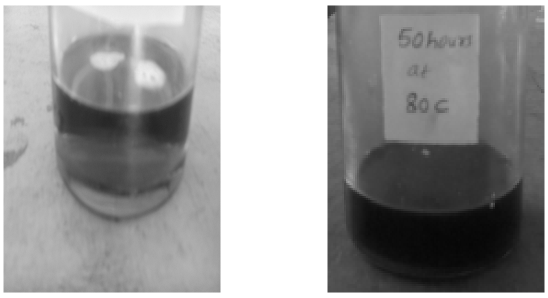


Fig. 3 Honge Oil Heated from 40 to 80°C for 50 Hrs

5.3 Preparation of indigenous MR fluid

Two combinations of Honge oil based MR fluids were prepared with 20 % and 30 % by volume of carbonyl Iron particles as suspensions, 5 % by volume of grease as additive and remaining part as carrier liquid. The grain sizes of carbonyl iron particles available commercially were in the order of 6 to 9 μm with 7.86 g/ml as density. MR fluids were prepared by taking a desired quantity of carbonyl iron powder and added the right volume of Honge oil of density 0.932 gm/cm^3. The constituents were mixed thoroughly using a glass stick with subsequent addition of additives on to it to obtain a homogeneous mixture. The properties of indigenously prepared MR fluids are shown in Table 5.



(a) (b)

Fig. 4 Honge Oil (a) Without Heating (b) With Heating (50 Hrs at 80 °C)

Table 5: Properties of Indigenously Prepared Honge Oil Based MR Fluid

Viscosity (Pa-s) at 27°C (82°F)	Density (g/cm^3)	Flash Point (°C)
0.08	1.55	>251

5.4 Comparison of magnetic field strength

Electromagnetic circuit as shown in Fig. 5 having two similar solenoid coils was used [11] to generate the required magnetic field. Specifications of the coils are given in Table 6. Theoretical and experimental magnetic fields generated by the coil are compared for their characteristics. Theoretical magnetic field generated is determined as follows. The theoretical value of magnetic field density [25] (without any core) at any point on the axis of a finite solenoid was determined using Eq. (3). Then $B_{\text{with core}}$ and $B_{\text{without core}}$ of the solenoid coil in the presence and absence of iron core respectively were determined experimentally using Gaussmeter. Then relative permeability of iron core μ_r was determined using Eq. (4). Then the theoretical magnetic field densities (with core) at different points were obtained using Eq. 5. After the two solenoid coils are connected in series, the total magnetic field generated (B_T) is obtained using Eq. 6.

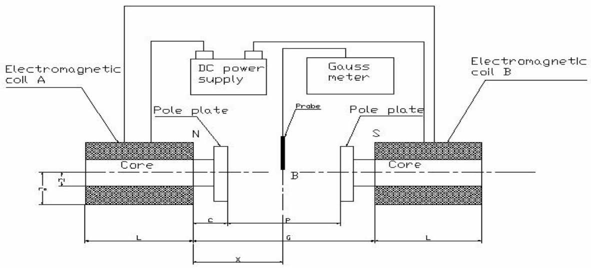


Fig. 5 Electromagnetic Circuit

Table 6: Specification of Electromagnetic Coil

Item	Details
Core Material	Cold rolled annealed steel
Core Diameter	40 $^{\pm (0.00,\ 0.02)}$ mm
Material and gauge number of copper coil	Copper, 17 gauge
No of solenoid coils	2
Resistance of each solenoid coil (Ω)	5.3 ohm
Inside radius of solenoid coil (r_1)	0.02 m
Outside radius of solenoid coil (r_2)	0.065 m
Length of each solenoid coil (L)	0.097 m
Number of turns per meter length (n)	17900
Relative permeability of the iron core (μ_r)	6.92

$$B=\frac{\mu_o in}{2(r_2-r_1)}\left[X_2\ln\frac{\sqrt{r_2^2+X_2^2}+r_2}{\sqrt{r_1^2+X_2^2}+r_1}-X_1\ln\frac{\sqrt{r_2^2+X_1^2}+r_2}{\sqrt{r_1^2+X_1^2}+r_1}\right]$$

(3)

$$\mu_r=\frac{B_{withironcore}}{B_{withoutironcore}} \qquad (4)$$

Where X_1, X_2= distances along the X-axis, from both ends of solenoid to the magnetic field measurement point (m)

B_T (with core) =B_T (without core)* μ_r *(5)*

B_T= Vector sum of B_{TA} and B_{TB} *(6)*

Where B_{TA} = Magnetic field generated at a distance X_1 from the coil A (Tesla), B_{TB} = Magnetic field generated at a distance X_2 from the coil B (Tesla).

For conducting the experiments, a DC regulated power supply (0 to 5A and 0 to 60V) and a Hall probe digital gaussmeter to measure magnetic field were used. By connecting the coils to the DC regulated power supply, in series, (Fig. 5) the magnetic fields generated for various current inputs from 0.5 to 4.5 A were measured. The magnetic fields generated with 4.5 A current at various gaps of 0.01-0.1 m (in steps of 0.01 m) between the pole plates are plotted in Fig. 6.

Experimentally a maximum magnetic field of 3816 Gauss (Fig. 6) was obtained when distance between pole plates was 0.01 m, and magnetic field decreased with increase in the gap. Experimental values are compared with theoretical magnetic fields estimated using Eq. (6) and both are agreeable each other (Fig. 6).

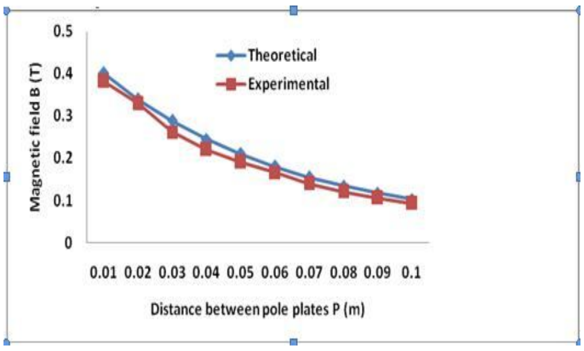


Fig. 6 Experimental and Theoretical Magnetic Field Generated in the Gap

6. Examination of Flow Nature of Honge Oil Based MR Fluid

Capillary viscometer with electromagnetic circuit as shown in Fig. 7 was used to examine flow nature of proposed MR fluid. Solenoid coils connected in series were placed on either side of the capillary tube of the viscometer. A constant distance of 0.01 m between the pole plates was maintained during the experiments. MR fluid taken in the cylinder (Fig. 7) was allowed to flow through the capillary, and subsequently the magnetic field was applied. The time to collect a fixed quantity of MR fluid without magnetic field was noted down. Next, the time required to collect the same quantity of fluid under magnetic field was measured by varying the field density. The procedure was repeated for current, in steps of 0.05 A till the flow of MR fluid was completely ceased and the results are plotted in Fig 8 (a) and (b) for 20% and 30% by volume as suspensions in MR fluid respectively. Two different ranges of magnetic field may be recognized in both the plots. In the first stage, up to a magnetic field of 165 G, the time needed for MR fluid flow remained almost same (Fig 8a). In the second stage, with increase in magnetic field, the time for MR fluid flow considerably rose high. Finally with further rise in magnetic field, the fluid flow completely ceased at 356 G. Similar flow nature was observed for 30% suspensions, but ceasing of MR fluid flow occurred at a lower magnetic field of 314 G (Fig. 8b) i.e., 20% suspension's MR fluid needed more magnetic field than 30% suspensions to cease the flow. Then yield stress (τ_{ys}) developed by MR fluid at non-flow conditions is determined theoretically using the model developed by Ginder [26] for intermediate flux densities (eq. 7).

$$\tau_{ys}=\left(6^{1/2}\right)\phi\mu_o\left(M_s\right)^{1/2}H^{3/2} \qquad (7)$$

Where μ_oM_s = saturation magnetization, Φ = Particle volume fraction, H = Applied field (oe).

The yield stress value of 0.5 kPa and 0.7 kPa were obtained for 20% and 30% by volume as suspensions respectively. In the absence of magnetic field, MR fluid contained in the cylinder flowed freely though the capillary without any hindrance. But with the application of external magnetic field, the fluid formed chains which restricted the free flow of fluid through the capillary. At low magnetic field either the magnetic chain may not have been formed or a weak chain of particles may have formed in the fluid with low resistance during the flow. But with increase in magnetic field, the dipole magnetic particles might have formed a single chain like structure close to one another without any gap. With further increase in magnetic field, the magnetic chains might have agglomerated and formed a columnar structure which completely obstructed the flow.

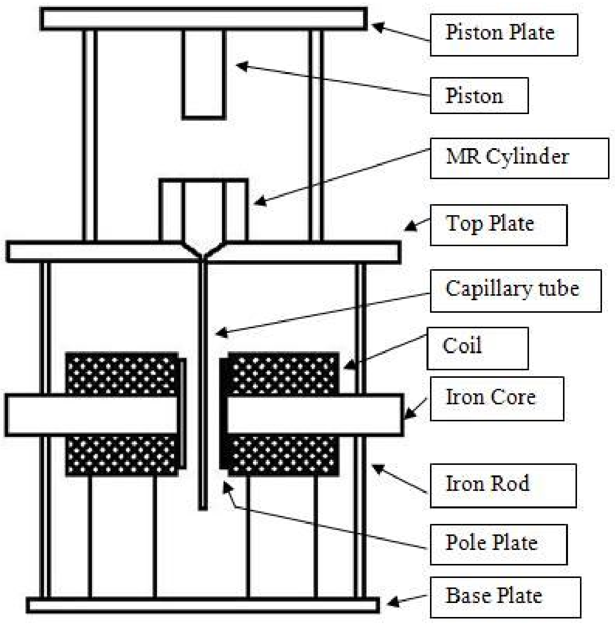
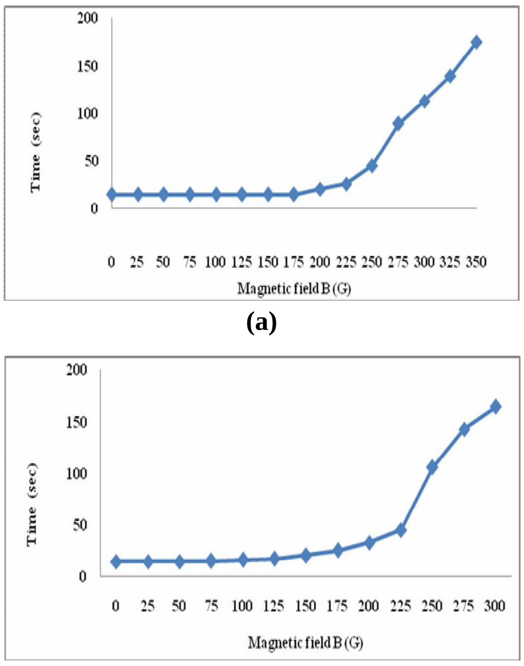


Fig. 7 Capillary Viscometer



(a)

(b)

Fig. 8 Graph of Flow Time vs Magnetic Field (a) 20% Suspensions and (b) 30% Suspensions

Thus this limiting value of maximum shear stress called as the yield stress, was responsible to cease the flow. When percentage by volume of suspensions was increased from 20% to 30%, there might have been more magnetic particles in the dispersed media which had more tendencies to form either magnetic chains or columnar structure. This might have caused low magnetic field itself to cease the flow for 30% suspensions compared to 20% suspensions. In total, the shear stress was increased with increase in any one of the parameters like either percentage of suspension or magnetic field or both.

Various tests conducted on Honge oil has shown that the oil is having better basic properties and also is stable for sufficiently longer period of time. The MR fluid prepared out of this may be used continuously for several hours in a day in its devices. Subsequent experiment carried out on Honge oil based MR fluid revealed that, a low magnitude of magnetic field has changed it from fluid like state to solid like state. This made the user aware of the quantum of magnetic field necessary for their applications.

7. Conclusions

In the era of highly polluted environment and global warming mostly in urban areas, due to non-biodegradable fuels especially petroleum make us think to use a bio-degradable, environmentally friendly low cost vegetable oils as an alternative. In the present paper, four such oils were considered as carrier liquids and after evaluating basic properties, Honge oil was selected in the preparation of a new generation MR fluid for examining the flow nature. The following conclusions are drawn after the above experimental investigations.

- Honge oil based MR fluid may be used for high temperature applications like MR machining because of its sufficiently high flash and fire point temperatures.
- Cloud and pour point temperatures of Honge oil are relatively low and hence can be applied to low temperature applications like in landing gear of an aircraft travelling in low temperature regions.
- This oil is found to be stable even upto 80 ° C temperatures for a heating duration of 50 hrs. Hence this oil can be used as carrier liquid of MR Brakes, clutches and suspension systems which are usually exposed to higher temperatures for several hours in a day.
- A non flow state of MR fluid is obtained experimentally at a magnetic field of 356 G and 314 G for 20% and 30% by volume of suspensions in Honge oil respectively. These data are useful while using this fluid in any devices to remains in the flow state at all times.
- The theoretical yield stress of 0.5 kPa and 0.7 kPa were obtained for 20% and 30% by volume

of suspensions respectively at the respective magnetic fields determined experimentally above.

- The 20% suspensions MR fluid needed high magnetic field and developed low yield stress to flow cease as compared to 30% suspensions.

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Nomenclature

Symbol	**Meaning**	**Unit**
SSU	Saybolt Universal seconds	Sec
ν	Kinematic viscosity	cSt
μ_o	Permeability of the free space	wb/A
i	Current in the wire	A
$\mu_o M_s$	Saturation magnetization	T
Φ	Particle volume fraction	%
H	Applied field	Oe