EXPERIMENTAL INVESTIGATION OF THERMAL THINNING AND SHEAR THINNING IN BEHAVIOUR OF MR FLUID

K.M.MOINUDDIN SIDDIQUE[1], G.KRISHNA KISHORE[2]

[1]PG Student, Dept. of Mechanical Engineering, GCET, Kadapa

[2]Associate Professor, Dept. of Mechanical Engineering, GCET, Kadapa

Abstract –

Magnetorheological fluids have the unique ability to change their apparent viscosity and yield stresses on application of an external magnetic field. Due to their smart property these fluids are gaining extensive usage in modern equipments. This report explains the fundamentals of MR fluid, their basic structure and behavior. To understand the physics of MR fluid, the analysis is divided into two parts: Macroscopic and microscopic analysis. The microscopic analysis involves the molecular simulation dynamics on MR fluid under the application of applied magnetic field. The particle motion is basically governed by magnetic, hydrodynamic and repulsive interaction. Fluid particle interactions are accounted via stokes drag while inter-particle interactions are modeled through approximate hard-sphere rejection /hard-wall rejections, respectively. The time evolution is considered to be magnetically quasi-static and the new position of the particle is recomputed at each instant in time by solving the governing differential equations using R K 4th order method. Further, the dynamic yield stress is determined using microscopic shear stress tensor equation and a number of observations such as dependence of dynamic yield stress and response time-scales on particle size, concentration, applied magnetic field and base viscosity which are crucial in predicting the behavior of MR fluids, is studied. The macroscopic analysis involved the viscosity measurement on viscometer and Rheometer and the modeling of viscosity with shear rate and temperature without application of applied magnetic field. An experiment is performed on MR brake to analyze the behavior of MR fluid under the application of applied magnetic field.

I. INTRODUCTION

Magnetorheological Fluid consists of a suspension of randomly oriented colloidal ferromagnetic particles in a carrier fluid. An externally applied magnetic field orients the magnetic grains and induces magnetic moment among particles. As a result, particles align themselves in the direction of magnetic field and form chain like structure, which restrict the motion of the fluid and increases the viscosity, turning the fluid suspension into a semi-solid. This phase change from liquid to semi-solid and vice-versa can be achieved rapidly and repeatedly by application of an external magnetic field. The MR fluid has attained greater importance because of its variable viscosity and high yield stress. Controllability (variable viscosity), responsiveness (in milliseconds), and functionality are the basic properties which make an MR fluid "smart". It has wide variety of technological applications, i.e. shock absorbers (variable damping coefficient), clutch (variable torque transmission), MR brakes etc. For commercial purpose it is used for low power exercise machine, control of seismic vibrations in structures, “Seal-Less” Vibration Damper**.** The Lord Corporation manufactured various MR fluid devices for commercial applications including heavy-duty vehicle seat suspensions, rotary brakes that provide a tunable resistance and prosthetic devices using smart MR fluid. Shear thinning can be defined as property of fluid due to which the apparent viscosity decreases with increase in shear rate. All Newtonian fluids have a constant viscosity at all shear rates and hence will not show shear thinning. Hair-styling gel and latex paint are good example of fluids showing shear thinning effect. The decrease in the viscosity of the fluid with increase of temperature is called thermal thinning. This effect is shown by all fluid. MR fluids show shear thinning and thermal thinning behavior.

MOTIVATION AND GOAL:

Due to growing use of MR fluids in present systems there is a greater need to identify the factors affecting the MR fluid behavior (viscosity) such as shear thinning, thermal thinning and dynamic yield stress (shear stress induces due to application of magnetic field). Also there is a need to analyze the effect of Particle size, response time and concentration on behavior of MR fluid under different applied magnetic field. Hence a study has been done and a qualitative pattern followed by MR fluid under various affecting parameters has been identified.

II. MOLECULAR DYNAMIC SIMULATION

Molecular Dynamic simulation simulates the motions of individual molecules. It shows a motion picture of the molecules moving relative to each other. It replicates the system on a computer using mathematical models. The molecular dynamic simulation, in principle, is entirely deterministic in nature. The need of Molecular dynamic simulation is as follows:

- To understand the physics behind the behavior of system from molecular point of view.
- To have a heuristic insight of various forces acting on molecules and their magnitude.

- To study the qualitative effect of various parameters involved in the system and analyze those parameters to obtain property values.

METHOD OF SOLUTION

The R K 4^{th} order method has been adopted for solution of the governing differential equation for both 2-D and 3-D model. An explicit method is used to determine x, y and z coordinates of each molecule in new time step along with input parameters. The flow chart for the program developed is given in Fig 1.

ALGORITHM

- Initialization all constants at t=0.
- Generate initial position for all n particles randomly.
- Calculate the new position of particle by solving governing differential equation using RK 4^{th} order method at $t_1 = t_0+h$.
- Print the new position of all particles at $t = t_1$.
- Increase the time step by h.
- Repeat the process until there is no significant change in position of all the particles.

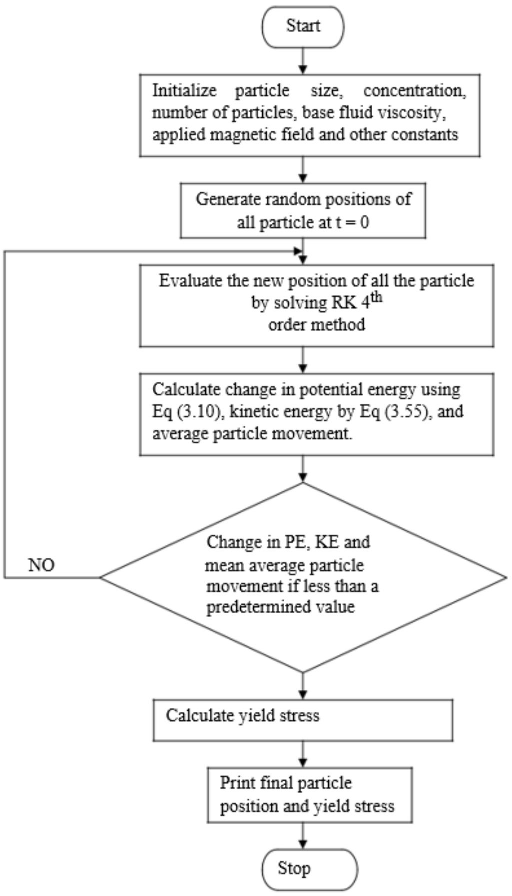

Fig.1 Flow chart for Molecular simulation dynamics of MR Fluid

III. RESULTS AND DISCUSSION

The physical parameters of the simulation are as follows:

S./No.	Property	Value
1	Fluid permeability (μ_f)	$6\pi 10^{-7}$ Tm/A
2	Particle permeability(μ_p)	2000 μ_f
3	Particle density	$7.86 \times 10^3 kg/m^3$
6	Applied magnetic field	$1.8 \times 10^5 A/m$
5	Particle size	$1.5 \mu m$
6	Base fluid viscosity	$0.01 Pa\text{-}s$
7	Time step (h)	10^{-9} second

Table 1 Input parameters

The range of magnetic flux applied to MR fluid is lies between zeros to saturation field of MR fluid. The typical range of the fluid is given by the B-H curve in Fig 2:

Operating Point in MR fluid

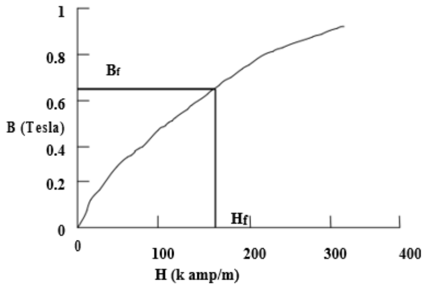

Fig.2 B-H curve of MR fluid

The saturation of the MR fluid is equal to the volume concentration fraction multiplied by the saturation magnetic flux of the magnetic particles.

IV. RESULT AND DISCUSSION

The results obtained from 3-D analysis did not show any significant deviations from results obtained by 2-D analysis, also the machine time consumed for calculations were higher compared to that of 2-D analysis. Further as the direction of application of magnetic field was studied for only one direction i.e. y-direction, hence the behavior of particles in z-direction were similar to that of x-direction. Moreover the visualization of 3-D results that is position of particles is quiet complex and not completely informative for analysis of fluid under various operating conditions, hence only 2-D results have been presented in this study. The results for the dynamic simulations for the 10% and 20% volume fraction of the MR fluids are shown in Fig 3 and Fig 4 respectively. At first the particle form short chains in the direction of the applied field, subsequently these short chains merge together and form longer chains. As the time progresses further these chains-like clusters continues to lengthen and align shown by Fig 5. The photograph of the structural formation of MR fluid obtained by using optical microscope also confirms the same result.

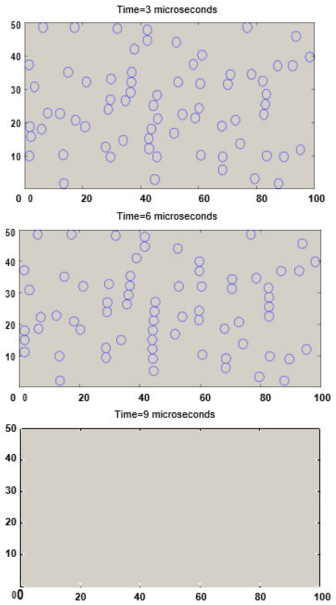

Fig.3 Dynamic simulation at 10% volume fraction

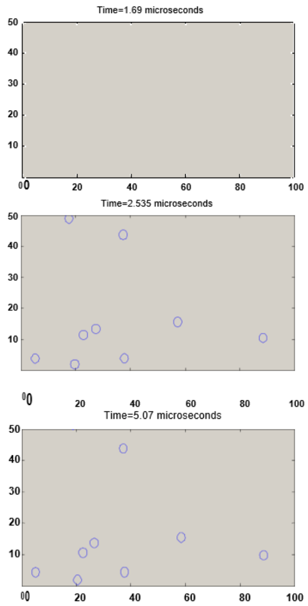

Fig.4 Dynamic simulation at 20% volume fraction

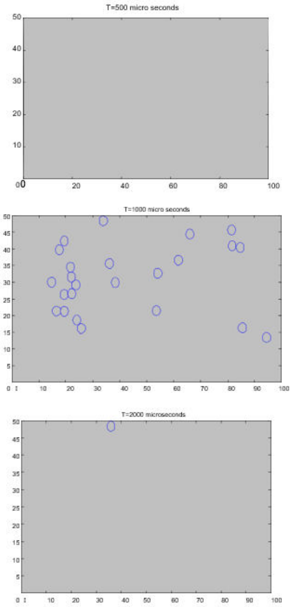

Fig.5 Dynamic simulation at 22% volume fraction at higher time step

RESULT

The result of the molecular simulation is as follows.

1) The structure formation under the application of magnetic field is a random phenomenon consists of columnar chains. Particles form short chains merge together and form longer chains. Therefore, the viscosity of the system increases with application of applied magnetic field.

2) The dynamic yield stress increases with increase in applied magnetic field (provided all other parameter remains constant). The magnetic force of interaction among the particles under the applied magnetic field is much higher than the hydrodynamic force developed by viscosity of the fluid at low shear rate.

3) The Dynamic yield stress increases with increase in particle size (provided all other parameters remains constant). With increase in particle size the agglomeration and settling down problems become predominant, but a decrease in particle size increases coercivity of the fluid**.** Hence depending on the application and constraints a suitable particle size has to be selected.

4) Since dynamic yield stress is governed dominantly by magnetic forces, there is little effect of temperature on system property (dynamic yield stress) when the magnetic field is applied. (Assuming the permeability of the magnetic particles is not affected by temperature)

5) The total shear stress consists of two terms: one is dynamic yield stress and the other is hydrodynamic stress. At low shear rate, hydrodynamic stress is negligible but at high shear rate, the hydrodynamic stress dominates. The shear thinning behavior will be prominent under

the application of applied magnetic field when the hydrodynamic force exceeds magnetic force. Therefore, the critical shear rate at which shear thinning happens, increases with increase in applied magnetic field.

CLOSURE

The structural formation is completely a random phenomenon. It depends totally on the initial position of the particle at which magnetic field is applied. The time taken to form columnar structures is inversely proportional to the volume fraction of the particle. It varies inversely with concentration in power of 1.22. A theoretical estimation of the same is found to be in power of (5/3). At higher applied field lesser time is required to form the structure. The base oil does not affect the structural formation but it influence the time required to form the equilibrium structure. With increase of base oil viscosity the time required to form the stable structure increases which is quite logical as with increase of base viscosity the hydrodynamic force increases and hence particle take larger time to form chain structures. The dynamic shear yield stress value increases with increase of applied magnetic flux and particle size. However, the variation in dynamic yield stress value with concentration is not found to be significant up to applied magnetic field of 180 kA/m. This simulation result is in good agreement with the experimental result.

Results and Discussions

The experiment is conducted on experimental set up described in the previous chapter using MR fluid as samples and viscosity reading is taken at different values of temperature and shear rate in absence of applied magnetic field. The range of temperature is 28^0C to 65^0C and the range of shear rate is 9.3 s^{-1} to 93 s^{-1}. The result is categorized as two effects which are described below as subheading.

Shear thinning

The viscosity is measured at different shear rate keeping the temperature constant, Fig 6, Fig 7 and Fig 8 show the graph of viscosity vs. shear rate respectively. The viscosity is found to decrease with increase of shear rate at all temperatures.

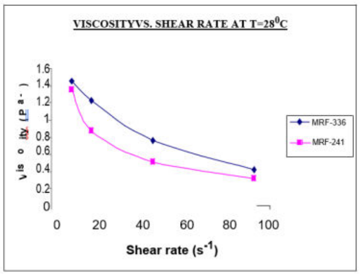

Fig.6 Shear thinning behavior at 28 degree Celsius

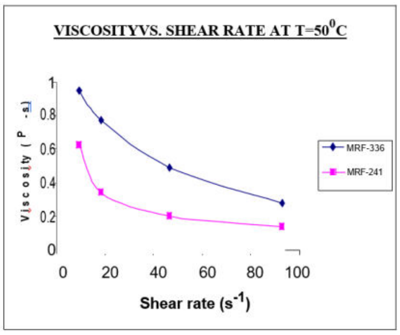

Fig.7 Shear thinning behavior at 50 degree Celsius

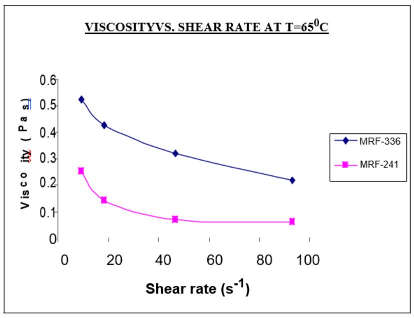

Fig.8 Shear thinning behavior at 65 degree Celsius

At constant temperature of 28^0C, the percentage change in the viscosities between the two fluids (w. r. t MRF-336) at the shear rate of 9.3 s^{-1} is 6.89, which increase to 25.44 at shear rate of 93 s^{-1} shown by Fig 6. Similarly, at constant temperature of 65^0C, the percentage change in the viscosities between the two fluids (w. r. t MRF-336) at the shear rate of 9.3 s^{-1} is 52.38, which increase to 72.09 at shear rate of 93 s^{-1} shown by Fig 6. Therefore, for all shear rates, with increase of temperature, the percentage change in viscosities between two samples increases.

V. SUMMARY AND CONCLUSION

The study is being done in two parts: Part-A describes the microscopic analysis of MR fluid under the application of applied magnetic field. The dependence of the input parameters (base viscosity, particle size and concentration) on the behavior of the system is being analyzed. Part-B describes the Macroscopic analysis in which an experimental set up is developed to analyze the affect of temperature and shear rate on the braking torque value of the MR brake(on state). Then, to have closure look on the viscosity behavior of the MR fluid (off-state), experiment is conducted on Viscometer and Rheometer. The analysis is found to be complementing each other and in good agreement with experimental data. The analysis can be concluded as:

- The structure formation under the application of magnetic field is a random phenomenon consists of columnar chains. Particles form short chains merge together and form longer chains. Therefore, the apparent viscosity of the system increases with application of applied magnetic field.
- The dynamic yield stress increases with increase in applied magnetic field (provided all other parameter remains constant). The magnetic force of interaction among the particles under the applied magnetic field is much higher than the hydrodynamic force developed by viscosity of the fluid at low shear rate. Hence, dynamic yield stress value will not get affected by the base oil viscosity.
- Since dynamic yield stress is governed dominantly by magnetic forces, there is little effect of temperature (thermal energy) on it when the magnetic field is applied. However, a further analysis is required to find out the effect of temperature on dynamic yield stress value as the magnetic permeability of the particles is also a function of temperature. The increase in temperature also affects the base oil viscosity.
- The Dynamic yield stress increases with increase in particle size (provided all other parameters remains constant). With increase in particle size the agglomeration and settling down problems become predominant, but a decrease in particle size increases coercivity of the fluid**.** Hence depending on the application and constraints a suitable particle size has to be selected.
- The total shear stress consists of two terms: one is dynamic yield stress and the other is hydrodynamic stress. At low shear rate, hydrodynamic stress is negligible but at high shear rate, the hydrodynamic stress dominates. The shear thinning behavior will be prominent under the application of applied magnetic field when the hydrodynamic force exceeds magnetic force. Therefore, the critical shear rate at which shear thinning happens, increases with increase in applied magnetic field.
- The off state steady flow measurement (performed on viscometer and Rheometer) revealed a prominent shear thinning and thermal thinning behavior of MR fluid. Also, there is variation in viscosity under applied magnetic field shown by MR brake reading. But the MR brake system has too much constrained, therefore a detailed analysis on magneto-rheometer is required to analyze temperature thinning.
- In the absence of the applied magnetic field, both Brownian and hydrodynamic forces are significant and will act into the system and hence, temperature has a significant role

in determining the viscosity of the MR fluid. Therefore, strong temperature thinning effect will observe in absence of applied magnetic field.

SCOPE FOR FUTURE WORK

- The off-state modeling of viscosity at high shear rate is required to be analyzed.
- The analysis has been qualitative due to nonavailability of Magnetorheological Rheometer. Hence an exact quantitative analysis is performed on Magnetorheological Rheometer for analyzing the shear thinning behavior and thermal thinning behavior on application of applied magnetic field.
- The constant a, b and c mentioned while modeling viscosity behavior with temperature and shear rate in off-state condition is important for synthesis point of view. Therefore, the validity of the constant and its modeling has to be verified by synthesis of MR fluid.
- The particle size used in simulation is assumed to be of uniform size. The structure formation can be made more realistic by taking different size of the particle (as in actual case the size are not same).
- The knowledge can be further improved by considering multibody hydrodynamic interaction and multi-pole interaction for magnetic forces.

REFERENCES

[1] Mark R. Jolly, Jonathan W. Bender, and J. David Carlson, "Properties and Applications of Commercial Magnetorheological Fluids," *SPIE* 5th Annual Int Symposium on Smart Structures and Materials, San Diego, CA, March 15, 1998.

[2] Genc Seval, "Synthesis and properties of Magnetorheological (MR) Fluids", dissertation, University of Pittsburgh, 2002.

[3] Larson Ronald G., "The structure and rheology of complex fluids", Oxford university press, New York, 1999.

[4] J.Huang, J.Q Zhang, Y.Yang, Y.Q.Wei, "Analysis and design of a cylindrical magneto-rhelogical fluid brake", Journal of Materials Processing technology, Vol -129, 2002, pp 559-562.

[5] W.H. Li and H.Du. "Design and experimental evaluation of a Magnetorheological brake", Journal of advanced Manufacturing Technology, Vol-21, 2003, pp 508-515.

[6] Wang, X., and Gordaninejad, F., "Flow Analysis of Field-Controllable, Electro- and Magneto-Rhelogical Fluids Using Herschel-Bulkley Model," *Journal of Intelligent Materials, Systems and Structures*, Vol.-10, No. 8, 1999, pp. 601-608.

[7] Stachowiak G. W., Batchelor A. W., "Engineering Tribology", Butterworth Heinemann, 225 Wildwood Avenue, Woburn, MA 01801-2061, 2001.

[8] Carlson J D and Weiss K D., "A growing attraction to Magnetic fluids", Machine design 8, Vol-61, 1996, pp 61-66.

[9] Genc Seval, Phule Pradeep P, "Rheological properties of Magnetorheological fluid", Smart Material Structure, Vol-11, 2002, pp 140-146.

[10] Kordonski W. I., Gorodkin S. R., Novikova Z. A., "The influence of Ferro particle concentration and size on MR Fluid Properties" , Academic Scientific Complex, "A.V. Luikov Heat and Mass Transfer Institute", Academy of Science of Belarus, 15 P. Brovka Str. , Minsk 220072 Belarus.

[11] M.Mohebi and N. Jamasbi, "Simulation of the formation of non-equilibrium structures in Magnetorheological fluids subject to an external field", Physical Review E, Vol-56, No-5, 1996, pp 5607-5613.

[12] Haile J.M., "Molecular Dynamics simulation: elementary Methods", Wiley-interscience publication, 1997.

[13] Larson Ronald G," The structure and rheology of complex fluids", Oxford university press, 1999.

[14] Bonnecaze R.T. and J.F. Brady, "Dynamics simulation of electrorheological fluid",J.Chem Phys ,Vol-96, No-3,1992, pp 2183-2202.

[15] Eric climent, Martin R. Maxey, George Em Karniadakis, "Dynamic simulation of self Assembled chaining in Magnetorheological Fluids", Langmuir, Vol-20, 2006, pp 507-513

[16] D.J.Klingenberg, Frank van Swol, and C.F.Zukoski, "Dynamic simulation of Electrorheological suspensions", J. Chem. Phys., Vol- 91, No-12, 1999, pp 7888-7895.

[17] Cullity, B.D., "Introduction to Magnetic Material", Reading, Mass., Addison Wesley Pub. Co., 1972.

[18] D.J.Klingenberg, Frank van Swol, and C.F.Zukoski, "Dynamic simulation of Electrorheological suspensions", J. Chem. Phys., Vol- 91, No-12, 1999, pp 7888-7895.

[19] Hass K.C., "Computer simulation of non equilibrium structure formation in electrorheological fluids", Physical review E, Vol-67, No-5, 1993, pp 3362-3373.

[20] Yun zhu, Michael McNeary, Neal Breslin, Jing Liu, “Effect of structures on rheology in a model Magnetorheological fluid”, Department of physics and astronomy, California state University, USA.

[21] T.Fujita, B.Jeyadevan, E.Kuzuno, N. Nakagawa, S. Hioki, “Formation of clusters and their effect on the viscosity of Magnetic and Electrorheological Fluids”, Mining college, Akita university, Japan.

[22] M.Whittle, “Computer simulation of Electrorheological Fluid”, Journal of Non-Newtonian Fluid Mechanics, Vol- 37, 1990, pp 233-263.

[23] R.T Bonnecaze, J.F. Brady, “Dynamic simulatio of an Electrorheological fluid” Journal of chemical physics, Vol-96, no-3, 1992, pp 2183-2202.

[24] H. V. Ly, F. Reitich, M. R. Jolly, H. T. Banks, and K. Ito, “Simulations of Particle Dynamics in Magnetorheological Fluids”, Journal of Computational Physics, Vol-155, 1999, pp 160–177.

[25] J.Huang, J.Q Zhang, Y.Yang, Y.Q.Wei, “Analysis and design of a cylindrical magneto-rhelogical fluid brake”, Department of Engineering Mechanics, Chongquing University, 600066 Chongquing ,China.

[26] W.H. Li and H.Du. “Design and experimental evaluation of a Magnetorheological brake”, Journal of advanced Manufacturing Technology, Vol-21, 2003, pp. 508-515.