14th Annual (International) Mechanical Engineering Conference – May 2006
Isfahan University of Technology, Isfahan, Iran

The Effect of Temperature and Electric Field on the Behavior of Electrorheological Fluids

Mohammad B.Ayani[1] and L.Hosseini[2]
Department of Mechanical Engineering Ferdowsi University of Mashhad,
P.O. Box 91775 -1111, Mashhad, Iran
mbayani@um.ac.ir

Abstract
An Electrorheological (ER) process occurs when the viscosity of fluid with dispersed particles is modified by the application of an electric field. The Electrorheological flowable dispersed fluids can be currently used for fixing of materials responding to mechanical loads and, as working media for dampers and dielectric actuators.
The present investigation has been undertaken with the aim of studying the parameters that effect on the apparent viscosity of low–concentration ER-fluid (diatomite in transformer oil). Results demonstrate increases in the viscosity by applying electric field. It is shown that the viscosity behavior can be reasonably modeled as a power–low fluid, with the viscosity equal to a consistency index, K, multiplied by the shear rate raised to the power n-1. Results indicate that both the consistency index K and the exponent n are influenced by voltage and temperature, where K has linear and n has exponential relation with temperature. The variation of the apparent viscosity versus temperature can be determined by these relations.

Keywords: Electrorheological Fluid –Viscosity – Electric field – Temperature

Introduction
An Electrorheological (ER) suspension is made from an insulating liquid medium embodying either a semi-conductive particulate material or a semi-conductive liquid material (usually a liquid crystal material). The rheological properties (viscosity, yield stress, shear modulus, etc) of an ER suspension could reversibly change by several orders of magnitude under an external electric field with the strength of several kilovolts per millimeter. Since its mechanical properties can be easily controlled within a wide range by applied voltage (almost from a pure liquid to a solid), the ER fluid could be used as an electrical and mechanical interface in various industrial areas. For example, it could be used in the automotive industrial for clutch, brake [1] and damping systems [2]. These materials have been used as ideal mechanical–electrical interfaces (for transferring and controlling mechanical movement) because of their very fast response time [3-5] and their reversible rheological properties (high increment in viscosity and yield stress). It also could be used in the robotic arm joints and hands [6]. It could also be used for military purposes. The potential applications have stimulated a great deal of interests both in academic and industrial areas since the ER effect was first described by Winslow [7] in 1949. There is a large body of literature on the mechanism of the ER effect and the design of industrially applicable ER devices.
Several researchers studied the influence of critical parameter on ER effect like electric field strength [8], frequency of the electric field [9], temperature [10], particle conductivity [11], particle dielectric properties [12], particle volume fraction [13], water content [14], and liquid medium [15]. The investigations on ER-fluid are extended to other branches of mechanical engineering like heat transfer and vibrations also caused a need to coupled analysis like fluid interfacing solid (FIS).
The effects of some parameters such as electric field and temperature on the viscosity of ER fluids are complex. Also the experimental result curves show the effect of those parameters on the viscosity

[1]- Assistant Prof.
[2] - B.S. Student

but they are not efficient in the analytical and numerical studies for ER fluids. In this study, it is tried to obtain a relation between viscosity and temperature for the most typically ER –fluid, namely, a suspension of diatomite in transformer oil by the parameter uses in constitutive equations for Rheological flow.

Mathematical model

One of the most specific characteristic of ER-fluid is the increasing of viscosity under external electric field. There are several experimental studies to measure the viscosity of ER fluid and explain the mechanism of this phenomenon.

Korobko [16] measured the variation of shear stress versus shear rate of the 3% of diatomite in transformer oil for four different temperatures. The results of his study are shown in Figs.1 and 2 for two different electric fields E=0.0kv/cm and E=25kv/cm respectively.

As shown in Fig.1 without an electric field, shear stress has an increasing trend with decreasing temperature. In the presence of an electric field for high temperatures in the range of action of the Electrorheological effect, the nonlinearity of the flow curves for low shear rates increases, however the nonlinearity zone reduces and outside this section a slope of the curves increase with increasing temperature. Such behavior on different sections is explained by counteraction of the increasing polarization of solid particales, the increasing effect of the field, the decrease in the viscosity of the disperse medium and desorption of the activator from the surface of particales under temperature action.

The simplest constitutive equations for Rheological flow are: [17]

$$\tau = K\gamma^{n} \qquad (1)$$

$$\mu = K\gamma^{n-1} \qquad (2)$$

where μ, γ, and τ are viscosity, shear rate, and shear stress respectively. The parameter K is sometimes referred as the consistency index and in the SI unites has the units of $pa.s^{n}$ while the exponent n is a dimensionless value.

The values of K and n base on eq.(1) can be determined from Figs.1 and 2 by curves fitting method, where those values are tabulated in tables 1 and 2.

The apparent viscosity of the ER fluid can be determined from eq.(2) and the data of table1. Figures 3 and 4 show the variation of viscosity versus shear rate of the 3% suspension of diatomite in the transformer oil for four different temperature for E=0.0kv/cm and E=25kv/cm respectively.

Figures 3 and 4 show the viscosity of ER fluid decreases by increasing temperature. Also these figures show the viscosity increases by factor 2.5 with applying the electric field with intensity equals 25 kv/cm.

By using the values of table 1, the variations of K and n versus T* can be plotted, where T* is a non dimensional temperature and equals to T/T_0.

Different functions such as linear, power law, and exponential functions are fitted to the variation of K and n with respect to T*. The sum square errors (SSE) and root mean square errors (RMSE) for these curves of K and n data are tabulated in table 3 – 6. The consistency index K is tabulated in tables 3 and 4 for two different voltage E=0.0kv/cm and E=25kv/cm respectively and the exponent n is tabulated in tables 5 and 6 for the same voltages. By comparing the data in tables 3 and 4, and tables 5 and 6 it can be concluded the linear function for the variation of K with respect to T* and the exponential function for the variation of n with respect to T* have higher accuracy than the other functions.

Figures 5 and 6 show the K versus T* for two different voltage E=0.0 kv/cm and E=25 kv/cm respectively. Those Figures show the coefficient K decreases with increasing temperature and increases with increasing voltages. The value of K varies from $0.045pa.s^{n}$ at $20^{\circ}C$ to $0.0126pa.s^{n}$ at $80^{\circ}C$. When the voltage is applied, K increases dramatically.

The data of n in table1 represent the parameter n is also depends on temperature and voltage. The variation of n versus T* for two voltage E=0.0 kv/cm and E=25kv/cm are shown in Figs.7 and 8 respectively. These Figures show the value of n increases with increasing temperature and decreases with increasing voltage. The decreasing in n with voltage is an indication of the reduced ER effect observed at high shear rates.

Results

In this study by using the experimental results for the variation of viscosity versus shear rate [1] and eqs. (1) and (2), the apparent viscosity on different temperature determined for the 3% of diatomite in transformer oil. The results show the apparent viscosity depends upon temperature and voltage.

The consistency index K decreases and exponent n increases with increasing temperature. By curve fitting method, it is concluded the linear and exponential function are the best function for the variation of K and n versus T* respectively.

The recommended relations for K and n in the absent of voltage are as follows:

$$K = -0.158T^{*} + 0.2051 \qquad (3)$$

$n=0.5393 \exp(0.4518T^*)$ (4)

And the recommended relations for K and n with E=25Kv/cm are as follows:

$K= -42.12T^*+50.75$ (5)

$n=1.247E^{-6}\exp(10.79T^*)$ (6)

These relations are satisfied only for 3% diatomite in transformer oil. By using of these relations and eq.(2) the apparent viscosity of that fluid can be determined at each temperature.

References

1. K. Shimada, T. Fujita, M. Iwabuchi, M. Nishida, and K. Okui, in: M. Nakano, K. Koyama Eds., Proc. Intern. Conf. on Electrorheological Fluids, World Scientific, 1998, p.680.
2. D.A. Brooks, in: M. Nakano, K. Koyama Eds., Proc. Intern. Conf. on Electrorheological Fluids, World Scientific, 1998, p.689.
3. D.J. Klingenberg and C.F. Zukoski, Studies on the steady-shear behavior of electrorheological suspensions, Langmuir 6, 1990, p.15.
4. T.C. Halsey, Electrorheological fluids, Science, V.258, 1992, p.761.
5. Y. Chen, A.F. Sprecher, and H. Conrad, Electrostatic particle-particle interaction in electrorheological fluids, J. Appl. Phys., V.70, 1991, p.6796.
6. J. Furusho, N. Takeue, G. Zhang, and M. Sakaguchi, in: M. Nakano, K. Koyama Eds., Proc. Intern. Conf. on Electrorheological Fluids, World Scientific, 1998, p.713.
7. W.M.Winslow, J. Apply. Phys., V.20, 1949, P.1137.
8. J.E. Stangroom, GB Patent 2119392, 1993.
9. H. Block, J.P. Kelley, A. Qin, and T. Watson, Langmuir 14, 1998, P.1081.
10. A.V. Lykov, Z.P. Shulman, R.G. Gorodkin, and A.D. Massepuro, J. Eng. Phys., V.18, 1970, P.979.
11. K.D. Weiss, D.A. Nilxon, J.D. Carlson, and A.J. Margida, Polym. Predrints, V.35, 1994, P.325.
12. Yu. F. Deinega, K.K. Popko, and N.Ya Kovganich, Heat- Transfer-Sov. Res.10, 1978, P.50.
13. J. Klingenberg and C.F .Zukoski, Langmuir 6, 1990, P.15.
14. H. Ueijima, Jpn. J. Appl. Phys., V.11, 1972, P.319.
15. T. Garino, A. Adolf, and B. Hance, in: R. Tao(Ed), Proc. Intern. Conf. On ER Fluids, World Scientific, 1992, p.59.
16. E.V. Korobko and Y. Korobko, Heat and Mass Transfer Institute, Academy of Belarus, 2000, p.525.
17. F. Kerith, Fluid Mechanics, Pb. Library of congress catalogin- in-publication data, 2000.

Tables and Figures

Table1- The values of consistency index K

T(°C)	20	40	60	80
E=0.0kv/cm	0.045	0.038	0.028	0.0126
E=25kv/cm	8.91	5.57	2.46	0.4

Table2 - The values of exponent n

T(°C)	20	40	60	80
E=0.0kv/cm	0.86	0.861	0.873	0.957
E=25kv/cm	0.057	0.129	0.256	0.551

Table3 - The values of SSE and RMSE for K in different function (E=0.0kv/cm)

Function	Linear	Power	exp
SSE	2.09E-05	6.68E-05	6.31E-05
RMSE	0.003208	0 .005781	0.005616

Table4 - The values of SSE and RMSE for K in different function (E=25kv/cm)

Function	Linear	Power	exp
SSE	0.4432	1.808	1.822
RMSE	0.4708	0.9508	0.9546

Table5 - The values of SSE and RMSE for n in different function (E=0.0kv/cm)

Function	Linear	Power	exp
SSE	0.001908	0.001979	0.001885
RMSE	0.03089	0.03145	0.0307

Table6 - The values of SSE and RMSE for n in different function (E=25kv/cm)

Function	Linear	Power	exp
SSE	0.01307	0.0001531	7.94E-05
RMSE	0.08084	0.00875	0.00631

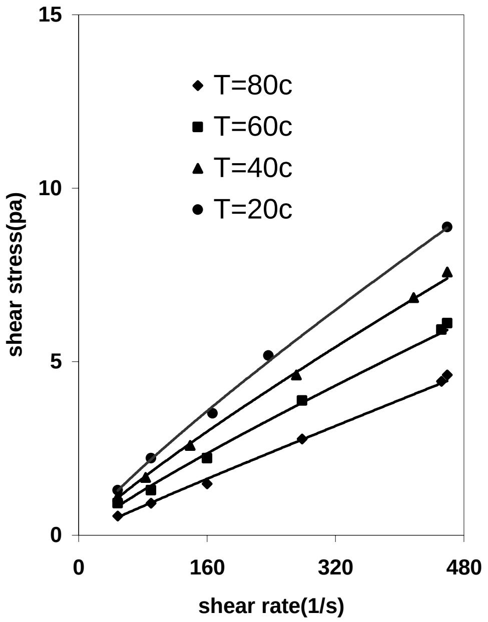

Fig. 1 - Flow curve of the 3% suspension for diatomite in transformer oil E=0.0kv/cm

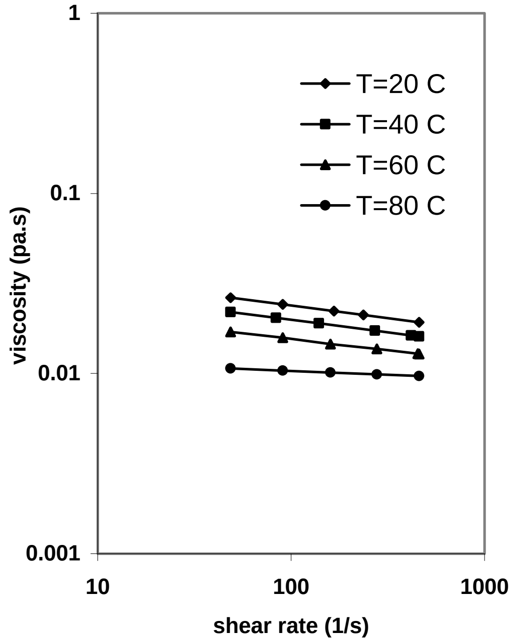

Fig. 3 - Viscosity vs. shear rate for the 3% suspension of diatomite in transformer oil for E=0.0 kv/cm

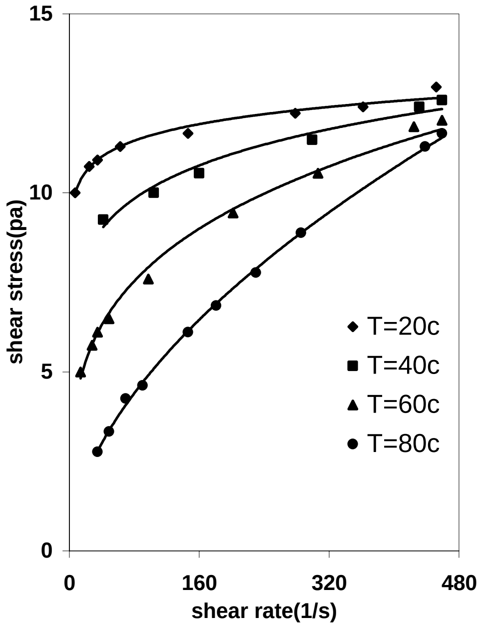

Fig. 2 - Flow curve of the 3% suspension for diatomite in transformer oil for E=25kv/cm

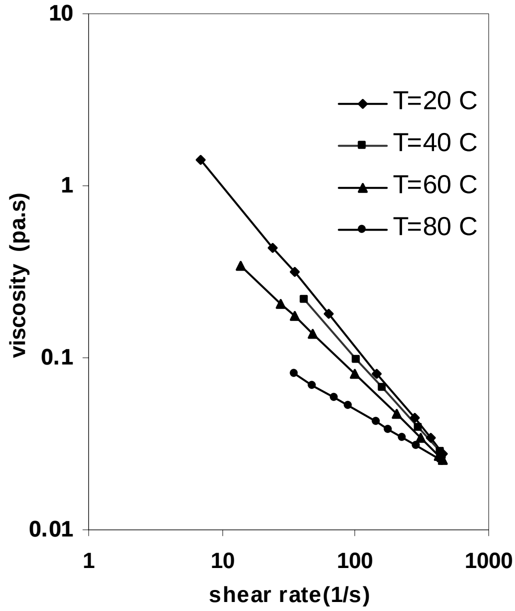

Fig. 4 - Viscosity vs. shear rate for the 3% suspension of diatomite in transformer oil for E=25kv/cm

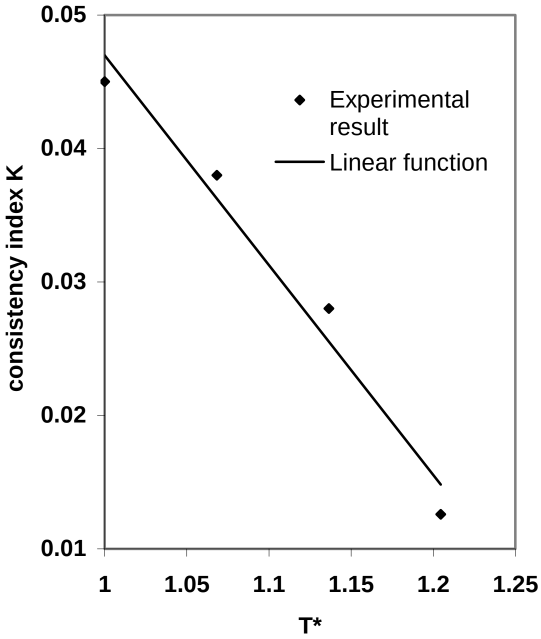

Fig. 5 - The variation of K vs. T* for the 3% suspension of diatomite in transformer oil for E=0.0kv/cm

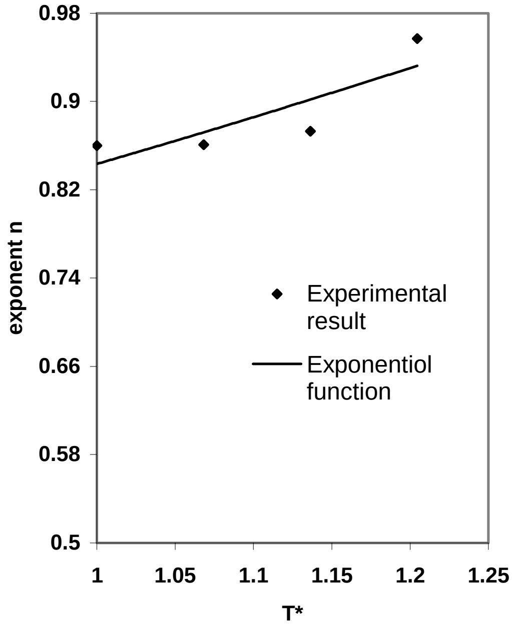

Fig.7 - The variation of n vs. T* for the 3% suspension of diatomite in transformer oil for E=0.0kv/cm

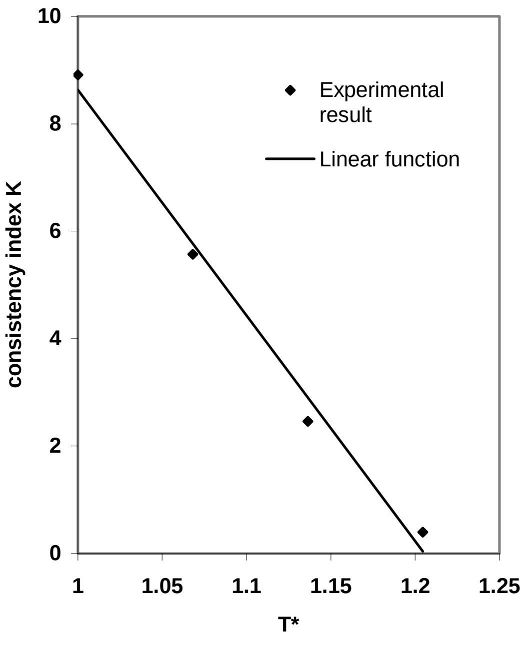

Fig. 6 - The variation of K vs. T* for the 3% suspension of diatomite in transformer oil for E=25kv/cm

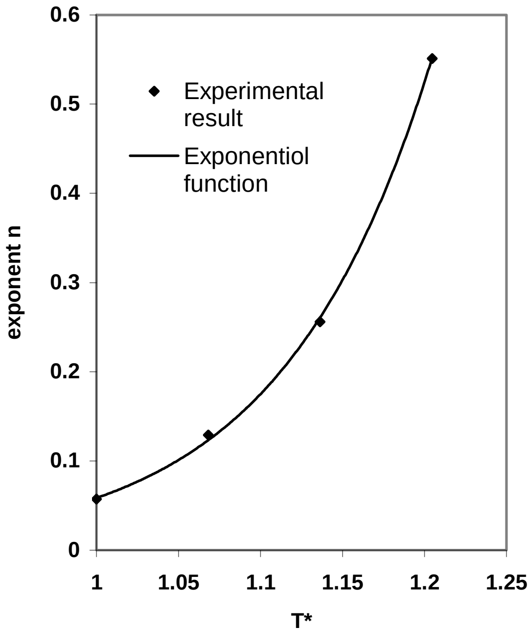

Fig. 8 - The variation of n vs. T* for the 3% suspension of diatomite in transformer oil for E=25kv/cm