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Electrorheological Fluids: Properties, Technology and Modern Applications

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Abstract - *Since last three decades, ER fluid has major importance in science, medical and engineering problems, which include vibration reduction and suspension. Electrorheological fluids are smart materials whose rheological properties are controllable through the applications of an external electric field. These rheological properties of ER fluid can be exploited in ERF devices for advanced technological applications. The optimal design of ERF devices requires proper mathematical modeling and basic governing equations. This paper presents the working principles, governing equations and mathematical framework for ER fluids. Also in this paper recent progress of ER devices and their applications have been discussed.*

Key Words: Electrorheological Fluid, Controlling Devices, Electrorheological Damper, Mechanical Polishing, Smart Materials.

1. INTRODUCTION

Electrorheological (ER) fluids are special viscous fluids, consisting of solid particles dispersed in an insulating carrier fluid, and that are undergo significant changes in their mechanical and rheological properties when an electric field is applied. Such kind of response takes place in millisecond scale. This property of the ER fluid can be exploited in different kinds of technological applications. They have broad applications potential in dampers, actuators, clutches, valves, etc [1].

The rheological changes occur in ER fluids when an external electric force is applied making the uniform dispersed solid particles to become polarized. After polarization, they start to interact with one another, and form chain like structure, parallel to direction of electric field lines and connecting the two particles. After strengthening of the electrical force, chains begin to make thicker column. The electrorheological effect of ER fluid is known as the Winslow-effect, it was named after scientist Willis Winslow who discovered it [2,3].

A change in the rheological properties of electrorheological fluid is related with change in its nature and structure. The columnar particles chain like structure provides the fluid a more yields stress. After expelling the electrical field, the particles of electrorheological fluid lose their polarization and return to their openly meandering state. The period of time over, that events happens, is on the order of milliseconds. An electrorheological material is a suspension of fine dielectric particles in an insulating medium showing controllable rheological behaviour by the application of external electrical force.

The fundamental properties of ER fluids based on particle size, density, base fluid properties, temperature and additives. A higher concentration of volume ratio of the dispersed particulates phase can offer the fluid a considerably higher electro rheological effect [4].

The rheological behaviour of electrorheological fluid can be classified under three modes of flow as

i) **Flow Mode: -** In this type of mode, two electrodes of the system are fixed and vibrational control is acquired by adjusting the flow motion between two fixed electrodes.

ii) **Shear Mode: -** In this type of mode, one electrode is free to translate or rotate relative to another fixed electrode so vibration control acquired by adjusting shear stress.

iii) **Squeeze Mode: -** In this type of mode, the electrode gap is changing and electrorheological fluid squeezed by normal force.

Among the other factors, the rheological properties of electrorheological fluid flow depends on particle density, particle size, particle shape, particle distribution, nature and properties of the base fluid, types of additives, electric force and range of temperature. Generally, in absence of electric field the nature of electrorheological fluids based on characteristics of base fluid, types of additives, particle volume ratio, etc., whereas in presence of electric field nature of electrorheological fluid based on the liquid-solid phase properties and the volume ratio of the liquid-solid phase.

2. PROPERTIES OF ER FLUID

ER fluids are generally consists of dispersion of polarized or electrically active particles in an insulating base fluid such as silicon oil or composed of liquid crystal polymers [5]. Electrorheological fluids are also referred as smart materials and by the application of external electric force on these fluids show extreme changes in their rheological behaviour. In this manner, typical electrorheological fluids can go from the consistency of a fluid to that of a semisolid fluid, and back, with reaction time about milliseconds. Such type of effect is also called the Winslow effect.

Electrorheological fluids contain suspension of micron-sized particles randomly suspended in a base fluid (usually oils, silicones, water). In absence of an external electric force, electrorheological fluids flow freely and randomly. If we apply a particular electric force then the micro sized particles polarize and align themselves with the applied electric force. This type of polarization and particle alignment enables electrorheological fluid to quickly increase its own viscosity and transform from fluid like state to a semi-solid like state. Because of its adjustable viscosity and quick response time, electrorheological fluids have attracted much interest in various areas of science and technology [6].

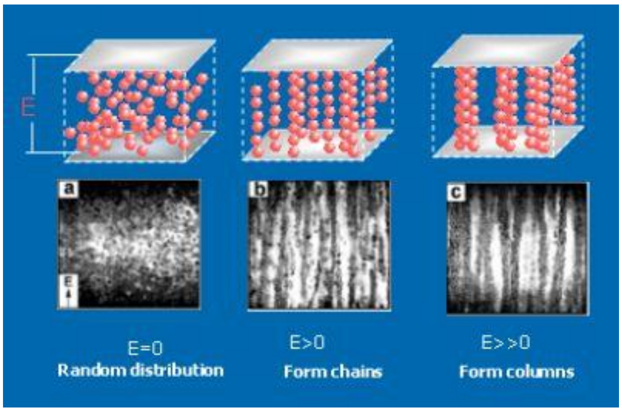

Fig –1: Alignment of particles

The properties of electrorheological fluids are not only related to the characteristics of the base fluid and particles, but also to their volume or mass ratio in relation to the base fluid. Presently, research concerning the properties and experimental methods used to produce ER fluids are kept secret. The fundamental and rheological properties of electrorheological fluids can be altered by changing the density of the electric particles and base fluid. In general, increasing the concentration of electric particles in the base fluid or increasing the strength of the electric force will increase the magnitude of the electrorheological fluid effect on the system. Also, the behaviour and properties of electrorheological fluids depends upon particle size, particle density, properties of base fluid, temperature and additives.

A higher concentration of volume ratio of the dispersed phase of electrorheological fluid can offer the fluid a much higher electro rheological effect, but also it can create problems. Sedimentation of particles is a major factor, since higher concentration of particles in ER fluid increase the amount of particle settling. The another major problem is temperature. When the temperature on electrorheological fluid increases, the viscosity of fluid decreases this results in diminishes yield stress. Rheological properties of electrorheological fluids are presented in Table 1. [7];

Table -1: Properties of Electrorheological Fluids

Properties	Normal Range
Maximum Yield Stress	$2-5$kPa
Maximum Field	~ 4kA/m (limited by breakdown)
Viscosity of Fluid	$0.1-1.0$ Pa-sec
Operable Temperature Range	$+10$ to $+90^0$C (Ionic, DC) -25 to $+90^0$C (Non-ionic, DC)
Stability	Can't endure impurities
Response Time	$< milliseconds$
Density	$1-2$ g/cm^3
Maximum Energy Density	0.001 J/cm^3
External Power Supply (Typical)	$2-5$ kV at $1-10$ mA (2-50 Watts)

One of the major properties of an electrorheological fluid is its variable yield stress that is the minimum stress need to cause the ER fluid to flow under the electric force. Often higher yield stress is expected and in recent electrorheological fluids its approximate range from 100 Pa to over 3 KPa. However, it is not easy to compare various electrorheological fluids and its behaviour because of lacking in standard analysis and different internal forces as well as the strong dependence of electrorheological behaviour on particle composition.

The main advantages of electrorheological fluids are:

- Electrorheological fluids are controllable and undergo a reversible change in their properties when exposed to an electric force.
- Electric forces are easy to supply and control.
- Electrorheological fluids are reasonable for analytical modelling and dynamic applications.
- The low density of the electric particles also helps to keep the density of the entire electrorheological fluid at a moderate level, ranging from 1 to 2 [gram/cm^3].

The controllable behaviour of ER fluid is used in many engineering applications where variable performance is greatly desired. The rheological response of electrorheological fluid to an external applied electric field could be observed in a variety of material rheological properties.

3. BASIC GOVERNING EQUATIONS

The set of governing equations for ER fluids in presence of electromagnetic field are given as [8],

$$\dot{\rho} + \rho\, div\, v = 0 \quad \dots (1)$$

$$\rho\dot{v} - div.T = \rho f + f_e \quad \dots (2)$$

$$\rho\dot{e} - k\Delta\theta = T.D + \dot{P}.\varepsilon + (P.\varepsilon)divv - \mathcal{M}.\dot{B} + \mathfrak{J}.\mathcal{E} + \rho r \quad \dots (3)$$

$$\varepsilon(P \otimes \epsilon + \mathcal{M} \otimes B) = 0 \quad \dots (4)$$

$$(T + \emptyset I).D + k\frac{|\nabla\theta|^2}{\theta} + \mathfrak{J}.\mathcal{E} \geq 0 \quad \dots (5)$$

$$div(D_e) = q_e \quad \dots (6)$$

$$curlE + \frac{1}{c}\frac{\partial B}{\partial t} = 0 \quad \dots (7)$$

$$div\, B = 0 \quad \dots (8)$$

$$curlH = \frac{1}{c}\frac{\partial D_e}{\partial t} + \frac{1}{c}(\mathfrak{J} + q_e v) \quad \dots (9)$$

$$\frac{\partial q_e}{\partial t} + div\,(\mathfrak{J} + q_e v) = 0 \quad \dots (10)$$

Where f_e is given by,

$$f_e = q_e E + \frac{1}{c}J \times B + \frac{1}{c}\left(\frac{dP}{dt} + (div.v)P\right) \times B + \frac{1}{c}v \times ([\nabla B]P) + [\nabla B]^T\mathcal{M} + [\nabla E]P \quad \dots (11)$$

Moreover, the thermodynamic pressure $\emptyset$ is defined as;

$$\emptyset = \rho^2\frac{\partial\psi}{\partial\rho} \quad \dots (12)$$

The material and balance equations i.e. equations from (1) to (5), excluding the terms because of the interactions of the electromagnetic fields and the material, are remain invariant under Galilean transformation equations is given by,

$$x' = x - xt \quad \dots (13)$$

$$y' = y \quad \dots (14)$$

$$z' = z \quad \dots (15)$$

$$t' = t \quad \dots (16)$$

In addition, the set of Maxwell equations from (6) to (10) are remain invariant under Lorentz transformations is given by,

$$x' = \alpha(x - xt) \quad \dots (17)$$

$$y' = y \quad \dots (18)$$

$$z' = z \quad \dots (19)$$

$$t' = \alpha\left(t - \frac{v}{c^2}x\right) \quad \dots (20)$$

Where $\alpha = \sqrt{1 - \frac{v^2}{c^2}}$ is the Lorentz contraction factor and if $v \ll c = \frac{v^2}{c^2} \to 0$ and then $\alpha \to 1$, then the Lorentz transformation reduces to Galilean transformation for small velocities comparable to light.

4. APPLICATIONS

Electrorheological fluids belongs to a class of smart materials and mostly used as a controllable fluids. The working behaviour of the ER fluids are utilized into three distinct modes of operation, as a) shear mode, b) flow mode and c) squeeze mode [4,9]. Electrorheological fluid technology has a many applications in the coming generation. This technology is utilized in the places where controlled fluid with varying viscosity is requisite. The important features of this technology are quick response, intelligent controllability and straightforward interface between electrical input and mechanical response or output.

This ERF technology is simple and includes less moving parts. Consequently, ERF based devices require less maintenance and have long lasting. Now day's automobile industries are utilizing this ERF technology. This type of technology is also used in medical and aerospace field. There is an implication for future research in ERF technology. In coming years, improved ERF technology will make it smart and advanced technology of future.

The applications of ER fluids can be categorized into four main areas: controlling devices, sensor devices, mechanical polishing and in detection of drugs delivery. The ER dampers, brakes, hydraulic valves, clutches, shock absorbers, robotic arms, gripping devices, human muscle stimulator and seismic frame structures are the examples of controlling devices of ER fluid.

4.1 ER Applications for Controlling Devices

The main characteristics of electrorheological fluid is that the mechanical properties of ER fluid can be continuously and reversibly balanced from the fluid state to solid like state by changing the effect of electric field on electrorheological fluid. From automobile industry, there is high requirement of ER fluid for preparation of automotive controlling devices like dampers, clutches, shock absorbers, brakes and hydraulic valves [10-12]. The ER fluid is smart material that has been designed as a workable engineering material, non-toxic to human, with high strength, low power consumption, wide temperature range, non corrosive to devices and good compatibility with sealing systems.

The ER damper is most common application of ER fluid in mechanical system. Actual ER damping devices are designed for meeting practical needs like suspension of system, shock absorber, control of system, automotive engine mount and design/ structure of system. There is lot of research addressing how ER damper works in semi-active suspension and its applications in automobile industry. In ER damper, in presence of applied electric field, ER fluid forms fibrillated chain like structure and it increases yield stress.

ER dampers [13] have been vastly used to control vibrations in the field of automobiles, railwayroad vehicles and civil structures. This applications are used to achieve a stability and comfortable journeys in vehicle. Smart structure applications of ER fluids incorporate aircraft wings, dash panels, robotic arms and helicopters.

Vehicle brake system, is the another possible application of ER fluid. A brake is a mechanical design that inhibits movement by absorbing energy from a moving system. Brakes are applied to rotating wheels to stop a vehicle system and it converts kinetic energy into heat. The friction brake is the most common technique utilized in brake system. However, in this system there are certain limitations like periodic replacement, time-delay, bulky size and so on. Electrorheological fluids are a type of controllable fluids, and inducing a great attention in these days. In this fluid shear stress is almost independent of the shear rate, but vary according to the applied electric field [14]. Making use of this property of ER fluid, the ER brake system is developed. MR brakes commonly work in the shear mode but might also work in the flow mode.

A haptic devices based on an electrorheological fluid developed for preparation of joystick that adjust the movement of a cursor on a system screen [15]. This type of haptic devices can be utilized in various fields like assisting interface for blind persons working with computer, computer games, and operation of machines.

4.2 ER Sensors

ER fluid has potential applications in smart and advanced electronics, with the fluid incorporated in components such as sensors, rollable screens, and keypads sticks. The ER fluid sensors are active sensors and used for self-monitoring and control in building structure design. This kind of sensor also utilized as a detector of seismography and to find the working performance of bridge vibrations [10]. Another study of ER sensor proposes the response for active vibration for dynamic system.

4.3 ER Mechanical Polishing

Electrorheological (ER) fluid assisted mechanical polishing operation is the ultra precision finishing technology that has been used to polish lenses, dies and diamonds. The rheological properties of ER fluids are key to their successful implementation into a precision finishing and polishing process. This method of polishing developed to overcome fundamental limitations of traditional finishing methods [16]. The mechanism of the ER polishing is shown in Fig. 2.

The technology of ER mechanical polishing of finishing for optics, lenses, ceramics and semiconductors is one of the most promising uses of the electrorheological effect.

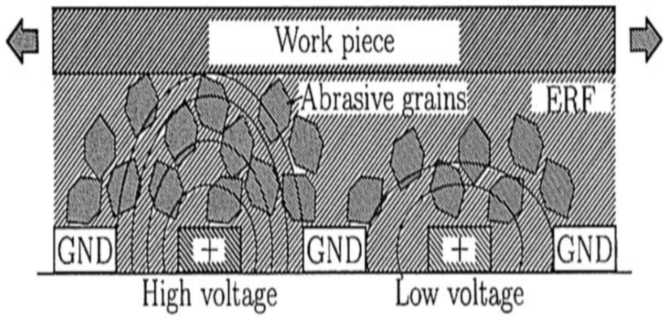

Fig –2: ER polishing mechanism

The process of ERF polishing is shown in Fig. 3. A convex lens is located at some fixed distance from moving wall. The electromagnet is located below the moving wall which generates variable magnetic field on the MR fluid. The essential characteristics required for electrorheological fluid polishing are as follows [17]:

- High concentration of particles
- High yield stress
- Resistance to corrosion
- Sedimentation stability
- High polishing efficiency

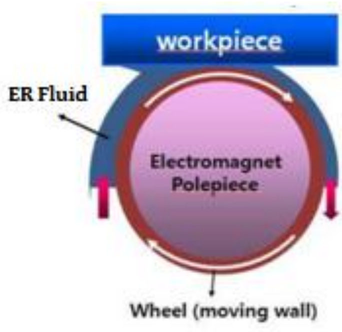

Fig –3: ER polishing process

The advantages of ER finishing over traditional methods are given below [18]:

1. ER finishing is a non-contact process of treatment that generates no surface and surface damages during finishing process.
2. Electric field on ER fluid resulting high efficiency of finishing and polishing. There is no limitation on the size of the particles.
3. This process is very safe and there are no wearing parts or system elements to be periodically restored. Hence, the polishing area provides stable and reproducible conditions for finishing.
4. The mechanism of the ER finishing provides predictable quality of finishing and polishing of desired product.

4.4 ER Applications for Detection of Drug Delivery

The feature of ER fluid is also used for detection of drugs delivery process. In this process, the fundamental simulation shows that partial ordering of the fluid particles may decrease the diffusion pathlength of the electrorheological fluid [10]. By using this property of ER fluid, the drugs molecules may have minimum distance to travel before being released, effecting in higher stress rates. The arrangement and ordering degree of freedom of ER particle can be regulated by applied electric force, and hence release rate can also be regulated by an external electric force. Hence this type of equipments used for detection of drug delivery with ER fluid gives quick and significant response for prediction of possibility.

5. CONCLUSIONS

The devices based on ER fluids have a very promising potential future including dampers, polishing devices, robotic arms, hydraulic valves, clutches, brakes, etc.. Most of them have been utilized commercially in advanced engineering applications like polishing machines, cars and exercise equipment. This paper deeply explains the common applications of electrorheological fluids in various areas of science and technology.

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