CHAPTER-I

INTRODUCTION

AND

LITERATURE REVIEW

This chapter contains the basis of the research work carried out by the researcher in the field of Electrorheological Fluid (ERF). It has five sections, namely

- Introduction
- Electrorheological Fluid (ERF)
- Development in the field of ERF
- Aim of the research
- Organisation of the thesis

The section, Introduction traces the history of electrorheological fluid. The second section on Electrorheological Fluid (ERF) explains
different phenomenon related to electrorheological fluid. It contains some examples of practically used electrorheological fluids with their constituents and practical utility. The third section, Development in the field of ERF includes the research work already done in this field and scope of research to be done in the field. On the basis of survey done in the third section, the aim of the present research work is specified in the fourth section, namely Aim of the research. The last section in this chapter, Organisation of the thesis contains the structure of the thesis and substance of each chapter of the thesis.

1.1 Introduction

Many fluids undergo significant changes in their properties due to the application of a field, electric or magnetic, providing the possibility for the gainful exploitation of this fact in technological applications. As early as the 19th century (Duff, 1896 [34]; Quinke, 1897 [73]), scientists began studying electrorheological (ER) response, although it was not until research by Winslow that electroviscous phenomena gained prominent attention. In the late 1930's Winslow, an intrepid basement experimentalist, observed interesting phenomena
when dielectric particles suspended in oil were subject to an electric field. He saw the electrically induced formation of fibrous particle chains aligned with the electric field and, of more interest, Winslow found that the effective viscosity of the suspension could be varied by orders of magnitude by varying the applied electric field (W. M. Winslow, 1949[99]). In fact he observed that the viscosity increased with the square of the applied electric field. This electrorheological (ER) response is often referred to as the Winslow effect and fluids that show this behaviour are called electrorheological fluids (ERFs). He introduced the concept of controlling the viscosity of an electrorheological fluid by use of an electric field (Winslow, 1947[98], 1949[99]). Flow resistance of these fluids increased with field strength when exposed to AC electric fields on the order of 4kV/mm. He observed a fibrous structure composed of particle chains generally aligned with the applied electric field. Winslow hypothesized that these field induced particle chains increased the viscosity of the fluid. Electrorheological fluids are usually composed of fine solid particles and insulating oils. When an external electric field is applied to an ER fluid in a static state, the particles form regular structures. For ER flu-
ids under an external electric field, extra energy is needed to break these structures, showing a significant increase of shear stress and apparent viscosity of the fluids. Winslow recognized the potential of these new fluids with their tunable viscosities and patented several electro-mechanical devices such as clutches, brakes, and valves that could be controlled by varying the electric field (W. M. Winslow, 1947[98]; W. M. Winslow, 1962[100]). Although none of his machines were ever used commercially, there is now a renewed interest in designing controllable machines and devices using ER fluids, probably partially fuelled by the electronics technology available today to quickly access and analyze system data (M. Massie et al., 1994[66]; T. Sheridan, 1992[82]; T. Ushijima et al., 1988[94]; Virtual Technology, 1999[95]; Graf, 1996[47]) . Of course, the devices of Winslow are only a partial list of the possibilities, but even so it is apparent that these fluids could profoundly change many aspects of present technology and industry. Considerable interest has been evinced in the manufacture of electrorheological and magnetic fluids in view of their potential applications in clutches, shock absorbers, valves, actuators, and exercise equipment, to name a few (M. Massie et al.,
1994[66], T. Sheridan, 1992[82], T. Ushijima et al., 1988[94], Virtual Technology, 1999[95]). More recently, field dependent solids have been produced, by infusing elastomers with electrorheological fluids or embedding them with electrically conducting particles, known popularly as electro-active elastomers (Goldstein, 1990[45]). Similarly, magneto-active elastomers have been created by embedding elastomers with magnetically responsive particles ([82], [95], [94]). Such field dependent solids find potential uses in a variety of applications by virtue of their change of structure and its consequent effect on the elasticity and compliance of the material. Many of the currently available ER fluids, however, do not have the necessary properties for practical application. For example, they tend to settle out of suspension, have poor tribological properties, and, most importantly, do not have a high enough range of effective viscosity (or yield stress) for practical applications. Particularly for this latter problem, we must understand the underlying physics of the ER response in order to engineer better fluids.
1.2 Electrorheological Fluid (ERF)

Electrorheological (ER) fluids have electrically controllable stiffness, viscosity, and heat transfer properties. These fluids undergo significant changes in their properties due to the application of an electric field, providing the possibility for the gainful exploitation of this fact in technological applications. Electrorheological fluids are usually composed of fine solid particles and insulating oils. When an external electric field is applied to an ER fluid in a static state, the particles form regular structures. For ER fluids under an external electric field, extra energy is needed to break these structures, showing a significant increase of shear stress and apparent viscosity of the fluids.

1.2.1 Some Examples of Practically used ERF

An ER fluid consists of fine polarizable particles suspended in a fluid of lower dielectric constant. Typically such fluids are assembled with a continuous hydrophobic liquid phase (e.g. silicone oil) containing hydrophilic particles (e.g. Zeolite). The density of the particles is matched as closely as possible with that of the oil to
ensure good dispersion upon mixing of the ER fluid (Stangroom, 1978[84]; 1983[87]). An applied electric field aligns the dipoles of water molecules trapped in particles, thus polarizing the particles. Particle polarization changes their organization in the fluid and causes changes in fluid rheological properties. When particle chains are subjected to fluid shearing forces, the particles still attract even though they may be pulled away from each other (Duclos et al., 1988[33]). Higher electric field strength increases polarization and causes particle chains to pull together tighter and to lengthen the chains through the addition of more particles (Klingenberg et al., 1989[56]). These longer, stronger particle chains result in higher fluid viscosity and stiffness. At higher electric field levels (e.g. 3-4 kV/mm), destructive arcing can occur through the particle chains in the fluid.

Some of important Electrorheological fluids are

- polyaniline (PAn) powder dispersed in silicone oil, the concentration of volume ratio is 50% (Zhang Yong Liang et al. 2006[106]).
- LID 3354, manufactured by ER Fluid Developments Ltd., (ER
LID 3354 is an electrorheological fluid made up of 35% by volume of polymer particles in fluorosilicone base oil. It is designed for use as a general-purpose ER fluid with an optimal balance of critical properties and good engineering behavior. Solid and liquid are density matched to minimize settling. LID 3354 can be used in suitable equipment wherever electronic control of mechanical properties is required, such as in controlled dampers, actuators, clutches, brakes and valves. Its physical properties are: density: $1.46 \times 10^3 \text{kg/m}^3$; viscosity: $125\text{mPa.sec}$ at $30^\circ C$; boiling point: $>200^\circ C$; insoluble in water; freezing point: $<-20^\circ C$.

• LID 3354S, manufactured by Smart Technology Ltd. (Haptic Technology, 1999[50]; Sensable Technologies, 1999[81]). It is an electrorheological fluid made up of 35% by volume of polymer particles in silicone/fluorolube base oil. It is designed for use as a general-purpose ER fluid with an optimal balance of critical properties. Its physical properties are: density: $1.46 \times 10^3 \text{kg/m}^3$; viscosity: $110\text{mPa.sec}$ at $30^\circ C$; boiling point:
> 200°C; insoluble in water; freezing point: < −20°C.

1.2.2 Uses of ERF

Since the 1940's researchers have attempted to model the properties of ER fluids and have proposed applications which attempt to utilize their special characteristics in the operation of hydraulic valves, soft clutches, and active suspension systems. Early attempts to make these applications commercially successful were hampered by the relatively slow, nonlinear response of ER fluids under on-off control of high electric fields. Successful applications will require fast, precise control of the response of ER fluids, independent of application at low field strengths. Engineers and scientists have identified possible applications including vehicle suspensions, hydraulic valves and soft clutches that would utilize the special properties of ER fluids. Development of commercial applications of devices using ER fluids has been hampered by the inability to quickly and precisely control the ER fluid state. Electrorheological fluids have not responded with precision and accuracy, which suggests that a new strategy is necessary for successful commercialization to occur. Previous studies
have focused on varying essential aspects of ER fluids including ER effect, preparation of an ER fluid, particle temperature range, yield strengths, shear stress, and the control of systems harnessing ER fluid properties.

Some of the important scientific and industrial uses of electrorheological fluid are

- in hydraulic valve,
- in soft clutches (Bullough, Johnson, Hosseini-Sianaki, Makin and Firoozian, 1993[16]),
- active suspension system (S. B. Choi, 1999[20])
- suspension for automobile-Control over a fluids rheological properties offers the promise of many possibilities in engineering for actuation and control of mechanical motion. Devices that rely on hydraulics can benefit from ERFs quick response times and reduction in device complexity. Their solid-like properties in the presence of a field can be used to transmit forces over a large range and have found a large number of applications (T. Duclos, J. Carlson, M. Chrzan, and J. P. Coulter, 1992,[32]). Devices de-
signed to utilize ERFs include shock absorbers, active dampers, adaptive gripping devices, and variable flow pumps.

- For many years, the robotic community sought to develop robots that can eventually operate autonomously and eliminate the need for human operators. However, there is an increasing realization that there are some tasks that humans can perform significantly better but, due to associated hazards, distance, physical limitations and other causes, only robots can be employed to perform these tasks. Remotely performing these tasks by operating robots as human surrogates, which is referred to as telepresence, requires an intuitive way to allow the operator to feel like physically being present at the remote site (Burdrea, Zhuang, Roskos, Silver and Langrana, 1992[17]; Burdea, 1996[18]; Burdea and Langrana, 1993[19]). Haptic feedback is necessary to mirror the stiffness and forces to the human operator from the remote site, which can be virtual (Bar-Cohen, Mavroidis, Pfeiffer, Culbert and Magruder, 1999[6]; Bar-Cohen, Pfeiffer, Mavroidis and Dolgin, 1999[7]; Bejczy and Salisbury,
1980[9]). Using electroactive polymers or smart materials can enable to develop many interesting devices and methodologies to support the need for haptic interface in such areas as automation, robotics, medical, games, sport and others. The Electrorheological fluids may be used to allow feeling the environment at remote or virtual robotic manipulators. A new device has been introduced by Charles Pfeiffera, Constantinos Mavroidisa, Yoseph Bar-Cohenb, and Benjamin Dolginb (Johnson Space Center, 1997[55]) for operators to sense the interaction of forces exerted upon a robotic manipulator that is being controlled. An analytical model was developed by them and experiments were conducted on the so-called electrically controlled stiffness (ECS) element, which is the key to the new haptic interface. A scaled size experimental unit was constructed and allowed to demonstrate the feasibility of the mechanism by the group.

The list is a partial one and new applications of ERF in technology are innumerate. Scientists and engineers, therefore call it also a smart
Polymeric materials have been extensively investigated for use as particles and are often chosen for enhanced viscosity performance and specific mechanical applications (Stangroom, 1977[83]; 1978[84]; 1980[85]; 1984[88]; Block and Kelly, 1986[11]). Environmentally safe fluids that more readily transform from a Newtonian material to a Bingham plastic have also been examined (Stangroom, 1982[86]; Block and Kelly, 1986[11]). Despite progress in these areas of research, precise control of ER fluid response has eluded investigators. Investigators turned their attention to modelling the ER phenomena in an effort to better understand fluid response precision and speed. A simulation method was developed to describe structure formation in electrorheological suspensions (Klingenberg et al, 1989[56]). Tao and Sun (1991[91], 1991[92]) examined the ground state and the various phases that exist in the ER fluid. The dynamic stress-strain behavior of an ER fluid was investigated by Yen and Achorn (1991[101]). Properties were determined for an ER fluid consisting of 20% vol. zeolite particles, and a model was proposed to explain the mechanical response in terms of the dielectric mismatch between
particles, carrier fluid, and field (Conrad et al., 1991[21]). Current devices such as ER fluid based valves, clutches or hydraulic mounts typically do not react quickly or precisely enough to meet needs of the applications (Duclos, 1987[31]; Ushijima et al., 1988[94], Arguelles et al., 1973[4]). Stangroom (1983[87]) recognized the importance that feedback would add to the control of devices. Lloyd and Zhang, (1994[58]) and Zhang and Lloyd, (1992[102], 1992[103]) used low particle volume fluids to control transport of thermal energy by a feed-forward control method and found very slow ER fluid response. They reported that response time was several minutes as compared to fractions of seconds with high particle volume concentrations. Greater control of the speed and precision of ER fluid response was the objective of that study. Laboratory and analytical comparisons were made between state feedback and conventional open-loop control of a low particle volume concentration ER fluid in their study. Analytical models for the ER fluid and control systems were developed which predict ER fluid state responses to the application of both conventional and state feedback control of the fluid. Effective and efficient control of an ER fluid is necessary in order
to achieve the benefits of their controllable properties and successful application

1.3 Development in the field of ERF

Electrorheological fluids have been widely investigated in recent years for their wide potential on industrial applications. F.L. T. Bonnecaze and J. F. Brady (1992[14a]) proposed a detailed micromechanical model relating the bulk rheological properties to the suspension microstructure in 1991. Their endeavor was to understand ER fluids with a molecular-dynamics-like simulation. The simulation accurately accounts for both hydrodynamic forces due to an imposed shear flow and electrostatic forces due to the applied electric field. The simulation allows the observation of the time-evolved motions of the suspended particles and the instantaneous rheology of the suspension, so we can directly relate the suspension bulk properties to its microstructure and gain insight into the processes involved. In addition, the simulation method provides a means to test theories that describe ER suspensions, including constitutive models.

The Bingham model (Wineman and Rajagopal, 1995[96a]) is nor-
mally employed to describe the shear behavior

\[ t = \tau_E + \eta_o \dot{\gamma} \]

where \( t \) is shear stress, \( \tau_E \) is shear yield stress, \( \eta_o \) is low field viscosity, and \( \dot{\gamma} \) is shear rate. The shear yield stress is induced by the interactions between particles, and different polarization models have been proposed to approach the interaction force (H. Conrad, 1991[21]). The shear yield stress is found to be affected by many factors, such as external electric field strength, field frequency, dielectric mismatch between particles and host oils, particulate volume fraction, particle shape, temperature, shear rate, etc. (H. Conrad, 1991[21]; H. Block and J. P. Kelly, 1988[12]). Although the particle interaction is the key issue in the ER effect, researchers have found that the particle structure is also very important in the ER mechanism. Tao et al. have done much work on static structures of particles under electric fields (R. Tao et al., 1991[91]; 1991[92]). Although ER fluids have been widely investigated under the shear mode which is important for so many applications, the low shear yield strength has been a crucial restriction for industrial ER applications. So recently some
investigators have turned to the study of the compression mode of ER fluids. This mode can produce compressive stresses much higher than the shear yield stress.

Early electrorheological fluids were suspensions of linear dielectrics in a non-conducting fluid which on the application of an electric field of appropriate strength could change their viscosity by several orders of magnitude. Initial attempts at the manufacture of such fluids were complicated by the lack of a proper understanding of the detrimental role of water in such suspensions. Winslow (W. M. Winslow, 1949[99]) is credited with the earliest observations on the behaviour of electrorheological fluids. Since his early work, great strides have been made in the manufacture of such fluids. Ferroelectric materials have been used as the suspended medium with a view towards gainfully employing the existence of a Curie temperature, on either side of which the suspension can exhibit drastically different properties. Recently, there has been a suggestion to use superconducting ceramic particles in a non-conducting fluid with the hope that the voltage requirements to produce significant changes in the material properties can be considerably reduced. The main stumbling blocks, that have
prevented the translation of the physically observed changes in the material properties to the fabrication of devices, are the abrasive nature of the suspended medium that erodes the device in which the electrorheological material is used, the lack of structural stability of the suspension that leads to the settling of the particles and the enormously high voltage requirements that are necessary to produce a significant change in the material properties. Great strides have been made to overcome all of the above impediments. Polymer based particles have been produced (R. Bloodworth, 1994[13]) that helps to mitigate the problem of abrasion and the addition of stabilizers has alleviated the problem of settling in the suspension, while the use of ferroelectrics and newer electrorheological materials can significantly reduce the voltage requirements. Thus, electrorheological fluids are at the brink of having their potential being realized.

While a general frame-work can be developed for the whole class of field dependent materials, its generality inhibits a detailed analysis and thus in this study here, we shall restrict ourselves to electrorheological fluids. Electrorheological fluids lend themselves to be modelled in many ways. The simplest approach for the mod-
elling of such suspensions is to treat them in a homogenized sense within the frame-work of continuum mechanics. Such an approach has been adopted by a variety of researchers (Atkin and Bulloch, 1991[4a]; Rajagopal and Wineman, 1992 [75a]; Wineman and Rajagopal, 1995[96a]). A slightly more complicated, but yet a continuum approach, is to model the suspension as a mixture of a particulate medium in a fluid that allows for the interaction between the constituents such as drag forces, virtual mass effect, Magnus effect, Basset forces, etc. (Rajagopal, Yalamanchili and Wineman, 1994[74a]). A completely different perspective is provided by modelling based on direct numerical simulation that takes into account the dynamics of each particle due to the action of the other particles, and the interstitial fluid. When large numbers of particles are involved such an effort becomes insuperable even for the simplest of flows. There have been numerous one-dimensional models to describe the behaviour of electrorheological fluids (Conrad, Sprecher, Choi and Chen, 1991[21]). However, such models can be generalized in a non-unique fashion to lead to a plethora of three-dimensional models, that is, all these three-dimensional models would collapse to
the same one-dimensional model. Moreover, important issues such as frame-indifference and material symmetry cannot be treated within the confines of such theories. Recently, Rajagopal and Wineman (1992[75a]) developed three dimensional models, that satisfy appropriate invariance requirements, wherein the electric field was treated as a constant and not a field. A justification for such an assumption was that the gaps within which the fluid flowed were sufficiently small to render the assumption true. While this model captured some of the features exhibited by electrorheological fluids such as its Bingham like response, it failed to capture the viscoelastic response exhibited by such materials (Yen and Achorn, 1991[101]). In order to mimic the viscoelastic response of electrorheological fluids, Wineman and Rajagopal (1995[96a]) developed a model for electrorheological fluids, which in the absence of the electric field would lead to general models for viscoelastic fluids. It would be appropriate to point out that it is not definite that all electrorheological materials exhibit viscoelastic response. Of course, if the carrier fluid is viscoelastic we may expect the suspension to exhibit such characteristics. However, in the case of a carrier fluid that is Newtonian the viscoelastic-
like response observed may be due to the time taken to form the structure (alignment of the particles due to the field and the formations of chains) on the application of the field, this time constant being associated with the relaxation time for the material. However, even in the models developed in Wineman and Rajagopal, the electric field was treated as a constant and thus a parameter in the problem, whereby the complex interactions between the electrical, mechanical and magnetic fields are lost. In fact, there is abundant experimental evidence in the literature (Abu-Jdayil, Brunn, 1997[3]; 1996[2]; 1995[1], Wunderlich, Brunn, 2000[97]) that the behaviour of electrorheological fluids is strongly influenced by non-homogeneous electrical fields. This shows that a mathematical model of ERF capturing the behaviour of the fluid in a variable electric field is required to understand the fluid in detail. This will help to tune its viscosity more precisely for technological use.

1.3.1 Aim of the research

In order to take into account effects cited above, attempt is made in this research to develop a theory in which the electric field is treated
as a variable that is determined by solution of Maxwell’s equations. The constitutive theory for the fluids is kept relatively simple to make the modelling amenable to analysis. In addition to obeying the balance laws for mass, momentum, and energy, it require that all motions of the fluid meet the second law of thermodynamics which is assumed in the form of the Clausius-Duhem inequality. Of course, the fluid is also required to satisfy Gauss’ law, Faraday’s law, Ampere’s law, the conservation of electric charge and the conservation of magnetic flux.

1.3.2 Organisation of the thesis

This first chapter gives an account of the science related to electrorheological fluid, composition of some practically used ERFs, some important uses of ERF, recent research and development in the field of ERF. Finally this chapter identifies the research to be carried out in this thesis.

In the second chapter a model is developed which captures the above described features of ERF. Here the ERF is assumed to be a homogenized fluid within the frame- work of continuum mechanics.
In particular the complex interaction of the electro-magnetic fields and the moving liquid is taken into account, thus treating the electric field as a variable that is determined by Maxwell's equations. The final system describing the motion of ERFs is derived from the general balance laws of thermodynamics and electrodynamics by a non-dimensionalization and subsequent approximations which are realistic for electrorheological fluids.

In the third chapter existence of strong solutions for velocity in terms of electric field for the mechanical part of the system describing the flow of ERFs (i.e. the balance of mass and momentum) is shown. It is seen that the constitutive relation for the extra stress tensor implies that the system possesses $p$-structure, where however $p = p(|E|^2)$ is a material function and not a constant. Thus the model explains the dependence of viscosity on electric field.

In the fourth chapter a comparison between a strong solution of the continuous system and a weak solution of the fully implicit time-discretization of this system under the additional assumption of constant $p$-structure (i.e. $p = \text{constant}$) is shown.

The fifth chapter contains the discussion of results and future
scope of study in the field.

The list of references used in the thesis is given at the end of the thesis in an alphabetic order of last names of authors with a serial number attached to each reference.