

2
2000

This is to certify that the

thesis entitled

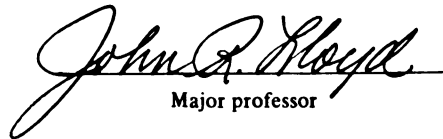
DYNAMIC SIMULATION OF THE ELECTORHEOLOGICAL
EFFECT IN A UNIFORMLY DISTRIBUTED
ELECTRIC FIELD

presented by

Nicolae Cristescu

has been accepted towards fulfillment
of the requirements for

Masters degree in Mechanical Engineering


Major professor

Date 2/24/00

LIBRARY
Michigan State
University

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.
MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE

**DYNAMIC SIMULATION OF THE ELECTORRHEOLOGICAL
EFFECT IN A UNIFORMLY DISTRIBUTED
ELECTRIC FIELD**

By

NICOLAE CRISTESCU

A THESIS

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

MASTER OF SCIENCE

Department of Mechanical Engineering

2000

ABSTRACT

DYNAMIC SIMULATION OF THE ELECTORHEOLOGICAL EFFECT IN A UNIFORMLY DISTRIBUTED ELECTRIC FIELD

By

NICOLAE CRISTESCU

Structure formation of particle-based electrorheological fluids subject to a uniformly distributed electrical field is investigated by a numerical modeling and simulation method. The structure composites are considered to be electrically nonconducting. Particles are treated as hard polarizable spheres in a neutrally buoyant environment. The simulated structure formation is similar to the one observed in previous experiments and particle concentration is shown to have a significant influence with respect to the time of complete chaining and reaching a state near dynamic equilibrium. The simulation predicts that the higher the particle concentration, the shorter the time of aggregation. Numerical results, based on experimental input values also replicates the trend observed in experiments using optical transmittance of energy through ER fluids.

To my beloved mother, Eugenia

ACKNOWLEDGMENTS

I am grateful to Dr. John R. Lloyd, Distinguished University Professor, my graduate program advisor, for selecting a challenging and modern subject of research, that made this work a difficult, but intellectually rewarding task. His guidance in completing this work and more important, the pursue of excellence in the professional activity are things to be remembered.

I benefited from the lectures of Dr. Clark J. Radcliffe and Dr. Mei Zhuang, while I was a student and later on, in this research. They were members of the examination committee and their assistance is gratefully acknowledged.

Without continuous support and encouragement of my beloved mother, Eugenia, I could not have finished this thesis and the graduate program. My gratitude for her, expressed in words, is just a pale form of recognition.

TABLE OF CONTENTS

List of Tables	vii
List of Figures	viii
Nomenclature	x
Chapter I	
1.1 Introduction	1
1.2 ER Effect	3
1.3 Materials used in ER Effect	6
1.4 Overview of Computer Simulation Reports	9
Chapter II	
2.1 Forces in ER Fluids	23
2.2 The Electrostatic Polarization Model	25
2.3 Structure formation	29
Chapter III	
3.1 Computational Model	32
3.2 Simulation Method	41
Chapter IV	
4.1 Results and Discussion	45
4.2 Time Scale	61
Chapter V	
5.1 Conclusions	63
5.2 Recommendations	65
Appendix	
1. Fundamental Issues	
1.A Polarization	66

1.B Electrostatic Potential. Electric Images	71
1.C Electrostatic Field. Electric Displacement	74
1.D Double Layer Theory	77
2. Hardware	79
 Bibliography	 86

LIST OF TABLES

1. Variation of Dipolar Force in the First Quadrant	81
2. Variation of Dipolar Force in the Second Quadrant	82
3. Variation of Dipolar Force in the Third Quadrant	83
4. Variation of Dipolar Force in the Fourth Quadrant	84
5. Mean Displacement of Particles	85
6. Typical Particle and Fluid Properties Used in Experiments	85

LIST OF FIGURES

Fig 1. Charge distribution of particles subject to electrical field	4
Fig 2. Attraction energy as a function of distance between particles	25
Fig 3. Coordinate system	27
Fig 4. Attraction between two particles aligned vertically	28
Fig 5. Repulsion between two particles aligned horizontally	28
Fig 6. Rotation and alignment of two particles	29
Fig 7. Mirror images of one particle	34
Fig 8. Repulsion forces between two particles	37
Fig 9. Repulsion forces between a particle and wall	37
Fig 1a-g. ER effect, volume particle concentration 10%	46-50
Fig 2a-f. ER effect, volume particle concentration 20%	51-54
Fig 3a-g. ER effect, volume particle concentration 35%	54-57
Fig 10. Kinetic of structure formation over entire time range	59
Fig 11. Initial kinetics of structure formation	60
Fig 12. Intermediate kinetics of structure formation	60
Fig A1. Atomic polarization	67
Fig A2. Molecular polarization	69
Fig A3. Orientation of natural polarized molecules	70

Fig A4. Orientation of natural polarized molecules in electrical field	70
Fig B1. Electric image of a point charge in a conducting plane	73
Fig B2. Infinite chain of electric images	74

NOMENCLATURE

A	Area	$[m^2]$
D	Electric Displacement Vector	$[C/m^2]$
E	Electrical Field Intensity	$[V/m]$
F	Force	$[N]$
L	Length	$[m]$
P	Dipole Moment	$[m \cdot C]$
Q	Electric charge	$[C]$
N	Number of molecules/particles	
R	Radius	$[m]$
T	Absolute temperature	$[K]$
U	Voltage	$[V]$
V	Volume	$[m^3]$
V_e	Electrostatic potential	$[V]$
W	Interaction Energy	$[J]$
a	Particle Diameter	$[m]$
r	Distance	$[m]$
r	Unit vector	
k_B	Boltzmann's constant	$[1.38054 \cdot 10^{-23} J/K]$
k_e	Specific inductive capacity	
k	Dielectric particle/fluid mismatch	
t	Time	$[s]$
v	Velocity	$[m/s]$

Greek Notations

α	Polarizability	
β	Dielectric Contrast Factor	
ϵ	Permittivity of material	$[F/m]$
ϵ_0	Permittivity of free space	$[F/m]$
μ	Viscosity	$[N \cdot s/m^2]$
χ_e	Susceptibility	
θ	Polar angle	$[degree]$

λ	Ratio polarization / thermal forces	
φ	Electric potential	[V]
σ	Surface charge per unit area	[C/m ²]
$\dot{\gamma}$	Shear rate	[1/s]
ρ	Density	[kg/m ³]
ϕ	Particle concentration	[%]
Λ	Dielectric tensor	

Superscripts

+	Positive
-	Negative
Br	Brownian
d	Dipolar
im	Electric Imagine
rep	Repulsion
w	Wall

Subscripts

A	Areal
a	Atomic
c	Continuum
e	Electronic
p	Particle
r	Relaxation
T	Total
V	Volumetric

Other

< >	Average
-----	---------

Chapter I

1.1 Introduction

Electro-rheological (ER) fluids are colloidal suspensions whose properties and characteristics can be controlled by application of an external electrical field over the entire fluid domain. They are composed and defined by the material properties of its composite main constituents (typically suspended particles and a carrier fluid).

Traditionally, these fluids were employed where the rheological behavior of the fluid was of particular interest. In recent years new studies have been conducted, which reveal that other transport properties are controllable, such as thermal and optical properties.

In the 1940's, Willis M. Winslow, a young electrical engineer, was inspired by an article published in "Electronics Magazine" describing the Johsen Rahbeck Effect about large forces of attraction which exist between electrodes separated by some types of semiconductors. One of his first applications was a photoelectric switch for turning the street lights on. Later he developed a dry clutch, which functioned erratically and "naturally" needed oil (Winslow M.W., 1949). These experiments, conducted in a step by step fashion, led to the use of powders dispersed in oil between

conducting electrodes to control the apparent viscosity of fluids, the magnitude of which was a function of the applied electric fields. W.M. Winslow patented his invention in 1947 and the patent office examiner called it the “Winslow effect” (Winslow M.W., 1953), although, electro-rheological phenomenon had been previously observed and reported by Koenig (1885) , Duff (1896) and Quinke (1897).

There is an effort in the engineering community to implement phenomena exhibited by ER fluids in marketable products. Typical applications include various mechanical devices as clutches, hydrodynamic valves, vibration isolation systems used in engine mounts and in helicopter blades.

Among applications resulting from the study of heat transfer phenomena, double-pipe and recuperative heat exchangers (Shulman, 1982) are to be mentioned. The heat exchanger employs ER fluids as the primary heat transfer agent, and a Newtonian fluid as the secondary agent. It is found that the ER effect increases the coefficient of heat transfer. Shulman reports a three fold increase in the convective heat transfer coefficient for ER effect in a double pipe heat exchanger, by controlling the concentration of diatomaceous earth in oil and the intensity of electrical field applied.

1.2 Electrorheological Effect

Typically ER fluids are suspensions of micron-sized hydrophilic particles suspended in a suitable liquid. These fluids undergo reversible changes in material properties and characteristics when they are subjected to an externally applied electrical field (Gandhi et. al., 1989).

ER fluids are a class of colloidal dispersion, that when subjected to an external electrical field exhibit reversible changes in rheological behavior. Also an ER fluid has Newtonian characteristics in the absence of an electrical field and becomes non-Newtonian under this influence. By imposing an electrical field upon an ER fluid, the particle mass distribution is changed as is the fluid stiffness characteristics for the case when fluid is in motion.

Once the electric potential is turned to zero, the particles return to a state of random distribution due to Brownian motion effects. The voltage required to activate the ER effect typically ranges from 100 V/mm to 10 kV/mm (Zukoski, 1993), but the power required may be very low due to the very low current densities which can exist for some fluids which are on the order of $10 \mu\text{A}/\text{cm}^2$. The time for the fluid to respond to the electrical field excitation may be very long for low particle concentrations or very fast for high particle concentrations.

When the electric field is applied it induces both molecular polarization and interlayer surface polarization. The induced dipoles make the particles orient along electric field lines, and then the particles move until they approach and form chain like structures which span the gap between the electrodes.

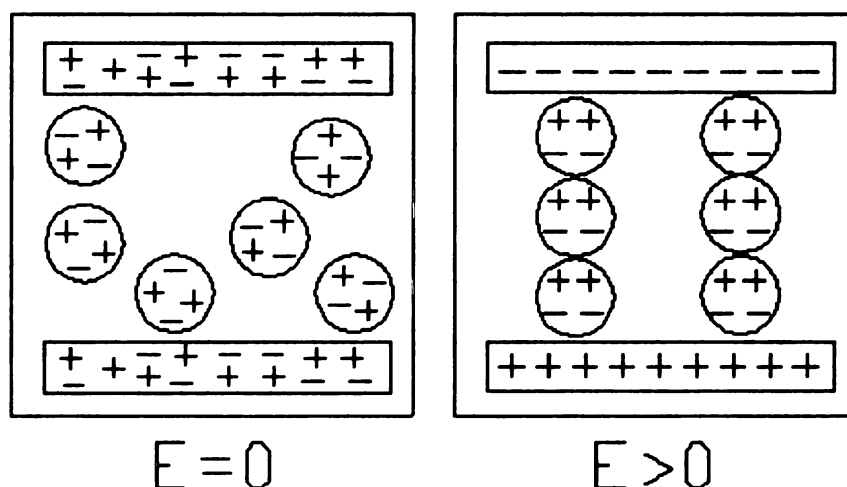


Fig.1 Charge distribution of particles under influence of external electrical field.

The induced dipole moment experienced by the particles depends on the material permittivity, conductance of the medium and particles, parameters of the electrical field, particle size and double layer characteristics. Winslow also studied the influence of additives, in particular of water, which can be absorbed by the particles, and as a result increase the

charge density of the electrical double layer, and then change the permittivity of the suspension (Winslow, 1949).

The initial theory, based on observations by Winslow, was that particle chains will become distorted under shear and will eventually break. If the field remains, new chains will reform again very rapidly. One concern about this model is the time scale in which the particle chains will develop. Klass and Martinek (1967) pointed out that ER activity is shown also at high AC frequency, and that these chains do not have the time to reform at such speeds. Brooks et. al. (1986) reported a time scale for fibrillation around 20 seconds which is considerably much larger than millisecond responses.

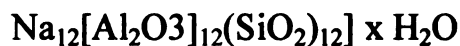
There is an ongoing research effort to study not only mechanical properties, but also other controllable fluid properties associated with the ER effect, such as thermal properties (Zhang and Lloyd, 1993), electrical properties (Shulman et.al. 1985), and optical properties (Gleb, 1974, Hargrove, 1997). Current research also is focused on understanding the determinant characteristic of the particle-fluid design which may be important in the development of ER fluid state sensor technology and on the use of these sensors to control fluid property variations in real time.

1.3 Materials used in ER structure.

The ER effect is present in two phase fluids, and in single phase materials such LCD crystals (Tao, 1995). The search for the new single phase fluids has been motivated by the numerous drawbacks the fluids have in typical applications: settling due to density differences between the particles and the suspending fluid, dielectric breakdown due to water molecule take-up, high power consumption when this water take-up occurs. One way to eliminate settling is by matching the densities of the two fluid components.

Zeolite material was discovered in 1756 by the Swedish mineralogist Axel Fredrick Cronstedt. He observed that heated samples emitted a gas, and this process was named after Greek words that mean “boiling stones”. Zeolites are large open framework structures and contain large polyhedral cages of atoms connected to each other by channels. The tetrahedral atom is usually silicone and is surrounded by four oxygen atoms (Pinnavaia, 1995). Aluminum atoms are substituted for some silicone atoms, thus giving the material the property of aluminosilicate with a framework structure with enclosed cavities that can be occupied by large ions and water molecules. These ions and/or molecules can move freely in that space.

The chemical formula for Zeolites is:



They have the capability of containing water molecules to a maximum content of 25 wt. % H_2O .

Of certain importance in the use of Zeolites is the fact that metal cations of Si and Al are not bound covalently into crystalline lattice (Pinnavaia, 1995). Thus they can migrate under the influence of an electrical field. This property opens the possibility of using the suspension in high temperature applications because the need of water as a charge carrier is not needed anymore.

In 1950 researchers from Union Carbide succeeded in the synthesis of Zeolites A and X and developed commercial technologies for gas purification, separation and catalysis using Zeolites (Pinnavaia, 1995). Due to their ability to enable ion exchange and sorbtion, they are widely used in radioactive waste storage water treatment, gas purification and animal feed supplements. Also polymers and semiconductor clusters assembled in Zeolites cages are the basic ingredient for nano-electronic materials. The Zeolites act as molecular sieves because they can incorporate selectively molecules in their channels and transport those.

Japanese researchers (Inoue, 1989) proposed to use composite particles for increasing the contribution of polarization, using particles made by a conducting material (metal) which are coated with a thin isolating layer.

Lord Corporation Inc. (Carlson, 1988) has created a crystalline material which possesses anisotropic permittivity and conduction only along a single axis. Current is conducted by means of protons and not by electrons, and they are attached to molecular carriers thus forming free ions.

One problem of these ER fluids is that particulate material often has a larger specific weight that will lead to sedimentation. Silica and some polymers particles have low density and thus are desirable to reduce sedimentation. One approach to overcome this inconvenience is to use hollow particles and to perfectly isolate them from the surrounding fluid. Another design proposed was light feather-like fibres, particularly phosphor-carbon fibres based on cellulose precursors (Korobko, 1991).

Although not so important as the dispersed phase, the disperse medium, the liquid, has to meet some requirements : stability to avoid degradation due to aging, purity, dielectric permittivity less than that of particles, non-toxic, hydrophobic, density around 0.95 g/cm^3 , break down voltage around 5 kV/mm . Several type of fluids are used: mineral oils synthetic dielectric fluids obtained by polimerization of unsaturated

hydrocarbons, ethers of various acids, polyoxyalkide compounds, kerosene etc.

In conclusion, the ER effect can be obtained with a wide variety of materials, particles and fluids. That makes the fundamental study of this phenomenon a challenging yet exciting task.

1.4 Overview of previous computer simulation reports.

Along with experimental investigations of the properties of ER fluids, numerical simulations have been developed (Bonnecaze 1989, Haas 1993, Klingenberg 1989, Martin 1998, Melrose 1991, Sun 1995, Tao 1991, Tao 1995). In general in these simulations the suspension is treated as polarizable spherical particles in a nonconducting medium. It is assumed that subject of polarization forces due to an applied electric field and hydrodynamic forces due to the viscous drag on particles were the primary forces on the particles. Some numerical simulations were designed for the case when ER composite is subject to a shear force (Bonnecaze 1989, Melrose 1991, Sun 1995), while other simulations do not include any movement induced by external shear force or fluid flow, in the presence of an applied electric field (Haas 1993, Klingenberg 1989, Martin 1998, Tao 1991, Tao 1995).

In order to model the ER phenomena effect some approximations have been made. Temperature effects are neglected. Brownian forces are assumed to be overwhelmed by electrostatic forces as proved later in this work, and there is no friction between particles and electrode walls. Particles are assumed to be spherical in form and are considered to be hard and compact. Almost all simulations present time “snapshots” of the ER phenomenon. Following is a computer simulation literature review, presented in chronological order for a better understanding of the evolution and trend of the research effort.

R.T. Bonnecaze and J.F.Brady, 1989 made a simulation with 25 particles, in an unbounded 2D monolayer. This simulation retained the underlying physics of the phenomenon. Particles are suspended in an incompressible Newtonian fluid of viscosity μ and density ρ . Their motion is governed by the Navier–Stokes equations. Brownian forces are neglected. Spheres are under the influence of an applied electric field along the “y” direction, and the shear flow is in the “x” direction. The Mason number (Ma), which measures the relative importance of shear forces to the electrostatic forces, is employed. The presence of particles in suspension makes two contributions to the bulk stress: an average mechanical stress

transmitted by the fluid due the shear flow, and an average stress due to the electrostatic interparticle forces.

The model of electrostatic interparticle forces is a good approximation for the case when the applied electric field does not vary too rapidly in space, and when higher order moments are small. The dielectric constant of the suspension can be computed knowing the bulk electric displacement:

$$\mathbf{D} = \epsilon \cdot \bar{\mathbf{E}} + \frac{N}{V} \cdot (\alpha \cdot \bar{\mathbf{E}}) \quad (1)$$

or:

$$\mathbf{D} = \Lambda \cdot \bar{\mathbf{E}} \quad (2)$$

where Λ is the dielectric tensor. The electrostatic equations are linear.

Their numerical solution indicates that viscosity increases with the inverse of Ma for $Ma \ll 0.01$. The increase in the total viscosity with decreasing Ma is due to both increasing hydrodynamic and ER viscosities. This increase is due to formation of chains of particles held together by electrostatic forces and pulled apart by hydrodynamic shearing forces. In the case of Ma of order $O(1)$ when there is a balance between electrostatic and hydrodynamic forces, the total viscosity approaches the zero field viscosity.

In 1989, Klingenberg, van Swol and Zukoski, introduced a simulation method based on the classical equation of motion of a particle under the influence of electric field and hydrodynamic flow. The system is made up of nonconducting solid spheres dispersed in a nonconducting fluid with no gravitational effects. Brownian forces are neglected, and the fluid includes a hydrodynamic viscous resistance due to the particle motion.

The dipole force is treated in a pairwise fashion. It ignores multibody interactions, and the value of the dielectric mismatch is considered to be small. In the authors opinion, multibody interactions and higher order corrections would produce only quantitative, not qualitative changes in anisotropic electric interaction. In order to simulate the electrodes as constant potential surfaces, point dipole interactions were used between the particles and their electric images. The simulation produces chains that span the gap between electrodes, and the final configurations are sensitive to the type of short-rang repulsion used in the computation.

In 1991 two other scientists, R. Tao and J.M. Sun, using Monte Carlo simulations, investigated the ground state of ER fluids in a strong electric field. Their results led to a body-centered-tetragonal (bct) structure lattice, made up of two types of chains, at room temperature. The 2-D computer model use the method of annealing which is useful for very large

scale optimization with many local minima energy. In this method the computing time for reaching a solution increases exponentially with the number of chains, thus a limited number of 16 chains were used. Both types of chains are considered to be infinite in length, and they induced dipolar interaction. There is repulsion between chains of same type and attraction between chains of different type.

The result is a square crystal region corresponding to a 301K temperature. The bct lattice is regarded as a compound of chains of class A and class B, where chains of class B are obtained from chains of class A by shifting a distance equal with a particle diameter in the direction of the electrical field. The explanation that bct lattice minimizes the dipolar interaction energy, is found in the fact that if two different chains are attractive and two similar are repulsive the ground structure has to have a chain of type A surrounded by B chains at the minimum distance and as far away from another chain A. The same explanations are made for chains B as well (Tao, 1991).

However, their simulation is based on the assumption that ER fluids are under a strong electric field, and that the parallel electrodes produce an infinite number of image dipoles. There are still open questions

about the behavior at lower electric field values as well as uncertainty about whether the ER system behaves as liquid or as a solid.

The answer to these questions would probably be given by a 2D Monte Carlo simulation, but even for small number of chains this would require more computing capabilities.

In 1991 J.R. Melrose from University of Surrey, U.K., examined the ER structure under shear, including the effect of Brownian forces. He used an algorithm that neglects the multibody interactions and is the linear version of the Langevin equation describing overdamped motion in a viscous medium. He used a steep power law repulsion between particles. The rotation of particles is neglected in the shear flow, and the shear is represented by a dimensionless Peclet number relating the shear to Brownian forces.

The model, that employs 108 particles, is characterized by four parameters: Peclet number, dipolar force, repulsion exponent and volume fraction. Due to competition between dipole, shear viscous, and Brownian forces, three distinct phases may exist: liquid, flowing crystalline, and shear string. Boundaries between phases are named “Stokesian transition” where a competition between shear and dipolar forces exist, and “Brownian transition” where a competition between thermal and dipolar forces exist.

More important is the crossover from Stokesian to Brownian transitions which can be driven by decreasing the particle size. This is good information for the design of ER fluid applications.

The results predict a layered crystalline phase in contrast with the previous chain model. They predict the importance of the particle size that will influence crossover for Stokesian to Brownian transitions. Finally the model provides a prediction of nonequilibrium phase diagram in sheared suspensions.

In the same year, 1991, H. Conrad , A.F. Sprecher and Y. Chen made a computer model based on the use of the Laplace equation of electric potential. The force is calculated as a function of the ratio of particle dielectric to fluid dielectric. The point dipole approximation is considered as being a simplification of the problem and leads to interactions that are smaller than what was observed experimentally. To correct this and to also consider the geometric configuration, scientists selected the Laplace equation as a better model. This is in better agreement with the experiment, and it is also in the range where dielectric mismatch is large. In their work Conrad et. al. (1991) computed the force between two spherical particles that form an infinite chain in the direction of the electric field, without taking into account the thermal or colloidal effects. The computational

results indicate that electric field distribution is intense in the region of particle contact, and also the electric field concentration depends on particle separation and polar angle. This observation led to the conclusion that geometrical arrangement of particles can have a two fold effect on the strength of ER fluids.

L.C. Davis, 1992, made a study based on the Tao and Sun (1991) report about the ground state of the ER effect. His approach was from a different perspective, the limiting case of $\epsilon_p / \epsilon_c \rightarrow \infty$. He determined the ground state by the method of computing the effective dielectric constant of the structure. Considering the electrostatic energy across the gap between surfaces of two particles, multiplying this with number of gaps, he equated this with the energy in a unit volume. The assumption that all the gaps are of the same type was made, but there was a distinction between gaps between two vertically aligned particles and the gaps between the diagonally aligned particles. The potential difference was twice as much as in the first model. From the computation of the free energy per particle for such lattice configurations as face-centered cubic (fcc), body-centered cubic (bcc), and body-centered tetragonal (bct) results indicate that bct has the highest energy, and this structure is thus the ground state for high and intermediate and low contrast dielectric ratios between particle and fluid.

K.C. Haas, 1992, presented a computer model study based on the Kingenberg, Swol, Zukoski (1989) model, but with emphasis on the effect of high electric field. He used a Monte Carlo method to randomly set the initial positions for 256 particles starting from an initial face-centered-cubic configuration. He found that chain aggregation in the final stages occurs with ten times greater formation times after the chain appears, in a gel-like state, mentioned also by Melrose (1991), with each chain connected to only two or three others.

In 1995, R.Tao and J. M. Sun presented a new type of structure, the single component phase, which was a polarizable fluid. The discovery of the ER effect of a liquid crystal polymer increased the interest due to the fact that there was no settling as observed in two components ER fluids. Thus one of the problems in the conventional ER composites was removed.

They investigated the viscosity of a polarizable fluid in a Couette geometry, and the results indicated that there are three stages of viscosity variation. In a weak electrical field, the fluid remains Newtonian, but the viscosity increases proportional to the electrical field intensity. In an intermediate electric field the fluid tilted and broke chains, and the fluid became non-Newtonian. Here the viscosity was related to the shear rate through a coefficient that depends on the dipolar energy and volume

fraction. In the simulation, the flow of the fluid was orthogonal to the electric field orientation because parallel alignment showed no viscosity variation. Also the bulk particles were allowed to move in all three directions but wall layer particles were not allowed to mix with bulk layer particles, to more closely replicate experimental observations. Particles were subjected to the classical equations of motion, with dipolar forces, image forces and short-range repulsive forces (Melrose's power formula). The collisions between particles were considered perfectly elastic. Wall particles experienced additional attraction forces towards the walls .

Since the flow was treated as viscous , this would generate heat which would be removed from one particle adjacent to wall layers by a renormalizing procedure. The computational method used was the fourth-order Runge-Kutta algorithm, with a fixed step. The results indicate a Newtonian and a non-Newtonian flow as the electrical field intensity increased from low to high. However for very large electrical fields the simulations predicted a Bingham plastic behavior, because the particles moved only when the applied stress was above the yield stress. Also there was a hysteresis observed because the relation between shear rate and shear stress depends on the flow history. Shear stress increased and decreased in equal steps, but the charge and discharge curves were different.

Also, in 1995 another computer model was developed by R. Tao, Q. Jiang, H.K. Sim (1995). It was based on the dipole model but with extended validity up to the Anderson's conduction model, in which particles are electrically conducting, and the ratio between particles/fluid dielectric constant is very large ascending to infinity. They mentioned that the point-dipole model, where spheres have a hard core, is good in predicting the ER effect in the range of small dielectric mismatch between particles and fluid. It also forms a base for developing the body-centered-tetragonal lattice (bct) observed experimentally.

Using the finite element method, they solved the Laplace equation for an infinite chain system, and the results were dependent on two parameters: the dielectric mismatch between particle and fluid permittivities and the distance between two neighbor particles. Based on the FEA result data, an empirical fit formula was developed to calculate the pair interaction force for the whole range of those two parameters. Comparisons between the FEA model and the point-dipole model, agreed very well in the range up to $k = 2$, where k is dielectric mismatch. There was a difference of 15% for $k=10$, and the difference increases as $k \rightarrow 100$ in the range of the conductive mode where the dipolar model is no longer valid.

Another group of scientists, J. E. Martin, R. A. Anderson and C.P.Tigges, from Sandia National Laboratories (1989 a,b,c), developed a computer simulation with a very large number of hard spheres (ten thousand). The simulation was done in the absence of Brownian forces and was athermal. It was performed in both a uniaxial and in a rotating electrical field. Results were compared with experimental data collected for ceramic and metal particles field-cured in an epoxy resin. The structure evolution was characterized by the anisotropy of the electrical conductivity and permittivity. At large concentrations, particles initially formed chains that slowly coalesced into columns containing microcrystalline regions and there were branching between columns and a significant loss in anisotropy. Also from this computer simulation information about velocity fluctuation, dipolar interaction energy, optical attenuation, tensor of gyration and microcrystallinity were obtained. They found that coarsening starts without thermal variations and was due to the presence of defects in the chains, which generate long range interactions between chains. This was in contradiction with observations made by Halsey and Torr (1990), that chain-chain interactions are very weak and coarsening can start due to thermal variations. One of the most significant characteristics in their simulation was concentration of particles which for low values determine chain alike

structure for early times, and hexagonal sheets at intermediate times. Chains zippered together and tended to form hexagonal sheets that sometimes were rolled in spiral columns. For late times and higher concentration the body-centered-tetragonal structures were dominant.

Their mathematical models were based on equations of motion for one sphere and took into consideration the balance of forces: hard sphere force, dipolar force, hydrodynamic force. It introduced a repulsive force dependent in the gap between surfaces of spheres. Based on the gap distance between surfaces, Martin et. al.(1998) were able to compute the electric conductivity of the structure. Assuming that capacitance due to the gap is a logarithmic function and if each contacting pair has its own capacitance, the whole structure may be considered as a capacitor network. Their study of emergence of crystallinity show that at low concentrations chain formations are significant at early times. As concentration of particles increases it is more likely that bct structures will form, without significant chaining. Also the time dependence of optical attenuation length, observed for 10% concentration is similar to coarsening exponent observed in light scattering experiments. It is worth to mention that, this model, based on equation of motion, which will be used also in this work, is a rich source of information about ER effect.

In this present simulation I was interested in modeling the ER effect with emphasis on the time response of the structure formation. Numerical results show, along typical physical behavior observed in experiments, a strong dependence between the particle concentration in the carrier fluid and time of chaining. Since the numerical results are based on real experimental input values, the program is also a prediction tool for future ER effect explorations.

Chapter II

2.1 Forces in ER fluids.

When an electrical field is not applied over a domain of interest, particles are subjected to Brownian forces which are, generated by the thermal energy. Brownian forces cease when the electrical field is turned on and they are overwhelmed by electrical forces. Adriani and Gast (1988) introduced a parameter λ that is the ratio between polarization and thermal forces:

$$\lambda = \frac{(\beta \cdot E)^2 \cdot r^3}{4 \cdot \epsilon \cdot k_B \cdot T} \quad (3)$$

Chain structure will be induced only if the polarization forces are much greater than the Brownian forces (i.e. $\lambda \gg 1$). When $\lambda \ll 1$ there is when no structure and for $\lambda = 1$ there is a transition phase.

Along with Brownian forces in the ER domain are also colloidal attractive and repulsive forces. Among them van der Waals attractive forces have a characteristic magnitude of $A / 12 h$, where A is Hamaker coefficient based on absolute temperature and Boltzmann's constant and h is the minimum particle surface to surface separation distance.

Repulsive forces could be electrostatic forces, and they are generated by double the layer overlapping. Also, repulsive forces are steric (polymeric) forces which develop when particle separations are of order of the thickness of the polymer layer surrounding the particle. Using the surface potential derived from electrophoresis, Zukoski (1989) calculated the ratio of attractive van der Waals to electrostatic repulsion forces and found that the latter are twice as large as repulsive double layer forces. Therefore one should expect the suspension to be flocculate at zero field conditions.

Viscous forces also act on the particles in the presence of a shear field, with a characteristic scale of $6 \pi a^2 \mu_c \dot{\gamma}$. At large enough shear rates viscous forces begin to break up the particle chains.

Most theories assume that the particles are spherical molecules surrounded by a field. Such an approximation is very realistic for inert gases, but may be extended also for simple diatomic and polyatomic molecules which do not depart far from spherical symmetry. For the case of an ER fluid under the influence of an external electric field, electrostatic forces should be taken into account. The magnitude of these forces is based on the principal that attraction decays as an inverse power of the distance between surface of two spheres, and that the repulsion force decays exponentially with the distance.

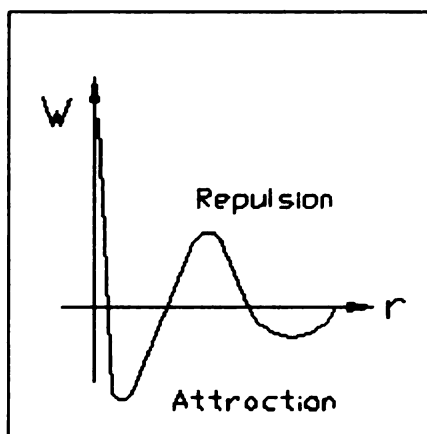


Fig. 2 Attraction / Repulsion energy, W , as a function of distance, r , for a pair of charged, infinitesimally small particles.

Thus attraction prevails at short and at large distances, and for intermediate distances the repulsion force is dominant. This leads to an energy barrier that keeps the particles apart (Bares, 1989).

For the liquid state it is common to consider that properties of the system are determined by the sum of pair interactions, but as Faraday Society Discussion (1965) indicates, three-body and higher order interactions are important, and they account for up to 5-10% of the value of the total forces obtained by taking into consideration only pair interactions.

2.2 The electrostatic polarization model.

The fundamental concept behind this model deals with the mismatch between the dielectric constants of the two phases. The particles

are treated as hard dielectric spheres suspended in a viscous dielectric fluid, and polarization of the spheres takes place when an electric field is applied. Another assumption taken in developing this model is that there are no free charges dispersed in the composite since the typical ER suspension has $10^7 \rightarrow 10^9 \text{ Ohm}\cdot\text{m}$ electrical resistance (Zukoski C.,1993).

A uniform electric field is applied over a domain with the nonconducting particles and the nonconducting fluid. At interfaces between the two phases, the mismatch in polarization induces a perturbation to the applied uniform electrical field. From a mathematical point of view, Laplace's equation describes the electric potential distribution:

$$\nabla\phi^2 = 0 \quad (4)$$

With the condition of continuity of normal components of the electric displacement, one can state:

$$\epsilon_p \cdot \frac{\partial\phi_p}{\partial n} = \epsilon_c \cdot \frac{\partial\phi_c}{\partial n} \quad (5)$$

and under the condition of continuity the electric potential requires :

$$\phi_p = \phi_c \quad (6)$$

Both conditions exist at the particle interface. Outside the particle the electric potential is written as (see fig. 3):

$$\varphi = -E_0 \cdot r \cdot \cos \theta \cdot \left\{ 1 - \beta \cdot \left(\frac{a}{r} \right)^3 \right\} \quad (7)$$

where β is the dielectric contrast factor :

$$\beta = \frac{\epsilon_p - \epsilon_c}{\epsilon_p + 2 \cdot \epsilon_c} \quad (8)$$

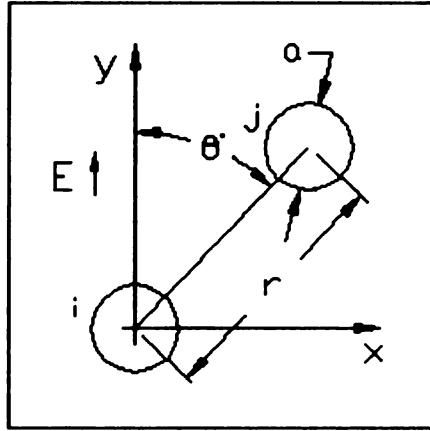


Fig. 3 - Coordinate system used to define the dipolar force between particles i and j

For the case of two particles, the electrostatic dipolar force between them is found solving equation (4) with conditions (5) and (6) and the Maxwell stress tensor:

$$F^d(r, \theta) = \frac{3\pi}{4} \epsilon_0 \epsilon_c a^2 \beta^2 E_0^2 \left(\frac{a}{r} \right)^4 \left[(3 \cos^2 \theta - 1) \cdot \vec{r} + (\sin 2\theta) \cdot \vec{\theta} \right] \quad (9)$$

Solving equation (9) for all angles of θ , indicates that particles are attracted maximally when their line of centers are aligned with the

electrical field and particles repel of each other when their centers are perpendicular to the field lines. At all other orientations the pair is under a torque that aligns the line of centers with the field orientation. The magnitude of the polarization force scales show quadratic dependencies on the particle size, particle polarizability, and electrical field strength.

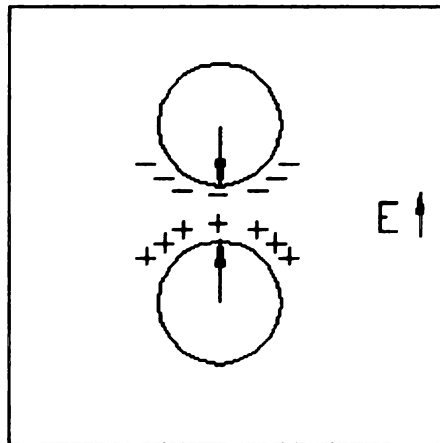


Fig. 4 Attraction between two vertical aligned particles (0° with electrical field lines).

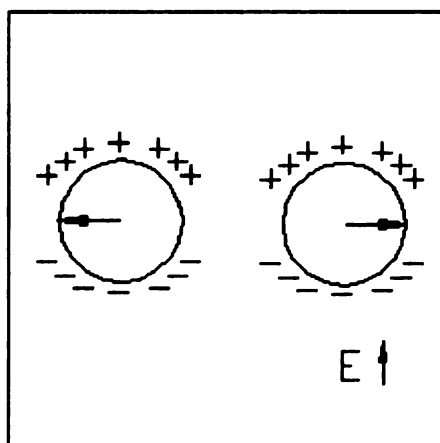


Fig. 5 Repulsion between two horizontal aligned particles (90° with electrical field lines).

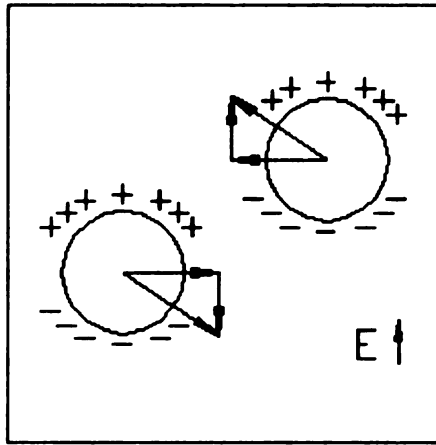


Fig. 6 Rotation and alignment of two particles that form other angle than 0° or 90° with electrical field lines.

2.3 Structure Formation

Anisotropy of the forces between individual particles induces a chain form of aggregation when an electric field is applied. As observed by experiment (Hargrove, 1997), they can span the entire distance between the electrode plates. At early times of ER chain developments, there are only single particle chains, but as times evolves, those chains have a tendency to attract each other, thus generating thicker columns. Looking at the values of the dipole force taken for angles around 90° or 270° made between electrical field lines and the line between two particles, one can expect that there will be a repulsion force between them. The answer to this paradox behavior is found in the long-range action of the dipole force, due to the fact that there are as many multibody interactions as there are particles in the domain. Also

the effect of image charges on each side of plates should take into account. Thus a chain of particles also has a chain of images located adjacent to the upper and lower electrode walls, and the overall effect is that forces between two or more of such chains is different than the dipole force between two particles. The force F between two chains of physical length L separated by a distance d is a periodic force in direction along the chain (Halsey T.C., 1992):

$$F \sim L \cos (2\pi z/c) \exp (-d/c) \quad (10)$$

where c is the distance between the centers of two particles and z is the distance between chains in the direction parallel to the field. The net result is that chains in the real domain repel one another with a short range force, but image chains outside the plates attract one another. Due to the fact that forces decay exponentially with the distance between chains, long range interactions become short-range interactions leading to a final state of packed chains rather than a single vertical chain structure.

Tao and Sun (1991) have conducted studies for the case when ratio between polarizability and thermal forces (λ) is $\lambda \gg 1$ and concluded that the preferred structure is a bodycentered tetragon made out of an infinite number of chains, packed together. Those studies were verified by

experiments (Chen et.al.,1992). Using glass spheres they found good agreement with their computational results.

The question that arises is why fibrillated structures are seen in most experiments. One possible answer may come from the work of Wilson and Taylor (1925) on the shape of dielectric liquid droplets in an electric field. Forces modeling the droplets are surface forces that keep the liquid droplet spherical, and dielectric polarization effects, which tend to elongate the droplet in the direction of the electrical field, this being more similar with the behavior of the two particles that align along the field. In the case of an ER fluid, the dominant forces are polarization and surface tension and they scale as E^2 . Also polarization forces are a volume effect, and they will predominate when the size of the droplet increases. When a high electric field is applied, this consideration becomes relative because there is no time to allow equilibrium to be established between the surface energy and polarization energy, thus the relaxation time τ_r is very low, thus the surface tension plays no role. It is the case of pure chains with a diameter close to that of a single particle (Halsey, 1992).

Chapter III

3.1 Computational Model

The purpose of this thesis is to develop a computational model which could lead to a better understanding of the response of the particle aggregation and the dynamics of chain formation as a function of the particle volume concentration in the host fluid. A numerical code was developed, based on the electrostatic dipole model, that simulates the ER effect including the time dependent behavior of developing structure.

In order to build the computational model, several assumptions and considerations are made about the ER composite materials and forces involved in this phenomena as well as thermal considerations. The particles are considered to be hard spheres of a uniform size. Materials, particles and fluid, are assumed homogenous, isotropic and electrically nonconducting, with a finite value of the mismatch between their dielectric constants. There are no inclusions of other third party materials or substances in the basic two materials, as for example the water molecules absorbed in Zeolite cages. The same remark is valid for the fluid.

In the following computations, where order of magnitude and time scales are involved, I used values of the laboratory experiments (Hargrove

1997), as follows: intensity of electric field $E = 1 \text{ kV/mm}$, Zeolite particle diameter $a = 25 \text{ }\mu\text{m}$, silicone oil (Dow Corning 550) viscosity $\mu_c = 0.125 \text{ Pa}\cdot\text{s}$, electrical permittivity of the fluid $\epsilon_c = 2.35$, and of the particles $\epsilon_p = 6.87$.

The other category of assumptions relate to the forces involved. Gravity forces are neglected, and the particles are considered neutrally buoyant. Repulsion forces are modeled in such a way that they prevent overlapping of the particles and interfering with domain walls. In the real physics, this type of collision will determine a change of the velocity vector both in direction and in magnitude. A mathematical model that reflects this, provides considerable integration difficulties. Viscous forces act as a hydrodynamic resistance against the movement of the particles. The expression of Stokes law for particle “i” is:

$$F_i^{\text{stk}} = 3 \cdot \pi \cdot \mu_c \cdot a \cdot v \quad (11)$$

or :

$$F_i^{\text{stk}} = 3 \cdot \pi \cdot \mu_c \cdot a \cdot \frac{dr_i}{dt} \quad (12)$$

Polarization forces are induced when an electrical field is applied over the ER composite structure. This interaction is considered to be pairwise, ignoring multibody interactions when a mean field calculation

(Adriani and Gast, 1988) is a better approach. In this simulation the first term of the pair electric interaction is used, and the rest of the terms become important only for large differences in permittivities mismatch, which is not the case of this simulation. The interaction between two spheres under an uniaxial electrical field is given by (Martin et.al., 1998):

$$F_{ij}^d(r, \theta) = \frac{3\pi}{4} \epsilon_0 \epsilon_c a^2 \beta^2 E_0^2 \left(\frac{a}{r} \right)^4 \left[(3 \cos^2 \theta - 1) \cdot \vec{r} + (\sin 2\theta) \cdot \vec{\theta} \right] \quad (13)$$

where β is defined by eq.(8) and the following definition is made:

$$F_0 = \frac{3 \cdot \pi}{4} \cdot \epsilon_0 \cdot \epsilon_c \cdot a^2 \cdot \beta^2 \cdot E_0^2 \quad (14)$$

The interaction between a sphere and the electrode wall is treated also as point dipole interaction between the center of the sphere and its reflected image over the electrode. It thus satisfies the condition that the electrode is solid and has a constant potential.

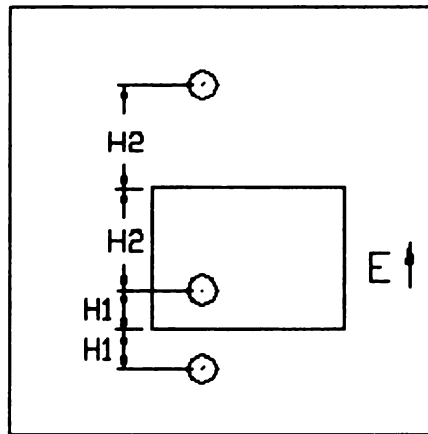


Fig. 7 Mirror images of one domain particle.

The mathematical expression for the particle-image interaction is the same as eq.(13), but here r is the distance between the particle and its image :

$$F_{ij}^{d,im}(r, \theta) = \frac{3\pi}{4} \epsilon_0 \epsilon_c a^2 \beta^2 E_0^2 \left(\frac{a}{r} \right)^4 \left[(3 \cos^2 \theta - 1) \cdot \vec{r} + (\sin 2\theta) \cdot \vec{\theta} \right] \quad (15)$$

Brownian forces acting on spheres due to thermal motion will be proportional with $(k_B \cdot T / a)$, and in the case of zero electric field intensity they will induce diffusive aggregation of particles. A scale analysis is worth making between the Brownian forces and the electric induced polarization forces. For an electric field intensity $E = 1 \text{ kV /mm}$ and a room temperature of $T = 298 \text{ K}$, with $a = 25 \text{ } \mu\text{m}$, $\epsilon_c = 2.35$ and $\alpha = 2.9$ will give:

$$\frac{F_i^{Br}}{F_i^d} \approx O \left(\frac{k_B \cdot T}{\epsilon_c \cdot \epsilon_0 \cdot a^3 \cdot \beta^2 \cdot E^2} \right) \quad (16)$$

The result is $O(10^{-8})$ and thus the Brownian forces can be neglected.

Polarization forces will dominate over colloidal forces (Gast and Adriani, 1988). Thus the short-range repulsive forces that prevent overlap of particles will be treated as a hard sphere repulsion. This is also the case with particle interaction with walls. This approach is similar to the case of atoms

or small molecules where the decay length of repulsion is comparable with particle size.

In addition to dipolar interaction there is a short-range repulsive force that makes spheres repel each other strongly when they are colliding with each other. There are several forms to model this force: hard-core, soft-core, exponential rule (Haas 1993, Klingenberg 1989) and power rule (Klingenberg 1989, Martin 1998, Sun 1995). In this study I used the power rule as used by Klingenberg (1989). I have checked the influence of different power coefficients (eq.17,18). Powers smaller than 13 will lead to a stronger repelling force that will prevent particles from touching walls and themselves. Higher values will make the forces weaker and will have the opposite effect. Then as described above, particles will overlap the wall line and themselves. An exponential law will model very stiff forces and will require a smaller time step.

Since the particles are treated as hard spheres, the repulsion force is a function of the gap between two of them (Klingenberg, 1989):

$$f_{ij}^{\text{rep}} = \frac{2}{\left(\frac{r}{a}\right)^{13}} \quad (17)$$

Similarly, the repulsion force between a sphere and a nearby wall can be expressed as (Zukoski, 1989):

$$f_{i,w}^{\text{rep}} = \frac{2}{\left[\frac{r_w}{a} + 0.5 \right]^{13}} \quad (18)$$

Note that f_{ij}^{rep} and $f_{i,w}^{\text{rep}}$ are dimensionless.

Figures No. 8 and 9 represent the variation of the repulsive force. The diameter of the sphere was 0.025 mm and the distance between spheres or sphere and wall is from 0.025 to 0.029 mm, and between the center of the sphere and the wall is from 0.0125 mm to 0.017 mm. In fig. 8 “distsphere” is the distance between centers of two spheres.

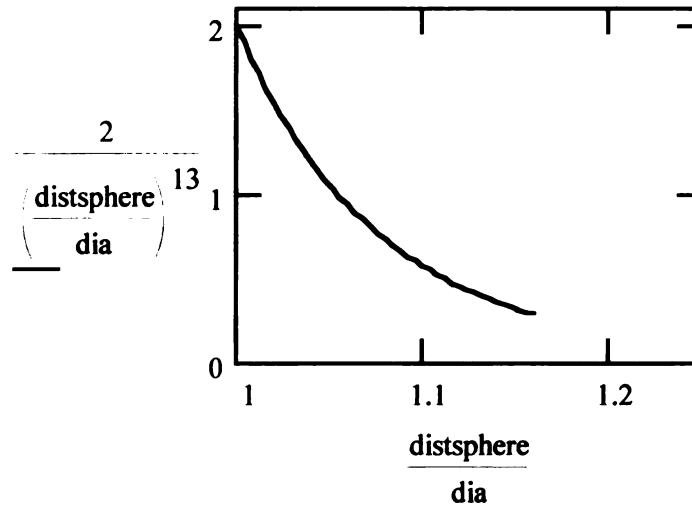


Fig. 8 Repulsion force between two particles

In fig. 9 “distwall” is the distance between the center of a sphere and the wall.

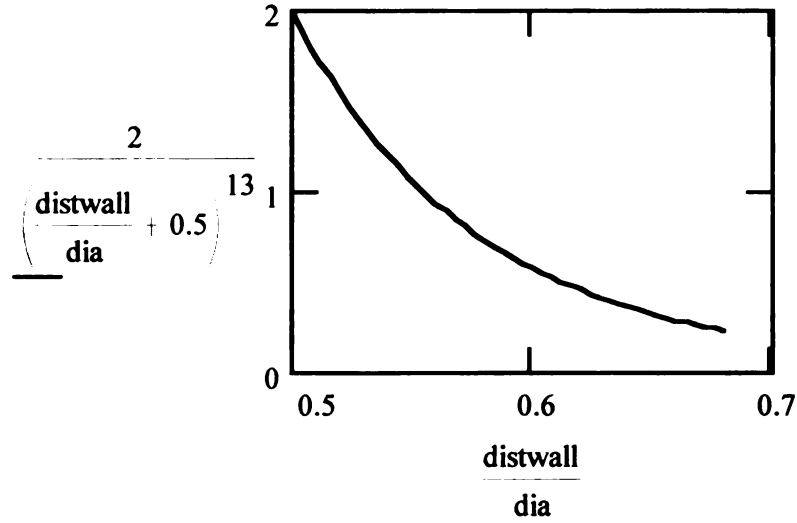


Fig. 9 Repulsion force between a particle and wall

The motion of the “i” sphere is governed by the Newton’s equation of motion:

$$F_i = m_i \cdot a_i = \sum F \quad (19)$$

where $\sum F$ is the summation of all forces acting on the “i”-th sphere and depends on the particle position.

Equation (19) can also be written in the form:

$$m \frac{d^2 r_i}{dt^2} = \sum F \quad (20)$$

or :

$$m \frac{d^2 r_i}{dt^2} = \sum_{i \neq j} F_{ij}^d + \sum_i F_{ij}^{d,im} - F_i^{stk} \quad (21)$$

Substituting eq. (12) in eq. (21) gives:

$$m \frac{d^2 \mathbf{r}_i}{dt^2} = \sum_{i \neq j} \mathbf{F}_{ij}^d + \sum_i \mathbf{F}_{ij}^{d,im} - 3\pi\mu_c a \frac{d\mathbf{r}_i}{dt} \quad (22)$$

In order to make governing eq.(22) dimensionless, the following scales are selected:

$$\text{length} \approx a \quad \text{force} \approx F_0 \quad \text{time} \approx 3\pi\mu_c a^2 / F_0 \quad (23)$$

The time scale represents the time required for a particle to move a distance equal with its diameter, under a constant force F_0 .

Dividing the expression of dipolar forces with F_0 one obtains the dimensionless expressions:

$$\mathbf{F}_{ij}^d / F_0 = \mathbf{f}_{ij}^d \quad \text{and} \quad \mathbf{F}_{i,w}^d / F_0 = \mathbf{f}_{i,w}^d \quad (24)$$

Also by dividing the right hand side of eq. (22) with F_0 and using the time and length scales, one obtains:

$$\frac{1}{F_0} \cdot m \frac{d^2 \mathbf{r}_i}{dt^2} = \frac{1}{F_0} \cdot m \cdot \frac{F_0^2}{9\pi^2 \mu_c^2 a^3} \cdot \frac{d^{*2} \mathbf{r}_i}{d^{*2} t^2} = \frac{F_0 \cdot m}{9\pi^2 \mu_c^2 a^3} \cdot \frac{d^{*2} \mathbf{r}_i}{d^{*2} t^2} \quad (25)$$

where the asterisk denotes dimensionless variables.

Following a similar procedure for the last term, the viscosity force in the eq. (22), one obtains:

$$\frac{1}{F_0} \cdot 3\pi\mu_c a \frac{d\mathbf{r}_i}{dt} = \frac{1}{F_0} \cdot 3\pi\mu_c a \cdot \frac{F_0 a}{3\pi\mu_c a^2} \cdot \frac{d^* \mathbf{r}_i}{d^* t} = \frac{d^* \mathbf{r}_i}{d^* t} \quad (26)$$

Finally the governing eq. (22) reduces to the dimensionless form:

$$\frac{F_0 \cdot m}{9\pi^2 \mu_c^2 a^3} \cdot \frac{d^{*2} r_i}{d^{*t^2}} = \sum_{i \neq j} f_{ij}^d + \sum_i f_{ij}^{d,im} - \frac{d^{*} r_i}{d^{*} t} \quad (27)$$

The order of magnitude of the group in the left side of the equation (27), with the variable values specified before, is:

$$\frac{F_0 \cdot m}{9\pi^2 \mu_c^2 a^3} \approx 10^{-7}$$

and can be neglected. Therefore eq. (27) reduces to the dimensionless form:

$$\frac{d^{*} r_i}{d^{*} t} = \sum_{i \neq j} f_{ij}^d + \sum_i f_{ij}^{d,im} \quad (28)$$

Eq. (28) is completed with the other two dimensionless terms as shown in eq. (17) and eq. (18) that represent the repulsion forces, and thus the final motion equation is:

$$\frac{d^{*} r_i}{d^{*} t} = \sum_{i \neq j} f_{ij}^d + \sum_i f_{ij}^{d,im} + \sum_{i \neq j} f_{ij}^{rep} + \sum_i f_{i,w}^{rep} \quad (29)$$

The equation of motion reduces to a first order differential equation, which implies similarity of solutions. That means that ER structures will be similar, with differences being related to the time scale of aggregation, which in turn depends on viscosity of the carrier fluid and the intensity of the applied electrical field.

3.2 Simulation Method

The method selected to discretize eq. (29) in this work is the self starting Euler Method which was described in Haas (1993), and Klingenberg (1989). The mathematical form of this method is:

$$y_{i+1} = y_i + y'_i \cdot \Delta t \quad (30)$$

It requires a value of the dependent variable at only one point to start the procedure. In this case the location of the sphere in the domain is the point of initiation. The Euler method moves the solution forward from any independent variable value y_i to y_{i+1} using only information known at y_i . The method is *explicit*, because y_{i+1} is the only unknown in the difference equation which permits evaluation of the y_{i+1} property terms of known quantities, that is i^{th} component quantity.

The 2D computation domain size is a rectangle with height $H=0.36$ mm and width $W=0.455$ mm, and the particle sphere diameter is $a=0.025$ mm, as was used the Zeolites particle in laboratory experiments (Hargrove, 1997). The geometrical dimensions are kept the same for all three versions of numerical simulations.

In order to modify the particle concentration (by volume), the number of particles, used in the simulation is changed. Fifty spheres

confined in a monolayer volume of (0.455 mm x 0.36 mm x 0.025 mm) represent a 10% particle volumetric concentration. Following the same rationale, one hundred spheres included in the same volume, represent 20% and one hundred seventy five, will represent 35%. Increasing the number of particles further, will lead to the condition where the total volume of the particles will become predominant and will lead to the “parking problem” when the particles will be moved by the simulation program. At the other extreme, small concentrations 1-2%, deal with volumes where large distances exist between particles and thus weaker forces exist between spheres. The computing time and the number of iterations under dilute particle concentrations increase dramatically.

Larger dimensions of the domain could have been used, but that would imply the use of a significantly larger number of spheres that will lead also to an increase of the computing time without any specific gain in the qualitative results of the numerical simulation. The time step used was $\Delta t = 0.0001$. A higher value would allow a faster marching in time, but that was found to lead to significant numerical errors and time grid dependence. Smaller time steps, although desirable for minimizing the errors, significantly increased the computing time.

There are three sets of simulations for 10%, 20% and 35%, each one having a different number of spheres and but with random initial positions. This is necessary to demonstrate that the simulation results are independent of any initial state. The reason these specific particle concentrations were selected, was to give information about time scale of ER effect response to the applied electrical field. Conrad (1993), in his experiments with Zeolites particles in mineral oil, used 20% particle concentration, in a study of shear stress. Also concentrations of 28% and 35% were used by Chen and Conrad (1995), in experiments of current densities in ER fluids. Hargrove (1997), in his experiments about optical transmittance in ER fluids used 2% particle concentration and particle sizes up to 40 microns.

The code also provides information about the kinetics of the structure formation. The averaged displacement of the particles at the specified time is computed and this is compared with the initial distribution locations. Displacement L of particle i between the initial time and time t is:

$$L_i^2 = (x_{i_t} - x_{i_0})^2 + (y_{i_t} - y_{i_0})^2 \quad (31)$$

and the mean value $\langle M \rangle$ of these L_i displacements, over N particles is:

$$\langle M \rangle = \sum_i L_i / N \quad (32)$$

The value of $\langle M \rangle$ will provide information about reducing ER activity, towards the equilibrium state as the time evolves.

Chapter IV

4.1 Results and Discussion

Numerical stability is one of the most important problems for a computer simulation. In this calculation the time step for numerical stability is related to the force gradient in the computational field which drives the speed of response the particles interaction to the various forces exerted on them. Time step Δt , must be chosen to ensure stability of integration of the equation and can be a fixed or variable value. There is a minimum potential well that occurs at $\theta = 54^\circ 44'$, where θ is the angle between electrical field orientation and the line between two hard spheres. The potential well is dependent on θ and it is important to find what is the maximum force gradient $\nabla F_{\max}$ a sphere might be expected to experience. When $\Delta t = 1 / \nabla F$, the particle will be in the harmonic well mode and will drop to the bottom of the well. If Δt is less than $1 / \nabla F$, the motion will be overdamped, and the particles will settle without oscillations. If Δt is less than $2 / \nabla F$ but greater than $1 / \nabla F$, particles will oscillate from one side to another side. For $\Delta t = 2 / \nabla F$ oscillations are undamped and when $\Delta t > 2 / \nabla F$ unstable behavior starts. (Martin J.E., Anderson R.A., Tigges C.P., 1997)

The force gradient over a group of particles, requires that all force gradients to be evaluated. One particular approach to ensure stability is to select a time step which is sufficiently small such as $\Delta t \leq 2 / \nabla F$. By a trial and error method one can select a Δt where this condition is satisfied. Then half of that time step was used in this calculation. If both results for $\Delta t = 2 / \nabla F$ and $\Delta t = 1 / \nabla F$ are in agreement up to four figures it was considered the larger Δt could be used. The value of the dimensionless time step in the present simulations and the time step is $\Delta t = 0.0001$.

The following is a group of graphical representations of particle response to applied electrical field based on numerical simulation. There are three groups of drawings for the three different particle concentrations: 10%, 20%, 35% .

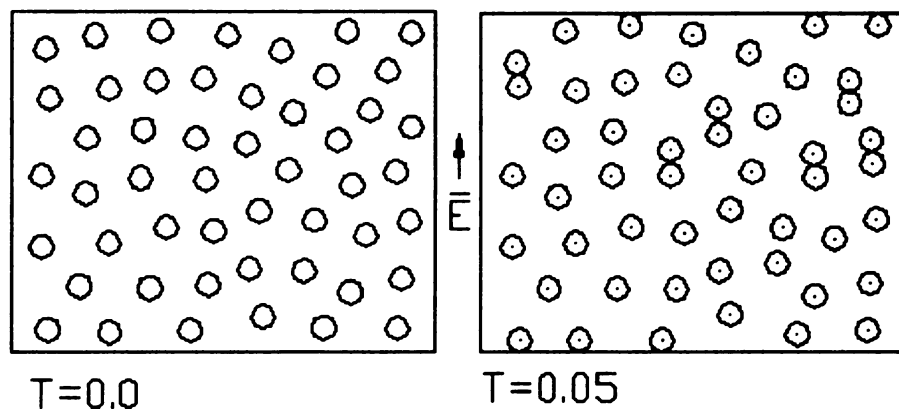


Fig. 1.a $\phi = 10\%$. Initial random displacement and first doublets formed.

In the first simulation (Fig.1a) for $\phi = 10\%$, fifty particles were set randomly in the 2D domain. At the first dimensionless time level $T = 0.05$, several particles are at upper and lower electrodes, and several doublets are established made. The majority of particles remain single particles.

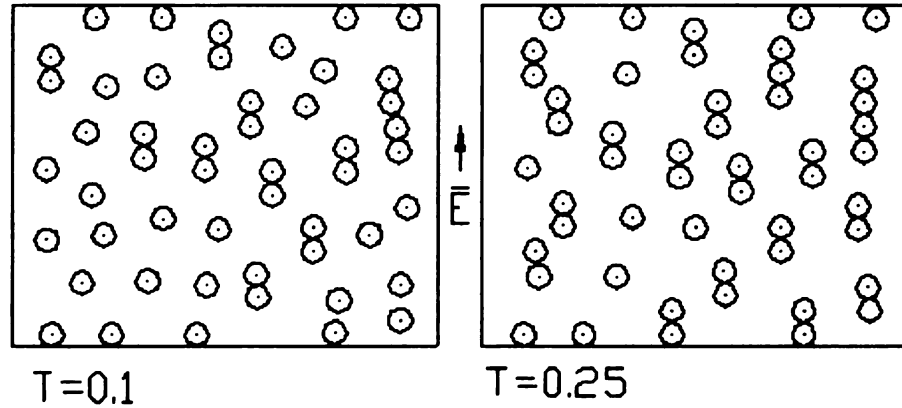


Fig. 1.b $\phi = 10\%$. First three and four particle chains.

At times $T = 0.1$ and $T = 0.25$, doublets begin to attract to each other and form small quadruple groups aligned with the applied field. Other doublets are formed and distances between single particles get shorter.

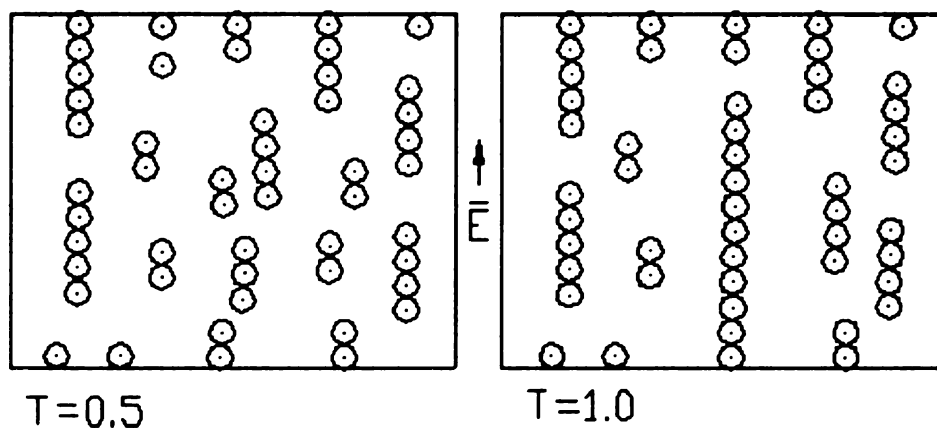


Fig. 1.c $\phi = 10\%$. Short chains group in longer chains.

For dimensionless time $T = 0.5$ and $T = 1.0$, vertical chain structures aligned along electrical field lines are evident. Groups of 5 particles form small chains, and there are just a few singles left. All other particles are involved in some form of attachment. At time $T = 1.0$ the first indication that chains have the tendency to span the gap between electrodes appears. There are no single particles left at this time.

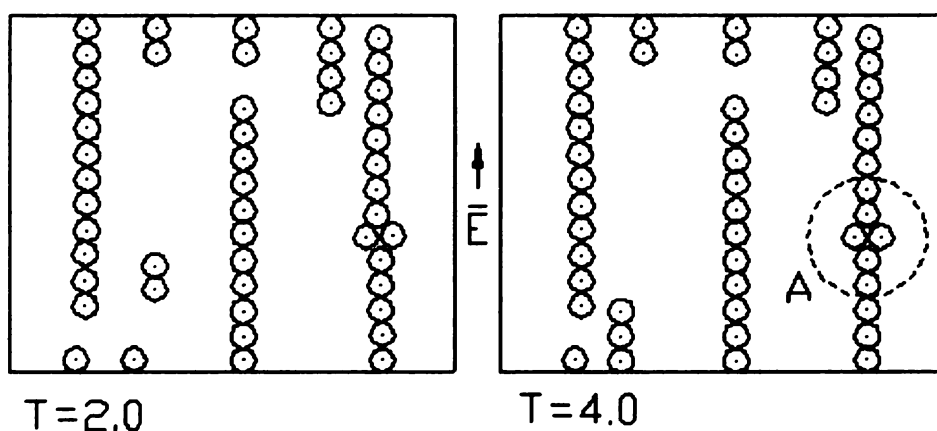


Fig. 1.d $\phi = 10\%$. Long chains have the tendency to span the gap between electrodes.

Three major chains are forming for the structure at times $T = 2$ and $T = 4$. The chains induce side attraction forces for the rest of the few remaining particles, and they eventually merge.

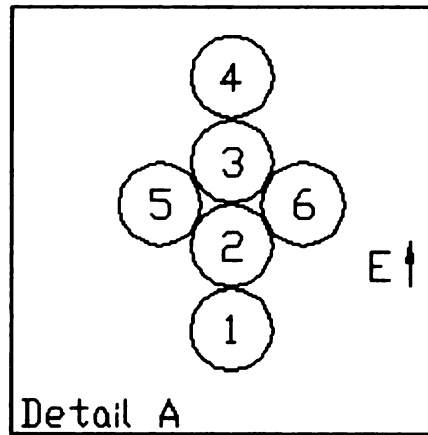


Fig 1.e Adjacent Minimum Potential Configuration

As seen in fig. 1.e, particles 5 and 6 are fixed in a position of minimum potential, and forming a double sided triangular lattice, which is basic to formation of body centered cubic structures.

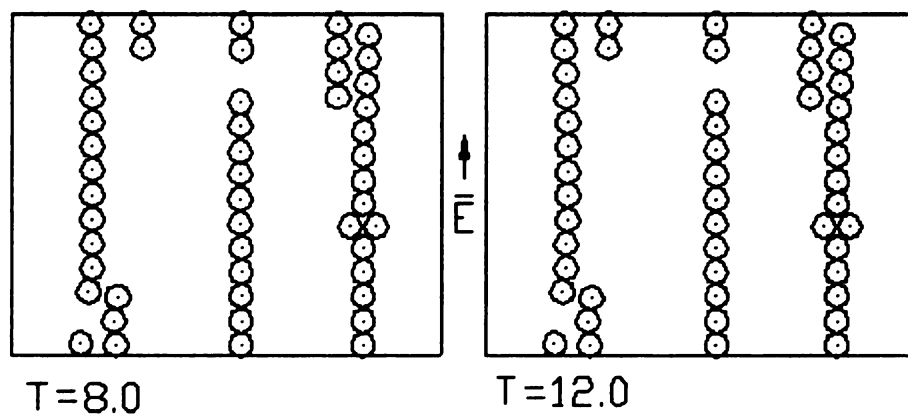


Fig. 1.f $\phi = 10\%$. Structure close to an equilibrium.

The next two time steps, $T = 8.0$ and $T = 12.0$ reveal that the structure reached a state near the equilibrium. There is not significant activity as time evolves. For the spheres which are aligned horizontally, the dipolar force is a repelling one, preventing them from touching.

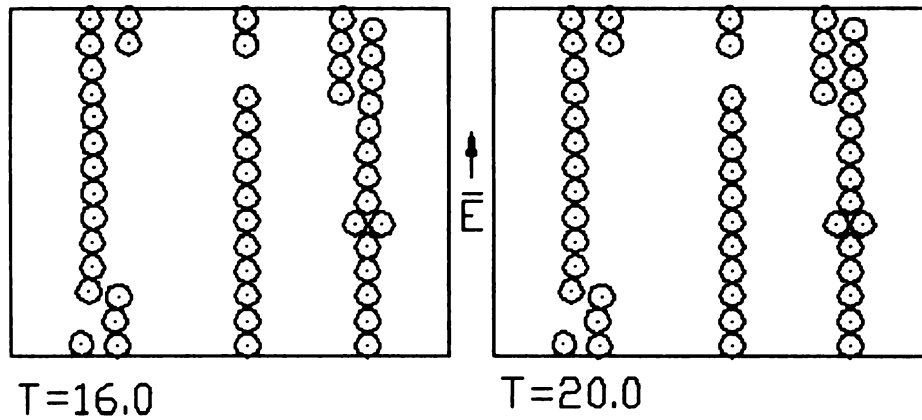


Fig. 1.g $\phi = 10\%$.There are only slight side movement of short chains attracted by longer ones.

The last two dimensionless times $T = 16$ and $T = 20$, show little activity, except for a weak side attraction force seen an upper doublet attached to the electrode, until it reaches an equilibrium distance.

In the second simulation series, with $\phi = 20\%$, at the first dimensionless time $T = 0.05$, the structure is more evolved than at lower the concentration. Not only have doublets already formed but also several short chains of 4-5 particles and 2 major chains with 8-10 particles are observed. Another characteristic is that the chains are not yet perfectly vertically aligned.

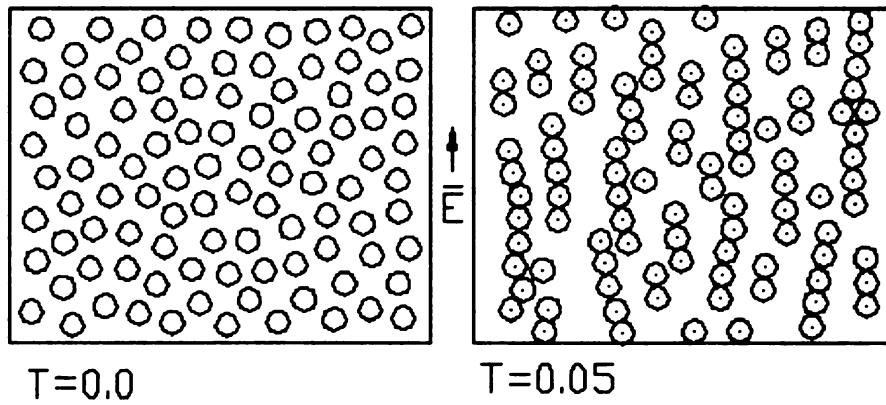


Fig. 2.a $\phi = 20\%$. Initial random configuration and first groups of 4-6 particle chains.

At the next two time levels $T = 0.1$ and $T = 0.25$ one chain spans the entire gap and most of the particles are involved in long chain structures which are almost imperfect vertically alignment.

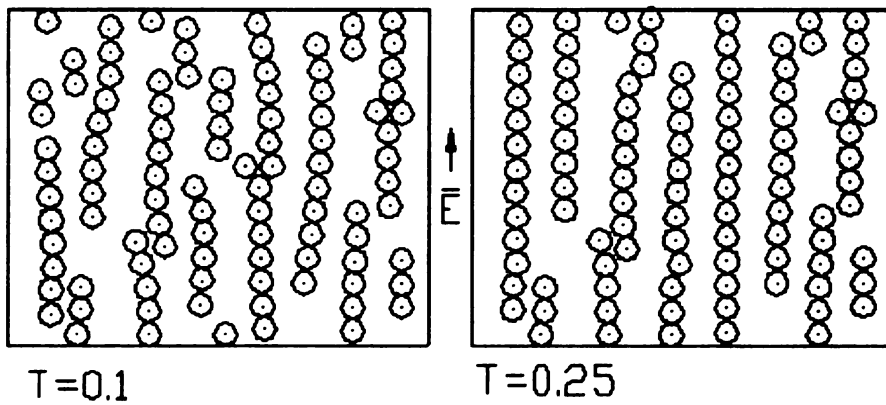


Fig. 2.b $\phi = 20\%$. Particles align in long chains.

For $T = 0.5$ and $T = 1.0$ a second complete chain is formed, and at one electrode a triangular formation occurs. Although this is only formed

by only three spheres, it resembles the larger scale pyramidal structure observed in experiments (Hargrove, 1997).

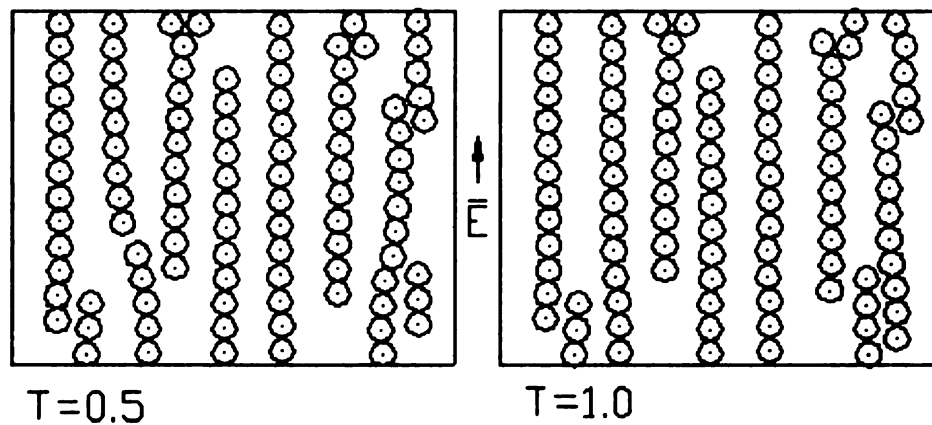


Fig. 2.c $\phi = 20\%$. Chains become vertically aligned.

Dimensionless times $T = 2.0$ and $T = 4.0$ are characterized by the tendency to form groups of vertical chains. Along with the previous two complete chains, there are two additional groups which close into a multiple chain structure.

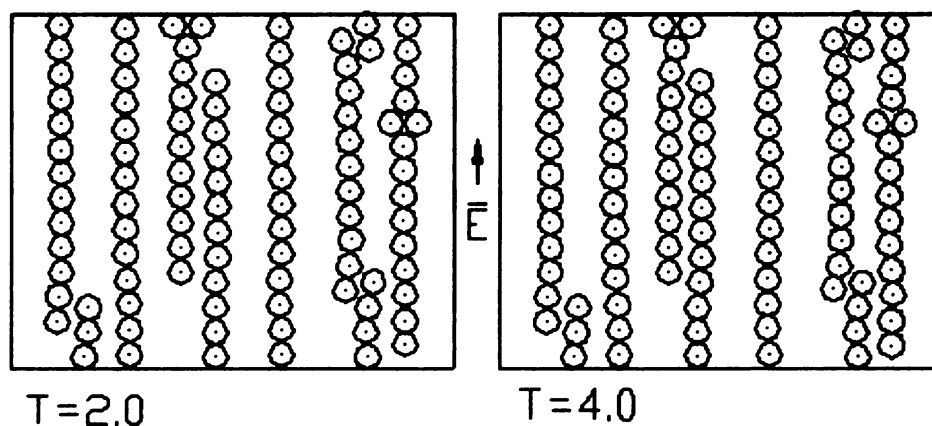


Fig. 2.d $\phi = 20\%$. Structure is already formed.

The trend observed in the previous time snapshots continue for times $T = 8.0$ and $T = 12.0$ in such a way that only one single particle chain remains, and the remainder of the chains are into three-chain structures. This is similar to the experimentally observed coarsening of the chain structure.

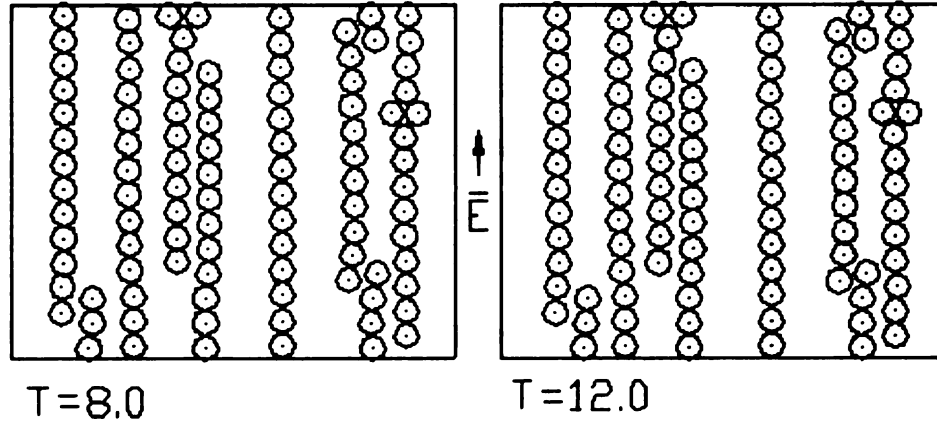


Fig. 2.e $\phi = 20\%$. Slow evolving of the structure.

In the next two timesteps of the 20% volume concentration, $T = 8.0$ and $T = 12.0$ show that coarsening and vertical alignment with electrical field lines are more evident. There is a lateral movement of a group of particles that are attracted in such a way that they form a new complete chain, showing good agreement with experimental observations (Hargrove, 1997).

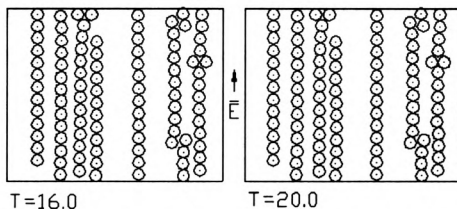


Fig. 2.f $\phi = 20\%$. Structure reached a state near equilibrium.

For the last numerical simulation, the volume concentration studied is $\phi = 35\%$. The magnitude of dimensionless times at which the particles position are displayed is significantly shorter.

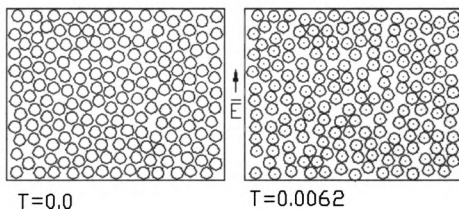


Fig. 3.a $\phi = 35\%$. Initial random distribution followed shortly by first aggregation characteristics.

At time $T = 0.0062$ almost all the particles are involved in doublets or short chains of 3-4 particles. Several of them are already

attracted to the surface of the electrodes. For the next two times, $T = 0.0125$ and $T = 0.025$, longer chains and almost complete chains are formed.

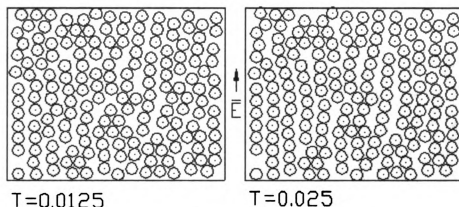


Fig. 3.b $\phi = 35\%$. Longer chains are formed at very early times of aggregation.

At $T = 0.05$ and $T = 0.1$ long vertical chains are more evident, with a tendency to become vertical aligned along field lines is clearly observable.

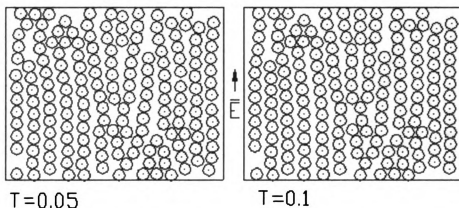


Fig. 3.c $\phi = 35\%$. Chains begin to align vertically.

Later at $T = 0.25$ and $T = 0.5$, along with complete chain formation, a new type of structure different from straight chain type is

formed. In some computer simulations, in the case of high electrical field and high particle concentration, a gel-like structure is observed also (Haas 1993, Martin 1997).

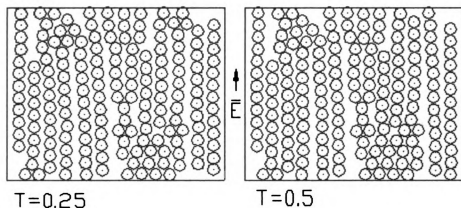


Fig. 3.d $\phi = 35\%$. Vertical alignment and chaining continue.

Results for $T = 1.0$ and $T = 2.0$, show that there are very slight changes in organizational structure.

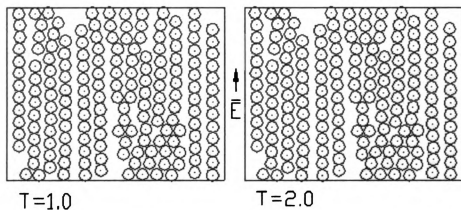


Fig. 3.e $\phi = 35\%$. Triangular structures can be identified.

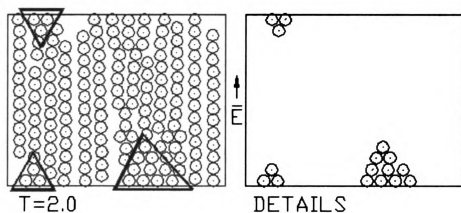


Fig. 3.f $\phi = 35\%$. Details of triangular structures.

In experiments, at electrode walls triangular structures were observed (Hargrove, 1997). A similar pattern was developed by means of numerical simulation of the current model.

For the last two numerical results at $T = 4.0$ and $T = 8.0$, the only activity noticed is a slight side attraction between some of the vertical chains.

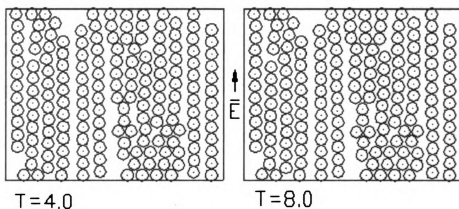


Fig. 3.g $\phi = 35\%$. Structure get close to an equilibrium.

The mean displacement $\langle M \rangle$ (eq. 31), for the entire number of particles is presented in fig. 10. This parameter gives a measure of the motion of the particle in each time step. The mean displacement as a function of time is shown in fig. 10, 11, 12. They appear to be similar: an initially rapid change in $\langle M \rangle$ is followed by a decaying rate of change thus indicating the approach to an equilibrium structure. As it was intuitively expected, for low particle concentration, the interparticle spaces are large, and dipolar forces weak. This leads to a larger time needed for the structure to reach an equilibrium. At the highest particle concentration $\phi = 35\%$, due to short interparticle distance, the mean displacement will have the smaller values. For the medium case of $\phi = 20\%$, results are in between other two extreme cases.

The results shown in fig. 10, are similar with experiment results reported by Andersland (1995). In that work, Andersland compared feedback and feed-forward control of low particle concentration (3% by weight) ER fluids. The average particle size used in those experiments was 10 microns, and the time of aggregation reported is longer than that obtained numerically in the present study. This is due to difference in particle size and concentration. But, the form of the variation of the mean displacement $\langle M \rangle$ and experimental state of ER fluid are similar.

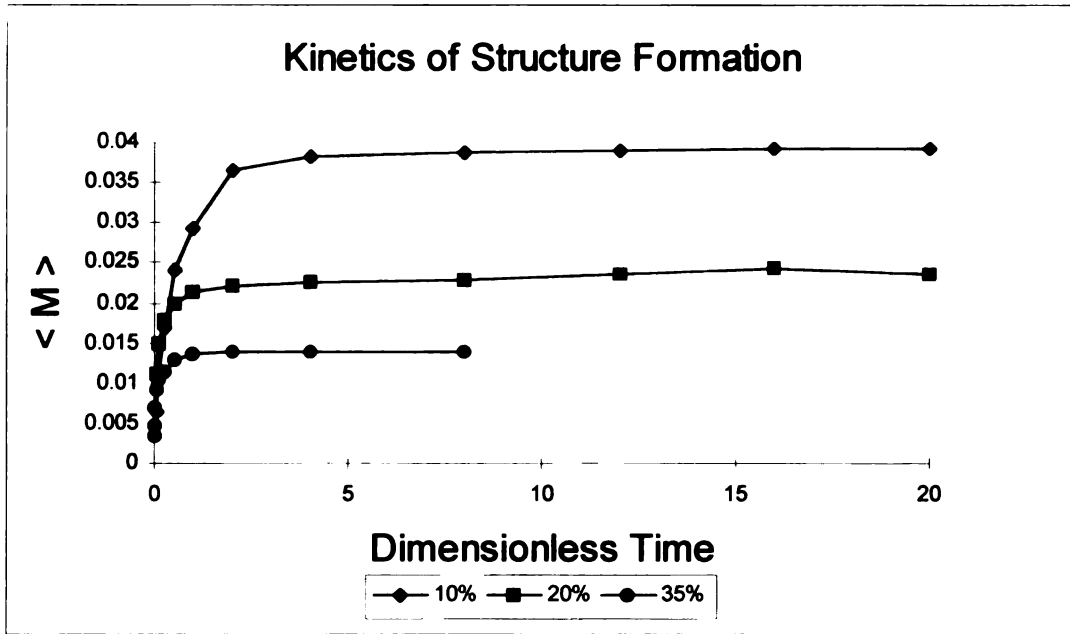


Fig. 10 Kinetics of structure formation over entire time range .

Fig. 11 presents a more detailed graph showing the early stage of particles aggregation. At the first time level 0.0062, the most of activity is shown by the highest $\phi = 35\%$. This is due to the short interparticle distances, with greater interparticle forces. Later on at time levels between 0.0125 and 0.25, mean displacement for the $\phi = 20\%$ is growing faster than in the other cases. This is due to the fact that at $\phi = 10\%$ and at early times, spaces are still large and forces are weak. For the other case, $\phi = 35\%$ short distances have already been traveled and this structure reaches a state close to an equilibrium. From dimensionless time level 0.25 and later, both $\phi = 20\%$ and $\phi = 35\%$ cases are moving with different pace towards equilibrium.

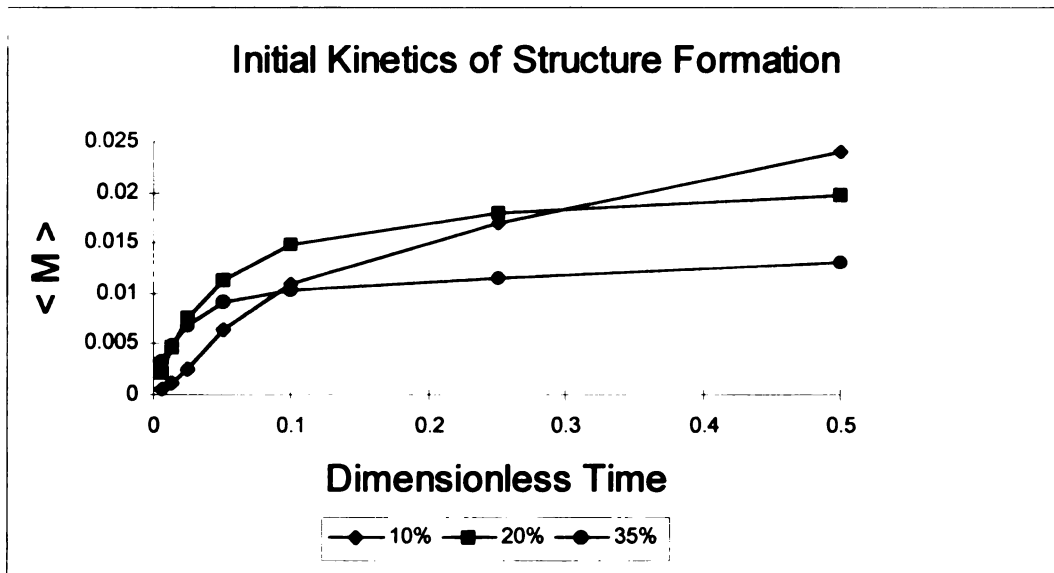


Fig. 11

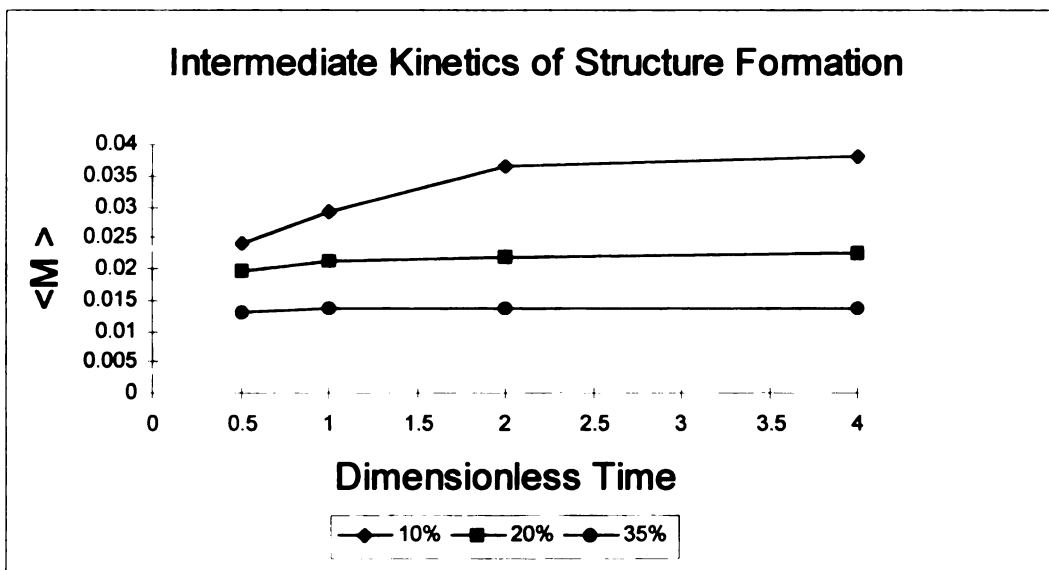


Fig. 12

Particles at 10% concentration tend to have a slower speed, due to weaker interparticle forces caused by the large separation distances. The distances they travel are longer thus the chaining process takes longer.

Once the chains that span the gap between electrodes are formed the rate of change of the structure decreases considerably. Further rearrangement is possible and is due to slow reaction to the particles in the chains.

In ER effect an important feature is the transition from short to long time behavior, or from random position of the particles to chain formation and beyond. As it is seen from the previous illustrations of the various simulations experiments, the initial state of randomness is followed by formation of short chains, which become longer with time. Next stages are when one or several complete chains are formed marking the transition to the long term behavior. When slow side movements of the chains are observed. The time scale associated with this transition as well the dramatic influence of the particle concentration in the ER effect can be seen from the simulation results. The real time, corresponding to any of the snapshots, can be computed, as described later, being a function of fluid viscosity, electrical field intensity and dielectric mismatch between fluid carrier and particles.

4.2 Time scale

The numerical equation of motion is of the form $\Delta m = \Delta d \cdot f(r, \theta)$ where the dimensionless time scales as:

$$\Delta d = \Delta t \cdot 3\pi\mu_c a^2 / F_0 \quad (33)$$

Substituting eq.(14) in eq.(33) will result:

$$\Delta d = \Delta t \cdot \epsilon_0 \epsilon_c \beta^2 E_0^2 / 4\mu_c \quad (34)$$

It could be observed that particle size does not affect kinetic phenomena. For values of $E = 1.0$ kV/mm and $\epsilon_c = 2.9$, $\epsilon_p = 6.87$ (Wu, 1996), $\beta = 0.31$ the real time depends on fluid viscosity. For example, the viscosities for three silicon oils provided by Dow Corning and used in experiments of Hargrove (1997) have the following values : silicon oil 704 has $\mu_c = 0.038$ kg/m.s, silicon oil 710 has $\mu_c = 0.554$ kg/m.s, and silicon oil 550 has $\mu_c = 0.123$ kg/m.s.

Introducing those values in eq. (34) will result in various real times corresponding to the unit value of the dimensionless time. Thus for silicon oil 704 one unit of dimensionless time is 61 milliseconds, for silicone fluid 710 is 898 milliseconds and for silicone oil 550 is 199 milliseconds.

Those values show the dependency upon viscosity of the aggregation time in a fashion that was anticipated, i.e. fluids with a higher viscosity exhibit a higher resistance to the motion of included particles. The intensity of electrical field E plays a very important role. It plays as the square of the field value being proportional to time.

Chapter V

5.1 Conclusions.

I have presented a study of a 2D structure formation of ER fluids. It is based on a simulation method previously used Klingenberg et. al. (1989) and Martin et. al. (1998). Here the emphasis was on the correlation between large, medium and low particle concentrations and dimensionless time levels, from early stages of aggregation up to equilibrium state. The code I wrote, along with calculations that relates structure configurations with the real time, can be a prediction tool. For future applications such as sensor development for instance, where difference in tens of milliseconds could be significant this simulation could be important. Geometrical position of chains, their number and the time it takes to form them, are important information for optical transmittance study (Hargrove, 1997) or in the study of thermal conduction (Lloyd, 1993), when chains are seen as possible preferred energy paths from one electrode to another. For this last type of study, a preferred concentration $\phi = 20\%$ seems to be appropriate, because the other two values 10% and 35% are fluid or particle dominated structures, thus their ER effect is less controllable. An analysis of the time scales in ER

suspensions, reveals that the dynamics of the structure formation can be accurately represented by neglecting the particle acceleration. This makes it possible for the particle motion to be represented by a first order differential equation. The only parameters that determine the real time scale are: electrical field intensity, fluid viscosity and dielectric constant of materials.

The approximations made in developing this model are numerous, but even so, the simulation results are in good agreement with experimentally observed physics that govern ER phenomenon. Thus, it is assumed that gravitational forces are negligible and structure is neutrally buoyant, at least in short times. This is an ideal condition for ER suspensions where settling of the particles occurs. There is no friction between the electrode surface and the particles and temperature has no influence except through viscosity variation. Particles, which in real experiments have a rectangular shape and thus exhibit a larger viscous resistance, are assumed to be perfect hard spheres. Another assumption refers to nonexistence of other materials, included in structure, as water is observed as being absorbed in Zeolite cages. Water plays a significant role not only as a source of ions, thus charge carriers in polarization process, but also in thermal conductivity of ER suspensions.

Simulation results show formation of short chains at early times and interactions of these leading to complete chains as time evolves. The role of the particle concentration is to decrease the time of transition between random position of the particles to orderly formed chains.

5.2 Recommendations.

For various positions of the particles in suspension, in the transition phase or when the chains are formed, another part of the code may compute the average thermal conductivity of the suspension at various time level. This can be done following the analogy between thermal conduction in layers or structured materials with the model of electrical resistances connected in series or parallel. Other ways of development is to implement the influence of the temperature. A good refinement will be modeling the influence of other materials included in particles as water in Zeolite cages, for thermal conductivity computation of ER structure. One way to improve the actual code is to use a more precise numerical method as for instance Runge-Kutta fourth order scheme, that will decrease the errors accumulated over a very large number of iterations. Also a code that will generate the random initial positions of particles will be beneficial and will provide a more uniform spread of particles.

APPENDIX

1. Fundamental Issues

A. Polarization

Polarization is created when charges of opposite signs are separated by a distance, and is related with orientation of charges and may appear in various forms. Under the influence of an electrical field atoms may have displacement of the electron cloud, charged negative, and a displacement of a nucleus, charged positive. This will have as result the polarization. Also a molecule may have natural polarity due to its atomic geometry, for instance water molecule. In other forms of matter, as solids or liquid continua, an internal charge gradient may induce polarization.

A dipole moment, or electric moment is the distance from the net negative to the net positive charge, multiplied by the net positive charge (Erigen, Maugin, 1990, p.29)

$$\mathbf{P} = Q^+ \cdot \mathbf{r} \quad (\text{a.1})$$

For a discrete particle as an atom, the atomic dipole is created through the action of an applied electric field, and the electron cloud is displaced from nucleus (Dulikravich G., Lynn R.S., 1995).

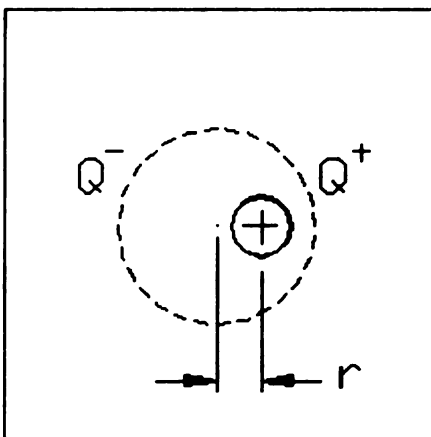


Fig. A1 Atomic polarization. There is an offset between nucleus center and electronic cloud.

Such a dipole moment can be produced also in a molecule, group of particles or a continuum in which positive and negative charges are separated. For groups of particles the moment is a sum of individual dipole moments.

For an average value of electric field $\langle E \rangle$ acting on a number of molecules, the average moment $\langle M \rangle$ will be proportional to average electric field, by a constant, which is the total polarizability of the molecules:

$$\langle M \rangle = \alpha_T \cdot \langle E \rangle \quad (\text{a.2})$$

The total polarizability is a sum of atomic, electronic and dipolar polarizability contributions:

$$\alpha_T = \alpha_a + \alpha_e + \alpha_d \quad (\text{a.3})$$

Each of the three types of polarizability is frequency dependent. When an alternating field is applied over a parallel plate condenser filled with polar material, the average orientation of molecules is changed. At low frequencies, all types of polarization may have time to reach the value they would have taken in a steady electric field. As frequency increases, polarization no longer has the time to reach this steady state value. The cut-off value is around $10^{10} \rightarrow 10^{12}$ Hz, over which the orientation polarization fails to reach an equilibrium. For higher frequency total polarization is restricted to:

$$\alpha_T = \alpha_a + \alpha_e \quad (\text{a.4})$$

Further on, although it is not the case for usual frequencies of the AC electric field applied, at ultra high frequency in the infrared region of spectrum, the domain of the natural frequency of atomic vibrations α_a will fail to attain equilibrium value, and also in the ultra violet and X ray frequency domain corresponding to electronic transitions between different energy levels in the atom, α_e will fail.

There are two sources of polarization. Those induced by an electrical field or natural polarization. The molecules, of any material are made of positive nuclei surrounded by negatively charged electrons, which move freely but are prevented from escaping by intense electric fields. When a molecule is under the influence of electric field, electrons tend to be displaced by the field, and thus they gather on the surface of the molecule resulting in an effective surface charge. The net result is that the molecule becomes a dipole.

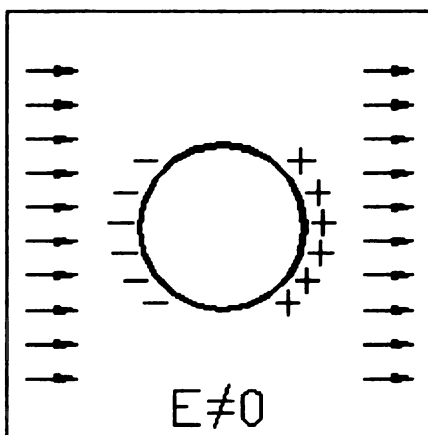


Fig. A2 Molecule polarization due to an external electrical field. Surface negative and positive charges are induced.

Polarization is a vector function of position and has same direction as electrical field in an isotropic dielectric. The other type of polarization is found in materials containing polar molecules that have dipole moments even in absence of an external field. For instance, water has

dipole molecules, the H end of molecule is positive and O end is negative charged.

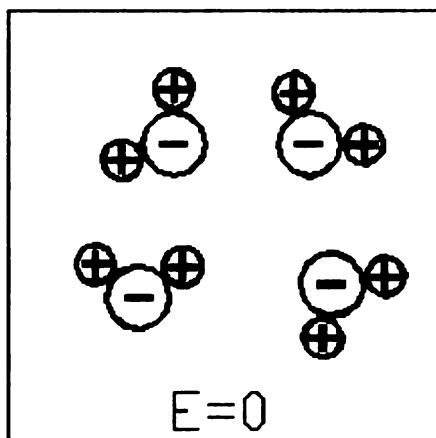


Fig. A3 Orientation of natural polarized molecules in absence of an electric field applied

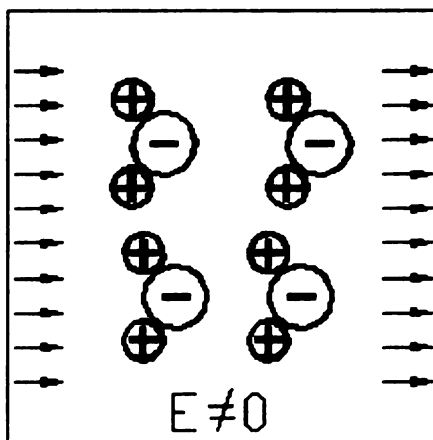


Fig. A4 Orientation of natural polarized molecules due to the influence of an electric field applied

In the absence of an external electrical field molecules of water will be oriented in random directions, so that even though each molecule has a moment, the average moment will be zero. When an electric field is applied, molecules tend to orient and the result is a net moment dipole which is proportional to the electric field intensity E , via a constant of proportionality, depending on the nature of the dielectric.

Formation of columnar structures is dependent upon the transport mechanism of the induced dipoles which in turn is dependent upon the properties of the composite materials, particles and fluid. Transport mechanisms of charges could be either bulk or surface phenomena.

There is a difference between the two types of polarization. The induced one is independent of temperature. The second one, the natural permanent dipoles are opposed to temperature agitation and according to the kinetic theory and it can be shown that resulting polarization is inversely proportional to the absolute temperature.

B. Electrostatic Potential. Electric Images

The work done in carrying a unit charge from one point to another in the field is independent of path and therefore electrostatic field is

conservative. The work may be written as the difference of potential energy at the end points:

$$V_e = \frac{Q}{4\pi\epsilon_0 r} \quad (b.1)$$

Where V_e is the potential function at a distance (r) from charge Q .

If we sum the potential of all charges we can get the total potential as a function of position and if charges are distributed continuously in space those form a charge density σ , thus for a volume element dv the potential function is:

$$V_e = \frac{Q}{4\pi\epsilon_0} \int \frac{\sigma dv}{r} \quad (b.2)$$

The electrical field E is normal to equipotential surfaces and any displacement on that surface must be at right angles to the force vector. The lines of force are everywhere tangent to E and they cut the equipotential at right angles.

Those concepts, initiated by Faraday are important in electrostatic problems involving conductors, in which charges are free to move and is difficult to predict their position. From Ohm's law we know that a current in a conductor is proportional to the electric field in it. For the static case when

the charges are at rest, the electric field is zero everywhere in the conductor that means the potential is constant and the surface is equipotential.

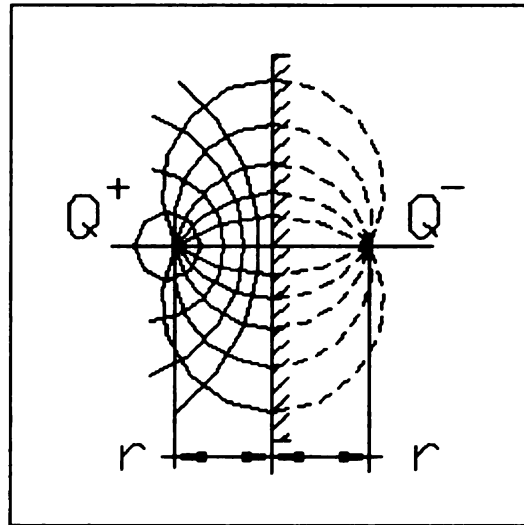


Fig. B1 Electric image of a point charge in a conducting plane.

For the particular case of a capacitor that has within its plates the ER fluid on which is applied the external electrical field it is necessary to consider image of the charges in order to represent the plates as surfaces of equipotential.

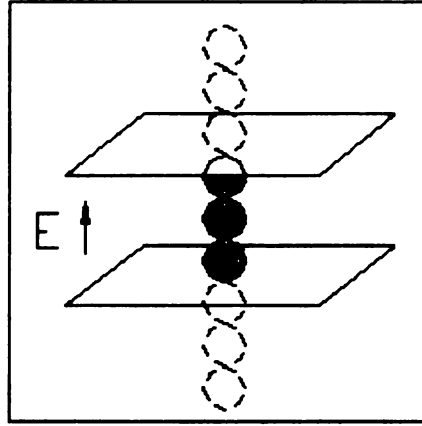


Fig. B2 Infinite chain of electric images above and below electrode plates.

In order to impose the equipotential surface condition a fictitious charge Q^- , behind the surface must be placed at a distance $(-d)$, thus surface is at mid distance between particle and its image.

This method is called the “method of images”, and is employed to satisfy the equation (b.1).

C. Electrostatic field. Electric displacement.

Coulomb’s law states that force F_{12} exerted by Q_1 charge on Q_2 charge is proportional to the product of both charges and inversely proportional to the square distance r separating the two charges.

$$F_{12} = \frac{Q_1 Q_2}{4\pi\epsilon_0 r^2} \cdot r_{12} \quad (c.1)$$

Where $\mathbf{r}_{12}$ is the unit vector pointing in the direction from Q_1 to Q_2 . The force is attractive if charges are of different sign and repulsive if they are alike.

In the case that one particle is fixed and another one is moving there is still a force exerted by the moving particle towards the other one, whatever the position may be. The ratio:

$$E = \frac{F_{12}}{Q_{12}} = \frac{Q_1}{4\pi\epsilon_0 r^2} \cdot \mathbf{r}_{12} \quad (c2)$$

is called electric field intensity, E .

Faraday introduced the concept of electric displacement flux D , in dielectric materials, which is related to the electric field intensity E , through permittivity of the medium ϵ .

$$D = \epsilon \cdot E \quad (c3)$$

For an isotropic medium ϵ is a scalar quality and vectors D and E are in the same direction but for an anisotropic medium, ϵ , becomes a dyadic tensor, and vectors D and E are no longer parallel.

Also if a conductor is placed in an electric field the outer electrons move freely unbounded from atoms. On the other hand if a

dielectric is placed in an electric field, electrons remain bound to the atoms but they have a displaced position from their nuclei, so the atoms behaves as atomic dipoles and is said that dielectric is polarized. Polarization vector P of a dielectric is related by other electric field vector as follows:

$$D = \epsilon_0 \cdot E + P \quad (c4)$$

and substituting (c.3) in (c.4):

$$\epsilon = \epsilon_0 + \frac{P}{E} \quad (c5)$$

also the rate:

$$k_e = \frac{\epsilon}{\epsilon_0} \quad (c6)$$

is called “ specific inductive capacity ” and equation (c3) can be written as:

$$D = K_e \epsilon_0 E \quad (c7)$$

The ratio of polarization P to $\epsilon_0 E$ is called susceptibility and is noted as χ_e :

$$\chi_e = \frac{P}{\epsilon_0 \cdot E} \quad (c8)$$

From the theory of polarization of a conductive sphere in an electric field we can find the value of polarizability of a molecule, by formula:

$$\alpha = 4 \pi \epsilon_0 R^3 \quad (\text{c9})$$

At this point a remark should be made: polarizability of a molecule is affected by the presence of other neighboring molecules and for further calculations a correction is required.

If there are N molecules each with an $(\epsilon \cdot E)$ moment, on a volume V , the total dipole moment per unit volume is:

$$P = \left(\frac{N}{V} \right) \cdot \alpha \cdot E \quad (\text{c10})$$

D. Double Layer Theory

When in consideration is taken not only one single dipole but a surface distribution of dipoles, the concept of double layer is introduced. Two surfaces that are separated by distance r , and carry surface charges $\pm\sigma$ per unit area. The dipole moment per unit area is:

$$P = \sigma \cdot r \quad (\text{d.1})$$

The double layer is equivalent with a parallel plate condenser and the potential difference between the plates is $(\sigma \cdot r) / \epsilon_0$.

Outside the double layer the electrical field is zero. Shul'man et.al. (1971) also uses the concept of double layer but distinguished two forms in which this is formed. One would be a very thin double layer associated with a conducting film made by the water particles, all surrounded in a non-

conducting fluid. The charge carriers under the influence of electric field can move, giving rise to a Maxwell-Wagner-Sillars (MWS), polarization. The concept of interfacial polarization was proposed by Maxwell (1892) to explain an “*anomalous*” dielectric dispersion observed in heterogeneous materials. Anomalous dispersion arise in mixtures as a consequence of continuity of the field vectors across the interfaces. The magnitude of conductivity and permittivity differences between components give the magnitude of the anomalous dispersion. The MWS theory is based on studies done on conducting particles in nonconducting medium, which is not the case of ER effect having the both materials electrically nonconducting. It has seen that an anomalous dispersion occurs even in this case, and more than that is present also in homogenous solutions not only in the heterogeneous ones as considered previously. One example in this case is polyhexyl isocyanates dissolved in xylene (Filisko, 1994), a situation in which there are no interfaces making the MWS theory restrictive and not general for all materials. On the other hand it is interesting to note that MWS polarization still occurs (Hedvig, 1977) in heterogeneous systems where water has been removed and it is assumed that the electric carriers may be of a different nature.

The second concept in double layer theory that Shul'man introduced was the dispersed double layer which depend on the ion surrounding media and thus the electrical conductivity. As seen in wet composites, water has a dramatic effect on double layer and on the bulk electrical conductivity of the system, a major ions transfer being associated with this case. In the past decade there were reports (Filisko et.al. 1988, 1989, 1990, and Brook and Kelly 1985, 1987) that indicates ER effects without any amount of water, leading to the conclusion that the mechanism that explain the ER effect should be unique in both cases, with or without water. In this new light, the theory of double layer is not so dominant and charge carriers are not a consequence of water absorbtion.

2. Hardware

Simulations were run on a personal IBM PC with a clock frequency of 400 MHz, 64 MB RAM, that I purchased and dedicated to this work. Also, I purchased the license to use Fortran software. To run 175 particles up to one unit dimensionless time it takes 1 hour and 16 min, or up to time level 8.0, the last numerical result, 10 hours and 8 min. For the simulations with 100 particles, the computer time is shorter, compared as same levels. Thus dimensionless time 1.0 is reached after 24 min of

computing, level 8.0 after 3 hours and 12 min and level 20.0, last numerical result, after 8 hours. For the simulations with 50 particles time is even shorter. Dimensionless time level 1.0 is reached after 6 min, level 8.0 after 48 min and level 20.0 after 2 hours.

Angle	Dipolar Force	
Degree	Radial Comp.	Tangential Comp.
0	2	0
5	1.977	0.174
10	1.909	0.342
15	1.799	0.5
20	1.649	0.643
25	1.464	0.766
30	1.25	0.866
35	1.013	0.94
40	0.76	0.985
45	0.5	1
50	0.239	0.985
55	-0.013	0.94
60	-0.25	0.866
65	-0.464	0.766
70	-0.649	0.643
75	-0.799	0.5
80	-0.909	0.342
85	-0.977	0.174
90	-1	0

Table 1. Variation of Dipolar Force in the First Quadrant

Angle Degree	Dipolar Force	
	Radial Comp.	Tangential Comp.
95	-0.977	-0.174
100	-0.909	-0.342
105	-0.799	-0.5
110	-0.649	-0.643
115	-0.464	-0.766
120	-0.25	-0.866
125	-0.13	-0.94
130	0.239	-0.985
135	0.5	-1
140	0.76	-0.985
145	1.013	-0.94
150	1.25	-0.866
155	1.464	-0.766
160	1.649	-0.643
165	1.799	-0.5
170	1.909	-0.342
175	1.977	-0.174
180	2	0

Table 2. Variation of Dipolar Force in the Second Quadrant

Angle	Dipolar Force	
Degree	Radial Comp.	Tangential Comp.
185	1.977	-0.087
190	1.909	-0.174
195	1.799	-0.259
200	1.649	-0.342
205	1.464	-0.423
210	1.25	-0.5
215	1.013	-0.574
220	0.76	-0.643
225	0.5	-0.707
230	0.239	-0.766
235	-0.13	-0.819
240	-0.25	-0.866
245	-0.464	-0.906
250	-0.649	-0.94
255	-0.799	-0.966
260	-0.909	-0.985
265	-0.977	-0.996

Table 3. Variation of Dipolar Force in the Third Quadrant

Angle Degree	Dipolar Force	
	Radial Comp.	Tangential Comp.
270	-1	-1
275	-0.977	-0.996
280	-0.909	-0.985
285	-0.799	-0.966
290	-0.649	-0.94
295	-0.464	-0.906
300	-0.25	-0.866
305	-0.013	-0.819
310	0.239	-0.766
315	0.5	-0.707
320	0.76	-0.643
325	1.013	-0.574
330	1.25	-0.5
335	1.464	-0.423
340	1.649	-0.342
345	1.799	-0.259
350	1.909	-0.174
355	1.977	-0.087
360	2	0

Table 4. Variation of Dipolar Force in the Fourth Quadrant

Dimensionless	Mean Displacement		
Time			
	10%	20%	35%
0.0062	0.0005	0.0022	0.0034
0.0125	0.0011	0.0047	0.0048
0.025	0.0026	0.0077	0.0069
0.05	0.0065	0.0113	0.0092
0.1	0.0109	0.0148	0.0104
0.25	0.017	0.018	0.0115
0.5	0.024	0.0198	0.013
1.0	0.0293	0.0213	0.0136
2.0	0.0364	0.022	0.0138
4.0	0.0382	0.0225	0.0138
8.0	0.0387	0.0228	0.0139
12.0	0.039	0.0235	
16.0	0.0392	0.0244	
20.0	0.0392	0.0237	

Table 5. Mean Displacement of Particles

Electric Field Intensity	E	1 kV/mm
Zeolite Particle Diameter	a	0.025 mm
Silicone Oil (Dow Corning 550)		
Viscosity	μ	0.125 Pa s
Fluid Electrical Permittivity	ϵ	2.35
Particle Electrical Permittivity	ϵ	6.87

**Table 6. Typical Particle and Fluid Properties
Used in Experiments**

BIBLIOGRAPHY

- [1] Adriani P.M., Gast A.P., 1988, A Microscopic Model of Electrorheology Fluids vol. 31 pp. 2757-2762.
- [2] Andersland R. M., 1995, M. S. Thesis, Feedback Control of Electrorheological Fluids, Michigan State University.
- [3] Bares J.E., Carlson J.D., 1989, Electrorheological Fluid Design : An Overview, Preceeding of the Second International Conference on ER Fluids.
- [4] Bonnecaze R.T., Brady J.F., 1989, Dynamic Simulation of Suspension of Dielectric Particles Forming an Electrorheological Fluid. Electrorheological Fluids, Proceedings of the Second International Conference on ER Fluids, Raleigh, NC, August 7-9, 1989.
- [5] Boon J.P., Yip S., 1980, Molecular Hydrodynamics, Mc Graw –Hill Inc. pp. 14-23.
- [6] Carlson J.D., 1988, Electrorheological Fluids, US Patent, 4772407 A.
- [7] Conrad H., 1993, Electrorheological Fluids : Characteristics, Structure, and Mechanisms. FED vol. 16, Electro-Rheological Flows.
- [8] Conrad H., Chen Y., 1995, Electrical Properties and Strength of Electrorheological Fluids, Progress in Electrorheology, Plenum Press, N.Y.
- [9] Conrad H., Sprecher A.F., Choi Y., Chen Y., 1991, The Temperature Dependence of the Electric Properties and Strength of Electrorheological Fluids, J. Rheol. 35(7) pp. 1393-1409.
- [10] Davis C.L., 1992, Ground State of an ER Fluid, Physical Review A vol. 46 No. 2, pp.719-721.
- [11] Dry C., 1991, Passive Tuneable Fibres and Matrics, Book of Abstract Conference ER Fluids, R.Tao, Ed. Carbondale, ILL, p.17.

- [12] Dulikravich G.S., Sean L.R., 1995, Electro-Magneto-Hydrodynamics (Part 1) Introductory Concepts, FED – vol. 235, MD – vol. 71 Developments in Electrorheological Flows ASME, pp. 50-54.
- [13] Gandhi M.V., Thomson B.S., Choi B.S., 1989, Journal of Composite Materials vol. 23, pp. 1232-1234, A New Generation of an Innovative Ultra Advanced Intelligent Composite Materials Featuring Electro-Rheological Fluids : An experimental investigation.
- [14] Eringen A.C., Maugin G.A., 1990 a, Electrodynamics of Continua-I, Springer-Verlag, New York, p. 29.
- [15] Filisko E. F., 1994, Molecular mechanisms associated with ER activity : anomalous dispersions. Developments in Electrorheological Flows and Measurement Uncertainty.
- [16] Gleb V.K., 1974, The Constant Electric Field Effect on Optical Characteristics of ER Suspensions, Minsk, AN BSSR Press, pp. 76-86.
- [17] Halsey T.C., 1992, Electrorheological Fluids, Science, vol. 258, pp. 762-763.
- [18] Halsey T.C., Torr W., 1990, Structure of ER fluids, Physical Review Letters, vol. 65, N0. 22, pp. 2820-2823.
- [19] Hargrove J., 1997, Ph.D. Dissertation, Analysis and Experimental Study of Radiative Heat Transfer Through ER Fluids. Michigan State University.
- [20] Hass K.C., 1993, Computer Simulation of Nonequilibrium Structure Formation in ER Fluids, Physical Review E, vol. 47, No. 5.
- [21] Hill E. Nora, Vaughn W.E., Price A.H., Davies M., 1969 , Dielectric Properties and Molecular Behavior, Van Nostrand Reinhold Co. Ltd. London.
- [22] Inoue A., 1989, Study of New ER. Proceeding of the 2-nd International Conference on ERF, Carlson V.D., Sprecher A.F., Conrad H., Raleigh N.C. pp. 76-83.

- [23] James M.L., Smith G.M., Welford J.C., 1993, Applied Numerical Methods for Digital Computation, pp. 466-477.
- [24] Klass D.L., Martinek T.W., (1967a), Electroviscous Fluids I. Rheological Properties. J. Appl. Phys. 38(1) pp.67-74.
- [25] Klass D.L., Martinek T.W. (1967b), Electroviscous Fluids I. Rheological Properties. J. Appl. Phys. 38(1) pp. 75-80.
- [26] Klingenberg D.J., van Swol F., Zukoski C.F. (1989), Dynamic Simulation of ER Suspensions, J. Chem. Phys. 91, 1989, pp.7888-7895.
- [27] Kitahara A., Watanabe A, 1984, Nonaqueous Systems in Electrical Phenomena at Interfaces: Fundamentals, Measurements and Applications, pp.119-143.
- [28] Korobko E.V., Dubkova B.I., Ragotner M.M., 1991, ER properties of Suspensions Dispersion Reinforced with Fibrous and Powered Components. Proceedings of the 6th National Conference on Mechanics and Technology of Composite Materials, Sofia, pp. 9-12.
- [29] Martin J.E., Anderson R.A., Tigges C.P., 1998, Simulation of the Athermal Coarsening of Composites Structured by Uniaxial Field. Journal of Chem. Physics.
- [30] Martin J.E., Anderson R.A., Tigges C.P., 1998, Simulation of the Athermal Coarsening of Composites Structured by Radial Field. Journal of Chem. Physics.
- [31] Martin J.E., Anderson R.A., Tigges C.P., 1997, Composite materials with Field Induced Anisotropy. Journal of Chem. Physics.
- [32] Melrose J.R., 1991, Shared Dipolar Suspensions, Physical Review A pp. 4789-4792.
- [33] Pinnavaia Th. J., Thorpe M.F., 1995, Access in Nanoporous Materials pp. 273-276.
- [34] Resnick R., Halliday D., 1978, Physics Part Two, John Wiley & Sons pp. 566-600.

- [35] Shul'man Z.P., Deinega Y.F., Gorodkin R.G., Maseputo A.D. 1971, Some Aspects of Electrorheology, Prog. in Heat and Mass Transfer vol. 4, pp. 109-125.
- [36] Shul'man Z.P., 1982, Utilization of Electric and Magnetic Fields for Control of Heat and Mass Transfer in Dispersed Systems. Heat Transfer Soviet Research, vol. 14, No. 5, Sept – Oct 1982.
- [37] Shul'man Z.P., Chobot M.A., Bukovich I.V., Korobka E.V. Sukhahova R.V., 1985, A Study of Dielectric Properties of ER Suspensions, Vesti AN BSSR, Tekh. Nauk. pp. 96-101.
- [38] Slater J.C., Frank N.H., 1969, Electromagnetism, pp. 13-17, pp. 41-44.
- [39] Smith J.W., Electric Dipole Moments, 1955, London, pp. 4-19, 173-176.
- [40] Sun J.M., Tao R., 1995, Viscosity of One –Component Polarizable Fluid, Physical Review E, vol. 52, No. 1, pp. 813-817.
- [41] Tao R., Sun J.M., 1991, Ground State of ER Fluids from Monte Carlo Simulations, Physical Review A, vol. 44, No. 10, pp. 6181-6184.
- [42] Tao R., Jiang Q., Sim H.K., 1995, Finite Element Analysis of Electrostatic Interactions in ER Fluids, Physical Review E, vol. 52, No. 3 pp. 2727-2734.
- [43] Tosi M.P., March N.H., 1976, Atomic Dynamics in Liquids, John Wiley & Sons Inc., New York, pp. 9-19.
- [44] Zhang C., Lloyd J. R., 1993, Enhancement of Heat Transfer Through an ER Fluid Based Composite Medium, Fundamentals of Heat Transfer in Electromagnetic, Electrostatic and Acoustic Fields, HTD, vol. 248, pp.75-82.
- [45] Zukoski C.F, 1993, Material Properties and Electrorheological Response, Annu. Rev. Mater. Sci. vol. 23, pp. 45-78.

[46] Zukoski C.F., Marshall L., 1989, Effects of Electric Field on the Rheology of Non –Aqueous Concentrated Suspensions, J. Chem. Soc. Trans. vol. 85, pp. 2785-2795.

[47] Winslow M.W., 1989, The Winslow Effect, Proceedings of the Second International Conference on ER Fluids, Edited by Carlson J.D., Sprecher A.F., Conrad H. , pp. ix-xii.

[48] Winslow M.W., 1953, Field Controlled Hydraulic Device, US patent 2661596.

[49] Winslow M.W., 1949, Induced Fibration of Suspensions, Journal of Applied Physics, vol. 20, pp. 1137-1140.

[50] Wu C.W., Conrad H., Chen Y., 1996, Influence of the Conductivity of the Oil on the ER of Zeolites / Mineral Oil Suspensions, vol. 217, Rheology and Fluid Mechanics of Nonlinear Materials, pp. 267-275.

MICHIGAN STATE UNIV. LIBRARIES



31293020611756