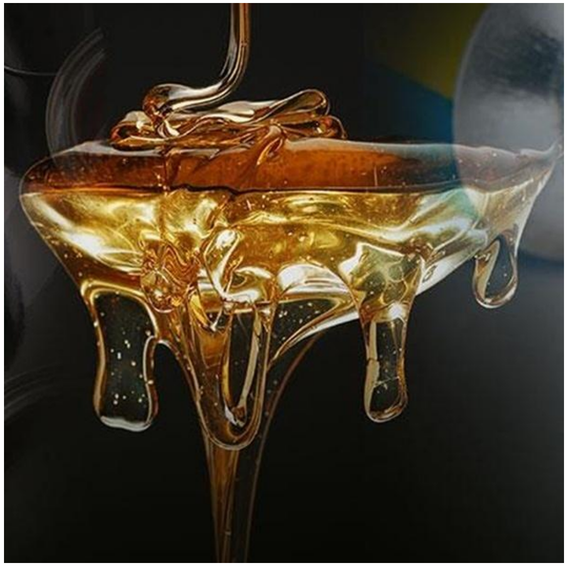


SMART FLUIDS

- ELECTRO RHEOLOGICAL FLUIDS
- MAGNETORHEOLOGICAL FLUIDS

Rheology

RHEOLOGY

Greek word Rheo-flow &Logia- study of * Rheology- study of flow

- **Branch of physics that deals with the deformation and flow of matter.**
- **Study of the plastic flow of solids/liquids/fluids.**
- **Addresses the behavior of real materials with properties intermediate between those of ideal solids and ideal liquids.**

When subjected to external forces, solids (or truly elastic materials) will deform, whereas liquids (or truly viscous materials) will flow. This property is rheology and it uses the visco elastic property of materials.

The term was first used by Eugene C. Bingham and Crawford

It applies to substances which have a complex microstructure… mud, sludge, suspensions, polymers and other glass formers (e.g., silicates), many foods and additives, bodily fluids (e.g., blood) and other biological materials .

Rheology in our daily life!

Squeezing toothpaste tubes, Pouring ketch up, kneading bread dough ,rubbing skin lotion ……… Rheology is simply one way of describing these sensations!!

Food Rheology addresses fluid and structural properties of raw materials, intermediate products, ingredients, and final products of the food.

These industrially important materials are called visco elastic materials.

Liquid food products are formulated to display desired rheological behavior, e.g., easy to pour from the bottle, flow in controlled manner and recover the viscosity upon pouring on the plate.






Types of fluids

Newtonian Fluids

- Single coefficient of viscosity for a specific temperature.
- This viscosity changes with temperature but does not change with the strain rate.
- Only a small group of fluids exhibit such constant viscosity.

Non-Newtonian fluids

- The large class of fluids whose viscosity changes with the strain rate
- The relative flow velocity is affected by strain
- Most of the ER fluids are non-Newtonian fluids.

ELECTRO RHEOLOGICAL FLUIDS

In synthesizing of smart materials

- **Actuators**
- **Sensors and**
- **Microprocessors / micro controllers play an important role.**

These sub systems have to be properly embedded into discrete regions of structural materials. Example : Fibrous polymeric composite laminate

The macro mechanical level engineering of smart materials depends on

- ✓ **the size**
- ✓ **The shape and**
- ✓ **the spatial distribution of the actuator.**

Actuator can be

- ✓ **Solid**
- ✓ **Liquid**
- ✓ **Gas**

} **On activation it changes its characteristics**

Activation is always an electrical/magnetic/electro magnetic phenomena.

One of the important actuators are - ER fluids

ER fluids are colloidal suspensions whose properties depend on electric field applied on them

Area of research:

- Controlling rheological properties
- Studying Electro hydrodynamic principles
- Applying Magneto hydrodynamics principles.

When a material (solute) dissolves in another material (solvent), a bonafide solution is obtained

Normal case : solute and solvent molecules are of comparable size and uniform distribution through out the solution. (Water –Glucose, Milk-Sugar)

Special case : Size of the solute >>> size of solvent than the solution obtained is colloidal dispersion . (Water - sand, Alcohol –carbon granules)

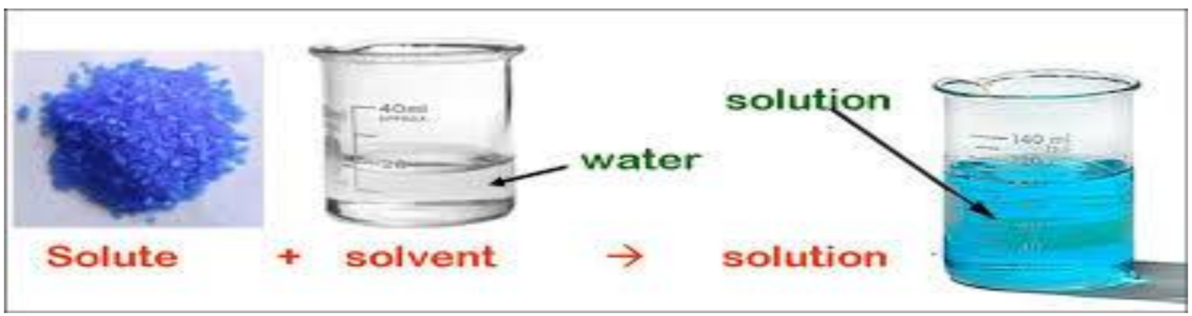
Study of colloidal dispersion needs both experimental and theoretical knowledge in the fields like Electrostatics ,Hydro dynamics, Surface chemistry Statistical mechanics, Polymer Science, Thermodynamics ,Organic chemistry, and Rheology.

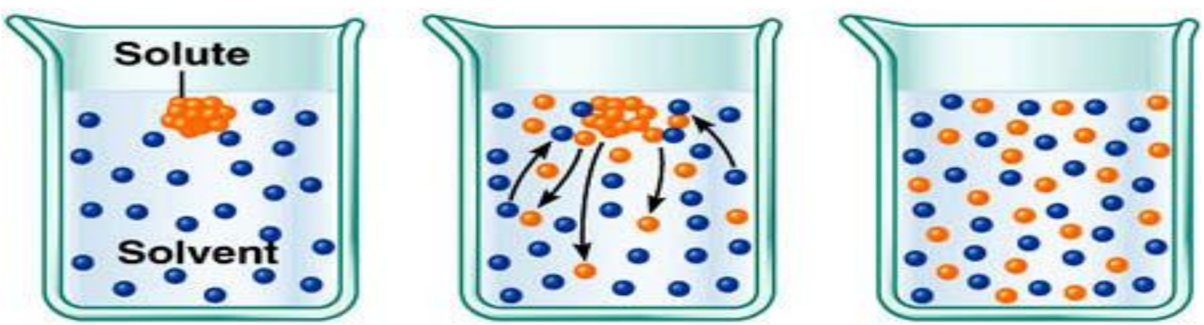
Solute Solvent table

Table 21-3

Possible Solution Combinations

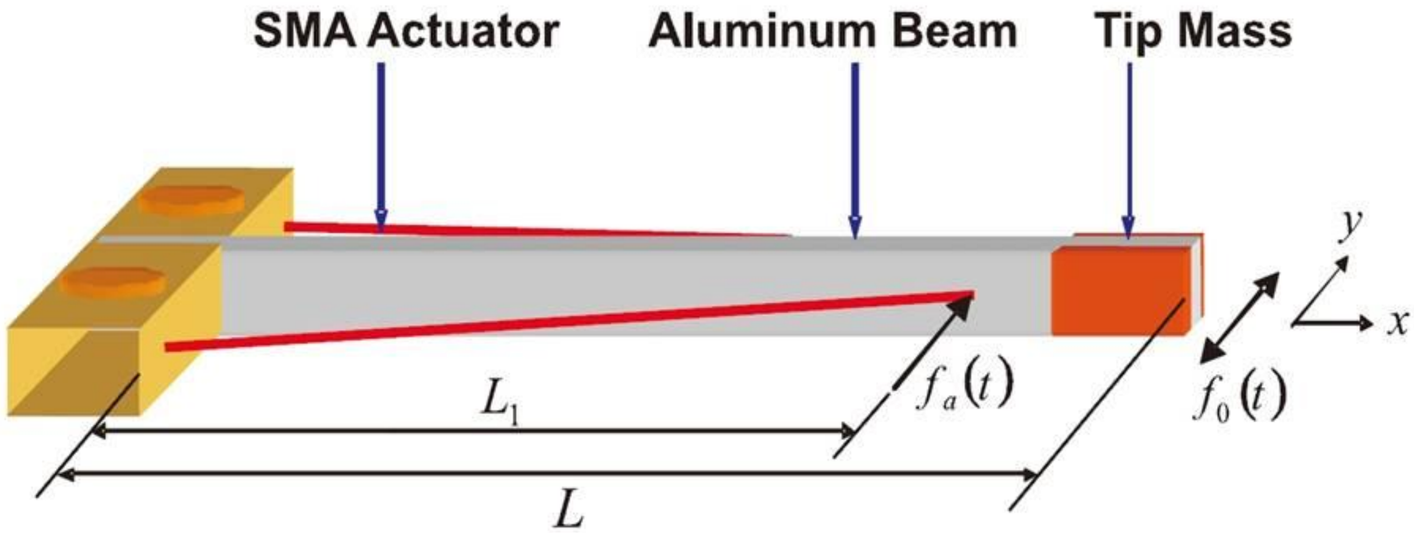
Solvent	Solute	Common Example
gas	gas	oxygen-helium (deep-sea diver's gas)
gas	liquid	air-water (humidity)
gas	solid	air-naphthalene (mothballs)
liquid	gas	water-carbon dioxide (carbonated beverage)
liquid	liquid	acetic acid-water (vinegar)
liquid	solid	water-salt (seawater)
solid	gas	palladium-hydrogen (gas stove lighter)
solid	liquid	silver-mercury (dental amalgam)
solid	solid	gold-silver (ring)





Typical ingredients for electro rheological fluids

Solute	Solvent	Additive
Kerosene	Silica	Water and detergents
Silicone oils	Sodium carboxy methyl cellulose	Water
Olive oil	Gelatine	None
Mineral oil	Aluminum dihydrogen	Water
Transformer oil	Carbon	Water
Dibutyl sebacate	Iron oxide	Water and surfactant
Mineral oil	Lime	None
P-Xylene	Piezo ceramic	Water and Glycerol oleates
Silicone oils	Copper Phthalocyanine	None
Transformer oil	Starch	None
Poly chlorinated biphenyls	Sulpho propyl dextran	Water and sorbitan
Hydro carbon oil	Zeolite	None


SMA Actuator
Aluminum Beam
Tip Mass
y
x
$f_a(t)$
$f_0(t)$
L_1
L

Electro Rheological phenomenon

When applying an external electric field to a static ie. Non flowing ER fluids the random structure of the suspension dramatically changes

The particles rapidly orientate themselves in relatively regular chain like columnar structures

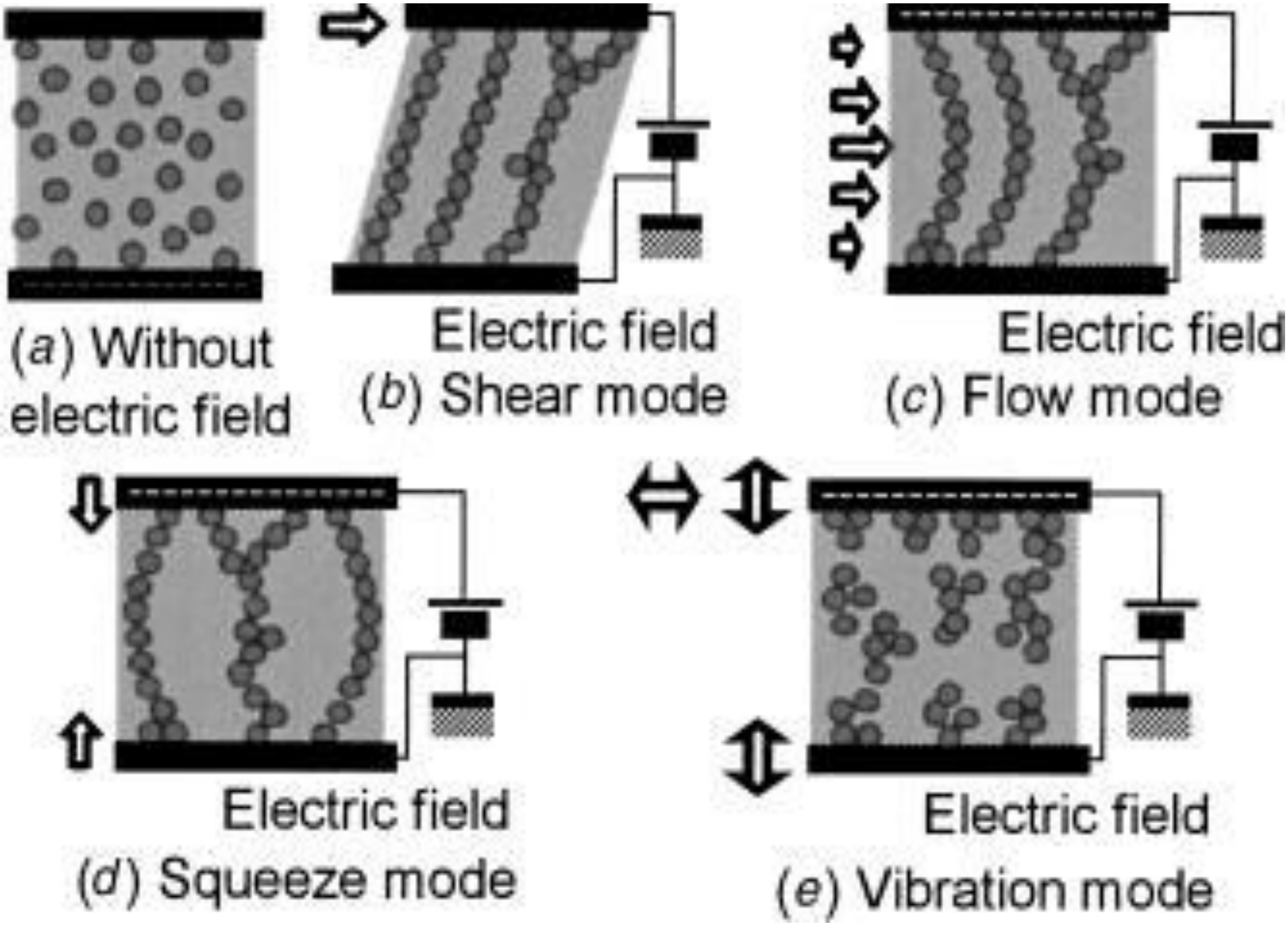
Koeing (1885), Duff (1896), and Quinke (1897) reported ER phenomenon.

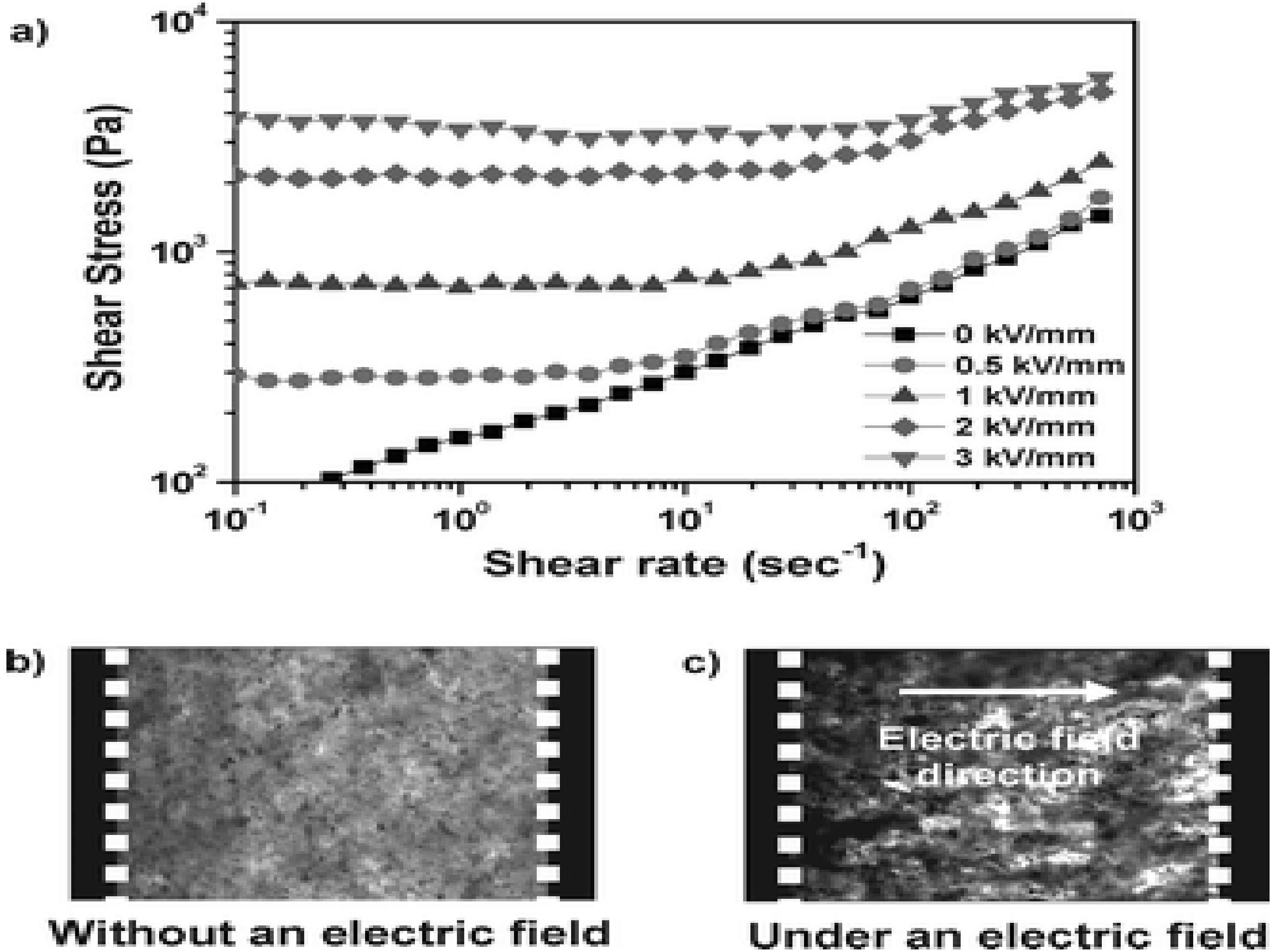
Willis winslow (1947) patented the clutch mechanism designed with ERF.

Experimental work: Study of fluid flow in the presence of electric field is going on

- Normally particles align themselves parallel to the electric field in vertical direction.
- Parallel electrodes are used & stationary fluid is present between parallel electrodes
- particles align themselves in orderly fashion

Theoretical work : Models logging – (fluid mechanics and electro magnetic systems experts have to propose models)


(a) Without electric field
Electric field
(b) Shear mode
Electric field
(c) Flow mode
Electric field
(d) Squeeze mode
Electric field
(e) Vibration mode


a)
Shear Stress (Pa)
10^4
10^3
10^2
10^{-1}
10^0
10^1
10^2
10^3
Shear rate (sec^{-1})
0 kV/mm
0.5 kV/mm
1 kV/mm
2 kV/mm
3 kV/mm
b)
c)
Electric field direction
Without an electric field
Under an electric field

Sub Groups of colloidal dispersions

Dispersions of Sols, Emulsions, Aerosols & foams

Sols: solid particles in a liquid. Milk of Magnesia is a sol with solid magnesium hydroxide in water, blood, pigmented ink, cell fluids and paint.

Sols

- ✓Solids in Solids – Mixture of two powders
- ✓Solids in Liquids – Quicksand : sand in water, gelatin: protein in water, Gels: liquids in solid.

Emulsions :

- ✓Liquids in Liquids - Oil and water(Mayonnaise: oil in water). Milk-water,

Aerosols

- ✓Liquids in gases - Air and water,
- ✓Solids in gases -Smoke: solid in a gas

Foams

- ✓Gases in Liquids - Fog : liquid in a gas.
- ✓Gases in Solids -Smoke: solid in a gas

ER Fluids are Sols

- ✓**Solids in Solids**
- ✓ **Solids in Liquids**

(both) → **Best actuators in smart systems.**

Based on Characteristics colloidal dispersions can be sub grouped

Lyophilic : Colloidal dispersion exhibiting solvent attracting characteristics

Lyophobic : Solvent repelling characteristics

If dispersing medium is water

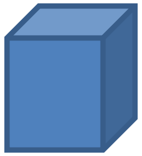
- Hydrophilic
- Hydrophobic

Terms and components of colloidal systems

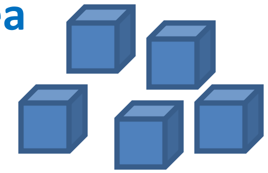
1) Surface area:

   Special feature is large surface area of micron sized particulate dispersed phase to surface area of dispersed phase reconstituted as a single piece of bulk material

1 cm cube of a homogenous solid material, Surface area = 6 cm^2



Small cubes with 10nm side, 10^{18} Cubes and 6 million cm^2 surface area



Role of interfacial surface chemistry is felt now

2.Electric double layer:

- ✓Kinetic stability of colloidal particles is due to surface electrical charges
- ✓ These surface charges are responsible for attracting ions of opposite charges to cluster in the neighborhood. An ionic atmosphere is now formed.
- ✓If there are 2 sub domains of opposite charges – it is electric double layer.

3.Amphiphiles :

- ✓These are strong surface active
- ✓Lower interfacial tension
- ✓Help to create new surface easily
- ✓These are molecules comprising of two discrete regions
  - Oil soluble (Lyophilic or hydrophilic)
  - Water soluble (only hydrophilic)

Example : surfactant (used as detergents and dispersing agents)

Surfactant: A chemical agent capable of reducing the surface tension of a liquid in which it is dissolved

Amphiphilles/ Surfactants are important to maintain stability of ER fluids

Reverse characteristics of ER Fluids

In the presence of an electric field :

1. **Pseudo phase changes of ER fluids (from liquid →Solid state)**
2. **Dramatic increase in flow resistance –depends on composition of ERF**
3. **Exhibits Non Newtonian characteristics**

In the absence of an electric field:

1. **No effective phase changes**
2. **Flow resistance is not changed**
3. **Exhibits Newtonian characteristics**

BINGHAM BODY MODEL **GRAPH 4.1**

Newtonian fluid → absence of an electric field → ER Fluid exhibits Linear shear stress Vs Shear strain rate

Bingham – Body model-Non Newtonian fluid → presence of an electric field → ER Fluid exhibits a static stress → this stress must be overcome prior to initiating flow rate.

Bingham-body Model.

Behaviour of typical ER fluid.

①

Fig. 4.1 A Bingham-body model for the isothermal constitutive behavior of a typical ER fluid.

Rheological Characteristics.

②

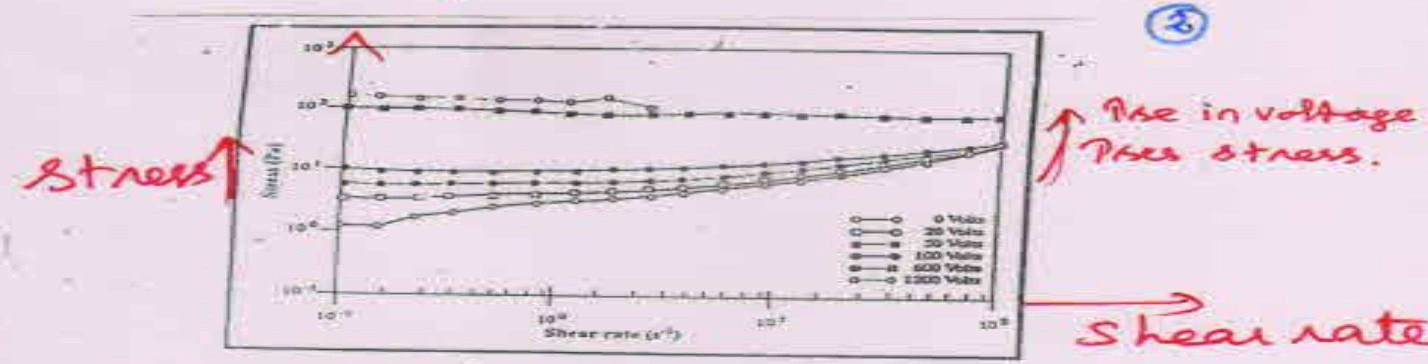
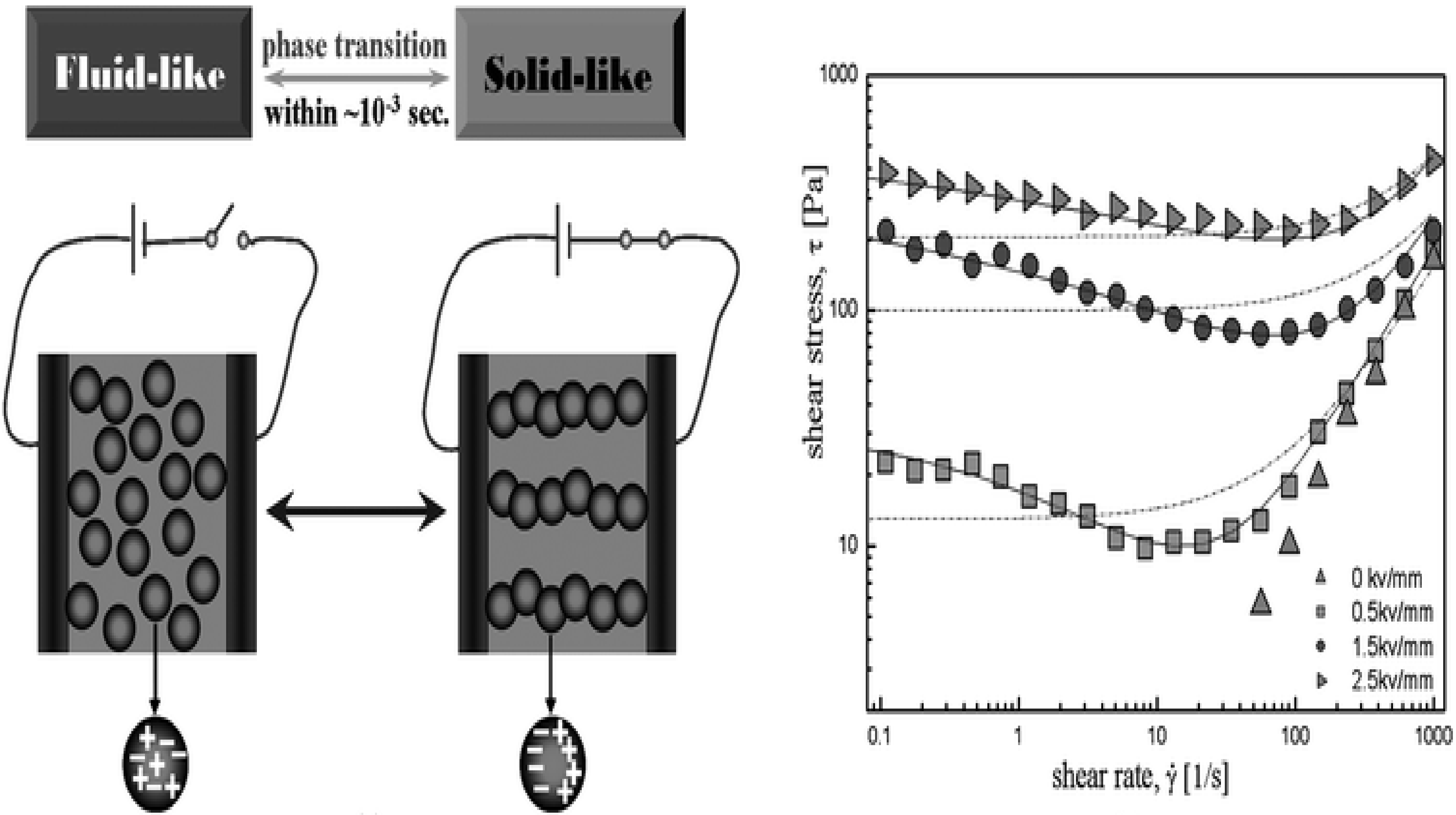


Fig. 4.2 Experimentally determined stress versus shear rate ...

ER fluid – 45% cornstarch & 55% Silicone oil by weight

* Controlling shear stress as a fn. of ① intensity of electric field imposed & ② strain rate

This property is best for ER fluid actuators.


Fluid-like
phase transition
within ~10-3 sec.
Solid-like
1000
100
10
shear stress, τ [Pa]
0 kv/mm
0.5kv/mm
1.5kv/mm
2.5kv/mm
0.1
1
10
100
1000
shear rate, γ̇ [1/s]
(a)
(b)

Stress Vs Shear rate characteristics of ERF GRAPH 4.2
Composition of ERF used: 45% corn starch + 55% silicon oil

Technique Used / Rheometrics involved:

- RMS 800 – Mechanical spectrometer
- Spectrometer is upgraded with 5KV high voltage attachment
- ER sample taken in a double walled test fixture
- 2 concentric Tubes with radial separation of 1 mm between two faces
- This tube accommodate the fluid sample
- across the test fixture a constant potential difference is maintained and stress –shear rate is studied
- the study is repeated at different voltage levels

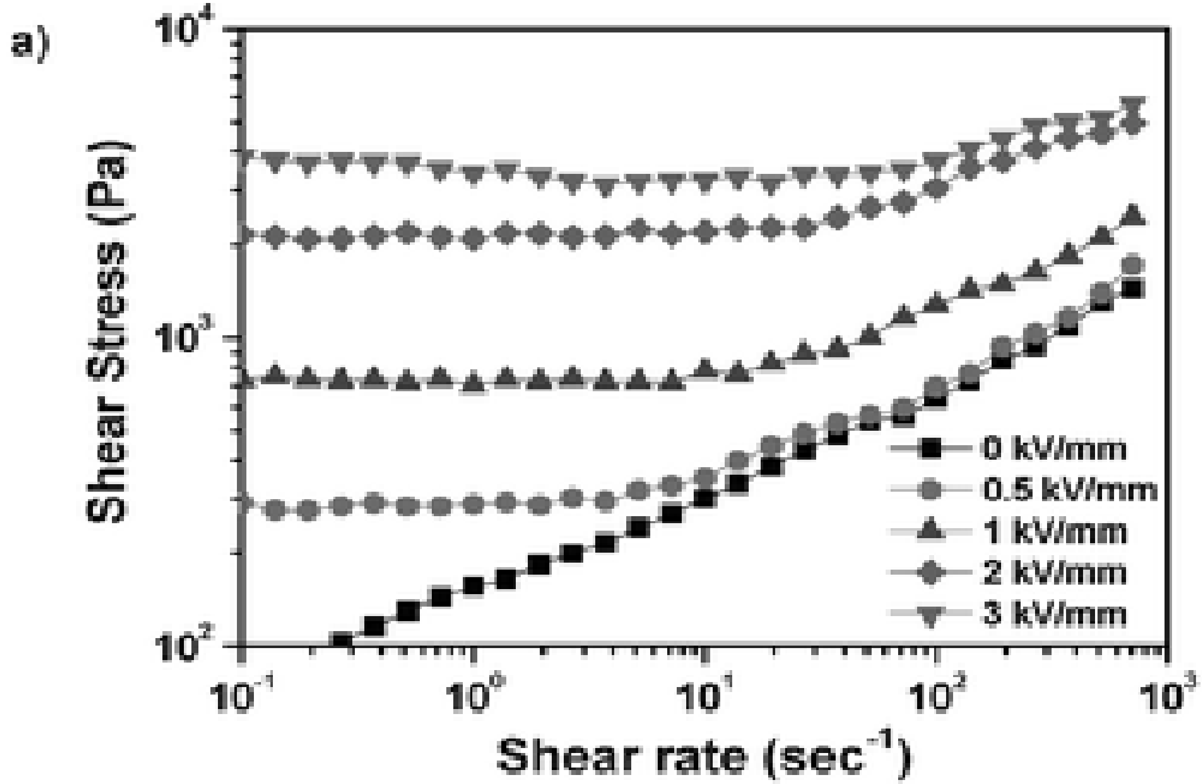
Shear rate Vs Shear stress graph - Bingham body model GRAPH 4.2

Increase in stress as a function of increase in voltage is observed

Characteristics inferred :

1. Shear stress can be controlled as a function of intensity of electric field applied .
2. Strain rate maintenance is important

Application: ER fluid actuators



Strain Vs Storage modulus graph GRAPH 4.3

Storage modulus → measure of the energy dissipation properties of the suspension

Characteristics inferred :

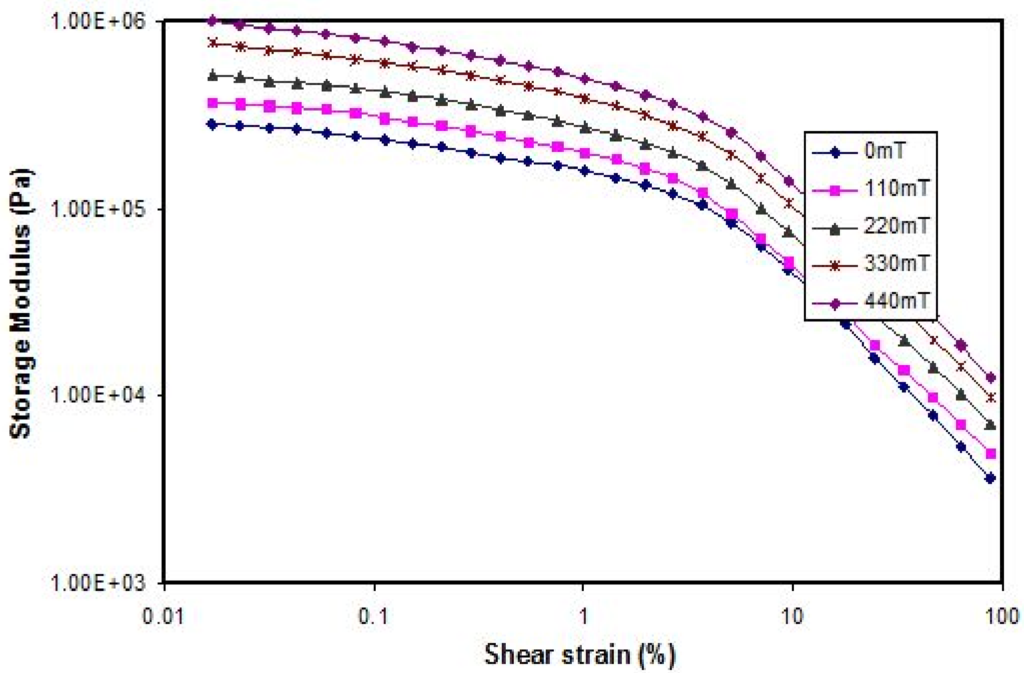
1.Storage modulus depends on the strain rate and applied voltage

2. Strain increases with increasing voltage

Application :

- ✓ **controlling the electro dynamic response of smart structures**
- ✓ **System damping can be actively controlled**

For field intensity	0.2 KV/mm	1.2 KV/mm
Storage modulus	200 Pa (low strain rate)	1000 Pa (high strain rate)



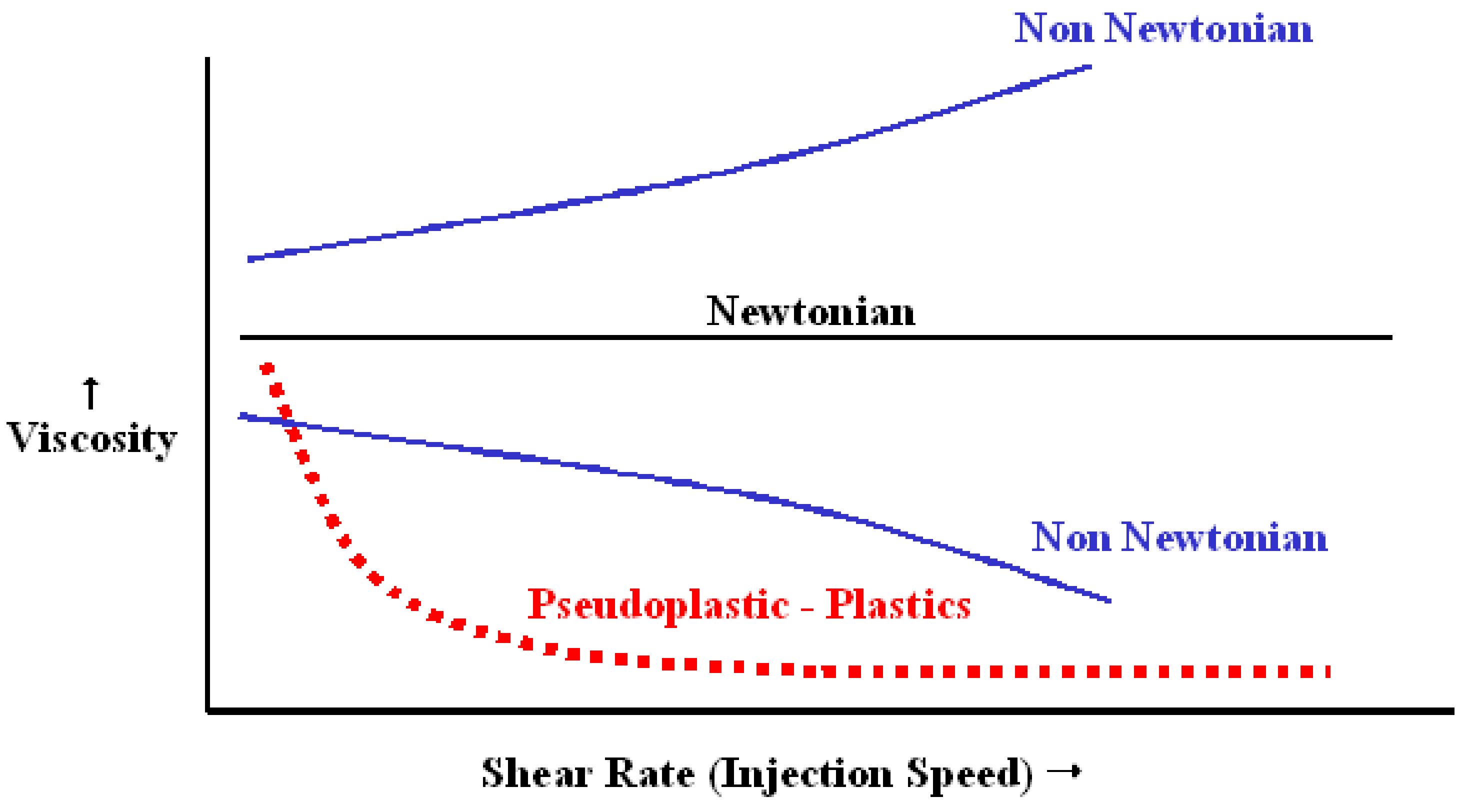
Shear rate Vs Non-Newtonian Viscosity GRAPH 4.4

Characteristics inferred :

1.No field: Viscosity decreases as shear rate increases (shear thinning takes place)

2. With Field(1000 V to 1KV): Shear rate increases with decrease in viscosity

Application : To employ colloidal suspensions for many engineering applications- change in viscous characteristics as a function of applied field



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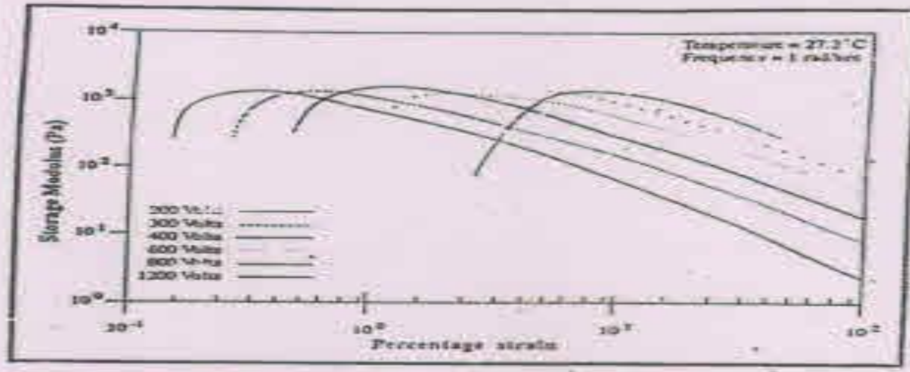


Fig. 4.3 Experimentally determined storage modulus versus percentage strain characteristics measured at different voltages for a hydrous electro-rheological fluid comprising 45% corn starch and 55% silicone oil.

4

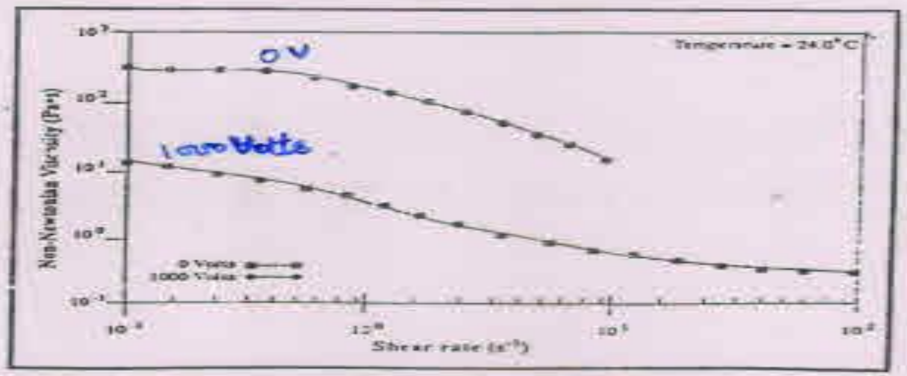


Fig. 4.4 Experimentally determined non-Newtonian viscosity versus shear rate characteristics measured at different voltages for a hydrous electro-rheological fluid comprising 45% corn starch and 55% silicone oil.

Principle characteristics of ER fluids

1. Electro mechanical characteristics
2. Electrical properties
3. Thermal properties
4. Dispersion stability
5. Viscous characteristics
6. Solvent characteristics
7. Solute characteristics

Electro mechanical characteristics

- ✓ Any ER based device or structure design depends on electro mechanical characteristics
- ✓ Relation between shear stress and applied electric field is used
- ✓ Low electric field intensity means high stress

Electrical properties :

- ✓ conducting properties are to know power consumption and heat dissipation
- ✓ Low heat dissipation is expected (to avoid secondary / ancillary cooling systems)

Thermal properties :

- ✓ ER fluids should be operative over broad temperature range
- ✓ Use of anhydrous fluids gives range as – 20^0 C to 70^0 C.

Dispersion stability :

- ✓ ER fluids developed for commercial applications must have > thermal stability
- ✓ density to particulate phase and continuous phase must be same to minimize sedimentation problems.

Viscous characteristics :

- ✓ low viscosity in the absence of electric field
- ✓ High viscosity in the presence of eclectic field

Solvent and solute characteristics :

Dispersant used should have property like

- ➢ low viscosity
- Low volatility
- ➢ Non toxic
- Non corrosive
- ➢ Non flammable(for high voltage applications – where spark / arching possibilities are more)

Dispersed Phase :

- ✓ should posses electrical attributes
- ✓ has to be easily atomized from bulk state (to the surface area)
- ✓ must be easily dispersed with minimal use of additives

Solute :

- ✓ must be non abrasive.

Four ingredients for heterogeneous dispersions

1.Continuous medium or solvent :

✓ low viscosity liquid (0.01 – 10 Pa)

Example : Paraffin, silicone oil, chlorinated hydrocarbons

✓ dielectric constant (2 - 15)

✓High electrical resistivity (1016-1010 ohm/m)

2.Particulate materials &

3. Organic activators

✓ clays with interstitial moisture

Example : Kaolimite, diatomite, poly sacchrides, silica

✓ Dispersed phase

- solid
- semiconductor
- Non conducting

✓Particle diameter 1 nm to 100 nm and surface area : 400 m^2 /g

4.Surfactants :

✓ These are added to achieve higher concentration of dispersed phase

✓Added in small quantities - 1 to 3 molecules / μm^2

Charge migration mechanism for the dispersed phase :

- ✓ It is mainly surface phenomena (or) bulk phenomena

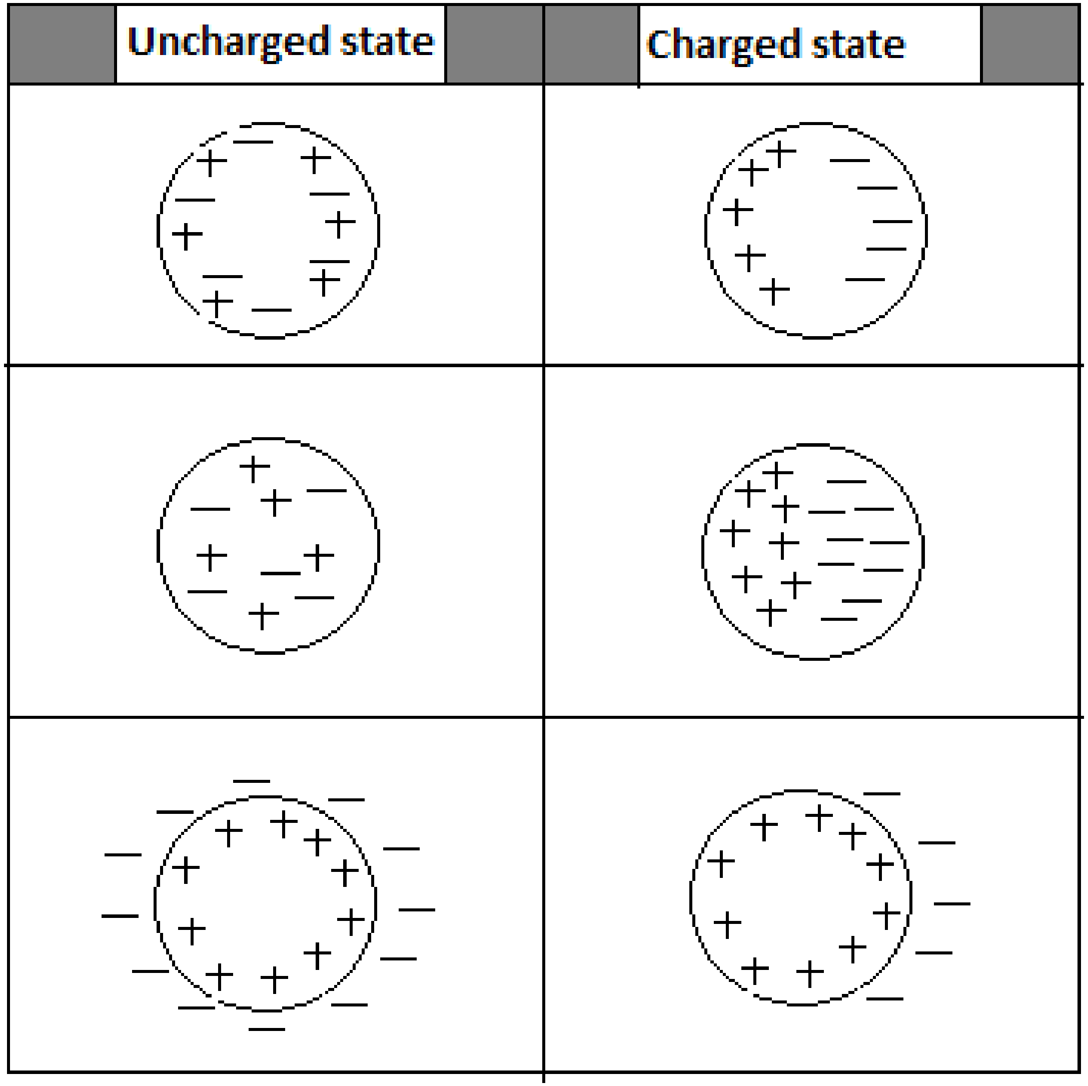
- ✓It depends on columnar structure formed

- ✓I t depends on transport mechanism
    - •dipole moment
    - •alignment of the dipoles

- ✓It depends on nature of the liquid
    - •porosity of the particle
    - •characteristics of the surfactants
    - •hydrous/anhydrous nature of the liquid

- ✓It depends on characteristics of surfactants used
    - •fluid density
    - •Properties of chemical activators present on the surface

CHARGE MIGRATION MECHANISM
ERF ACTUATORS



In the study of ER colloidal systems challenge for theoreticians :

✓ diverse transport mechanism

✓Interaction between electric and fluidic fields – highly complex

But, British and Russian scientists are able to change the global properties of ER fluids and to apply the properties in diverse range of products.

Example :

Various mechanical devices	Clutches, hydraulic valves
Vibration isolation system	Engine mounts, shock absorbers
Heat and mass transfer phenomena	Double pipe heat exchangers Recuperative heat exchanges

A smart structure subjected to prescribe loading shows

✓Static response → stiffness of the structure

✓Dynamic response →mass of the structure
→stiffness and energy dissipation
→nature of dynamic excitation

How to control the static and dynamic behavior of a general structure?

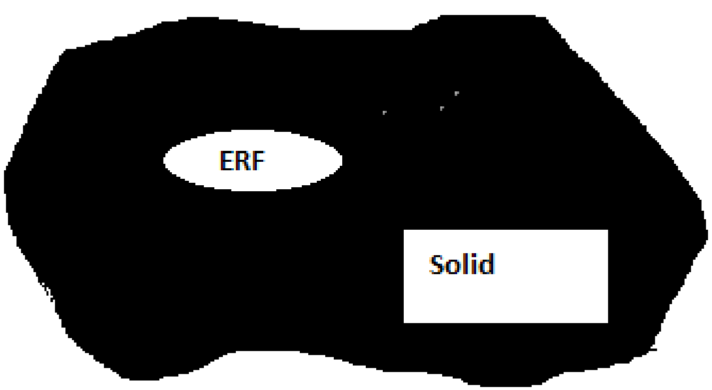
By controlling

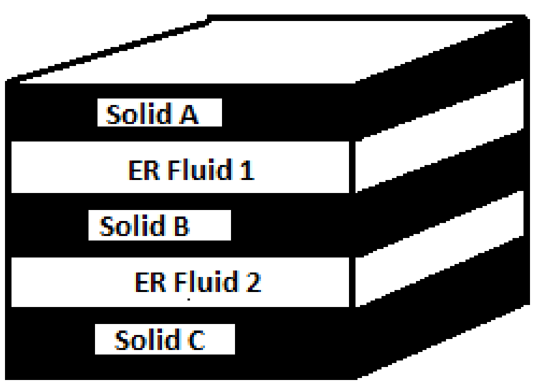
- the mass
- the stiffness and
- energy dissipation characteristics

But for a smart structure- ER fluids posses electrical dependent mechanical characteristics

When ER fluids are embedded with in an electrically conductive solid medium, the ability to control the global properties of the materials is available.

Mathematician should model and predict the electro elasto dynamic behavior of the system with single fluid domain and solid domain or laminate configuration





For the study of electro elasto dynamic behavior

Knowledge about

- **colloidal science**
- **modern advanced anisotropic solid materials**
- **fluid structural interaction phenomena**
- **electromagnetic field theory**
- **Control system theory**
- **Micro processors**
- **manufacturing process are needed**

Anyhow, basically the systems with ER fluids are based on

- **a solid material,**
- **a fluid medium and**
- **an electromagnetic effect.**

The designer can consider the stress fields associated with the above factors and the interaction between them.

Experimental Set up for studying dynamic response of a smart cantilever beam

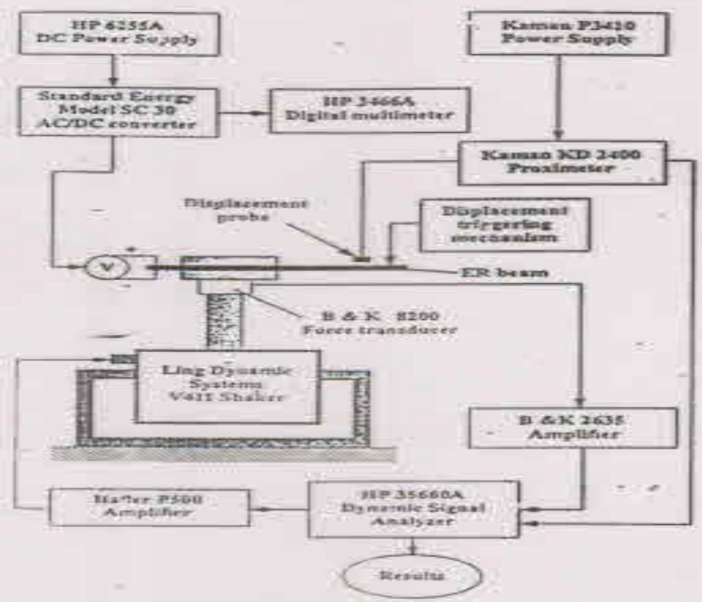


Fig. 4.21 Experimental apparatus for dynamically exciting a smart cantilevered beam

After synthesizing, characterization is important for a structural material in a dynamic mechanical environment

The transient and force response are important

They are characterized by

Natural frequency | Damping characteristics | excitation characteristics

Natural frequency and Damping characteristics: Depends on inherent mass, stiffness and energy dissipation characteristics

excitation characteristics: depends on harmonic stochastic and non linear

Selection of structural materials

X Traditional materials – Monolithic – steel or Al alloys

✓Advanced engineering polymeric materials

If one choose advanced materials proper combination of fiber and matrix materials is important.

Example : Graphite + glass fiber → unified common epoxy matrix material which is totally different from graphite epoxy material & glass epoxy material

After selecting the material

- ✓ steel
- ✓ Al alloys
- ✓ fiber combinations
- ✓ epoxy matrix materials.

} any one kind , ER fluid should be added

These suspension have diverse ingredients

Already in synthesizing

- ✓ the stacking sequence
- ✓ Fiber orientation
- ✓ Fiber volume fraction and
- ✓ manufacturing process parameters are considered

Now, to incorporate ER fluid in cavities

- ✓ Volume of a specific ER fluid needed
- ✓ Volume of a specific structural materials
- ✓ spatial distribution of the fluid within the solid
- ✓ the shape and the surface toughness of the solid at the fluid structure interfaces

Smart beams / plate structures embedded with ER fluids

Smart beam with ER fluids :

- ✓ static response
- ✓ transient response
- ✓ forced response

} of ER fluid domains

Variety of discrete constant electrical field intensities are given & the response are studied.

Experimental apparatus:

- Cantilever beam specimen
- Smart ultra advanced composite materials
- Graphite prepreg tap AS4/3501-6 manufacture by Herculus Inc
- Electrode : 3 plies with lay ups (90/0/90) for specimen A, B, C and (0/90/0) for specimen D
- Insulator – RTV silicone rubber adhesive

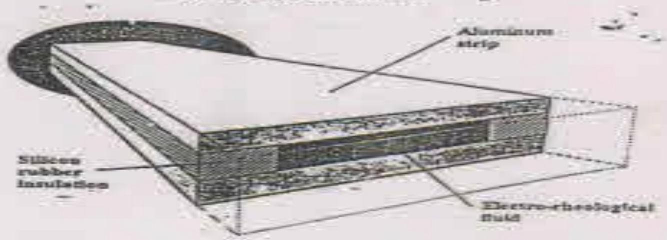
SMART BEAM

Electrode Surface Geometries

PV disk ▭ form

PV disks ○ are in shape.

Fig. 4.18 Schematic diagram of different electrode surface geometries for Class D and E specimens.



Al Strip
Silicone Rubber
Insulator
ER fluid.

Fig. 4.26 A schematic of a smart beam featuring a void filled with an electro-rheological fluid

Exptl Investigations of cantilever beam specimen responses ---

- different classes of beams
- different electrode materials
- different fluid volume fractions
- different geometrical dimensions . –

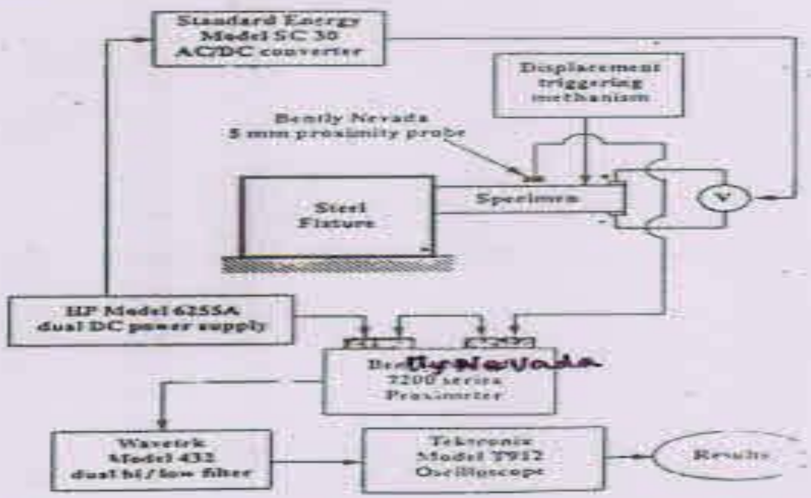


Fig. 4.11 A schematic diagram of the experimental apparatus

Characteristic studied :

1. **Load – deflection characteristics**
2. **Transient vibrational response characteristics (CRO O/P)**
3. **Electric field Vs sample A and B : Damping ratio increment and frequency increment**
4. **Electric field Vs sample A and B for two different lay ups (90/0/90 – 0/90/0) face materials**
5. **Controlled transient response of class B at room temperature (with and with out control)**
6. **Relative frequency increment and relative damping ratio increment of class A and C specimen.**
7. **Relative frequency increment and relative damping ratio increment of class D and E specimen.**
8. **Relative frequency increment and relative damping ratio increment of class A and F specimen.**

~~41 page~~

~~Electrode surface geometrics~~

~~Class D and E specimens~~

~~D → bonding of circular~~

~~E→ bonding of rectangular~~

~~Statistic response characteristic :~~

~~1. Rectangular pieces – superior response profiles for both frequencies and damping than circular pieces~~

~~2. Figure 8 shows both frequency increment and damping ratio increment.~~

~~Increases when electrode area in contact with ER fluid domain increases~~

~~Dynamic response characteristics :~~

~~The smart beam fixed to the head of an electro dynamic shaker in a cantilever configuration. So , the beam can be dynamically excited in a controlled manner.~~

ER fluid design parameters

- ✓ Cost – Toxicity
- ✓ dielectric properties – viscosity
- ✓ Surfactant – fluid density
- ✓ Additive – hydrous
- ✓ Anhydrous – particulate stability
- ✓ Non corrosive – power consumption
- ✓ Current density – electrode group
- ✓ Mechanical constitutive properties – thermal stability