(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: **0 448 874 A1**

# (12) EUROPEAN PATENT APPLICATION

(21) Application number: **90313585.3**

(51) Int. Cl.5: **C10M 171/00**

(22) Date of filing: **13.12.90**

(30) Priority: **22.12.89 GB 8929065**

(43) Date of publication of application:
**02.10.91 Bulletin 91/40**

(84) Designated Contracting States:
**AT BE CH DE ES FR GB IT LI NL SE**

(71) Applicant: **IMPERIAL CHEMICAL INDUSTRIES PLC**
**Imperial Chemical House, Millbank**
**London SW1P 3JF(GB)**

(72) Inventor: **Prendergast, Maurice Joseph**
**15 Kendal Rise, Beechwood**
**Runcorn, Cheshire WA7 2QL(GB)**
Inventor: **Case, John Reginald**
**4 Oakdale Avenue**
**Frodsham, Cheshire(GB)**

(74) Representative: **Draggett, Peter Thornton et al**
**Imperial Chemical Industries PLC, Legal Department: Patents, PO Box 6, Bessemer Road**
**Welwyn Garden City Herts AL7 1HD(GB)**

## (54) Electrorheological fluid apparatus.

(57) An ER apparatus comprising means containing an ER fluid, two electrodes in contact with the fluid, and means for applying an electrical potential between the electrodes, characterized in that the means for applying an electrical potential is capable of applying a cyclically variable potential, and the fluid has a d.c. conductivity at 25°C below 5 x $10^{-8}$ohm$^{-1}$.cm$^{-1}$, in particular where at least one of the electrodes is insulated, the applied potential is a sinusoidal a.c. potential at a frequency in the range of 5 to 150 Hz, the fluid is used in dynamic shear, and the ER effect in the apparatus shows a frequency related maximum.

EP 0 448 874 A1

# APPARATUS

The present invention relates to electro-rheological fluid apparatus (ER apparatus), that is, apparatus which relies for its operation on a large increase in apparent viscosity, in some cases to virtual solidification, of a so-called electro-rheological (ER) fluid under an applied electric field against a shear stress.

Examples include apparatus for the transmission of force by the solidified fluid, such as the transmission of torque in an ER clutch against shear stress between driving and driven surfaces, and apparatus in which valves are closed by the solidified fluid against the shear stress of hydrodynamic pressure on the solid plug, such as an ER damper using ER fluid valves.

ER apparatus is generally known, and the electric field applied in use of such apparatus is typically a d.c. field. In such apparatus the static yield stress of each conventional ER fluid increases with increasing applied electric field intensity, and the apparatus is useful in static applications, ie in a 'locked-on', 'solid' state, eg as a torque transmitter in a clutch.

However, in a steady d.c. field, the fluid in such apparatus generally has poor dynamic performance, in that the shear stress can decrease markedly, and possibly even exponentially with the shear rate (somewhat resembling the plastic behaviour of a solid past its yield point). Such apparatus and fluids are clearly of limited use in applications such as ER dampers, where good dynamic performance with a fluid already in shear is required.

Some ER fluids do however have a better dynamic performance. This makes them potentially useful in such dynamic applications, but they suffer from a number of practical disadvantages. ER fluids have hitherto appeared to require some d.c. conductivity to work, and may require a relatively high d.c. conductivity for good dynamic performance.

There is thus a limit to the field potential gradient which can be applied to the fluid in use. Above a breakdown value for that fluid, that d.c. conductivity increases markedly and there is arcing of electrical current through the fluid.

Conventional ER fluids have a number of further disadvantages which give rise to problems in their use in conventional d.c. ER apparatus. Thus, such fluids generally have a relatively low yield shear stress to field intensity ratio, a relatively high d.c. conductivity, and a relatively low electrical breakdown voltage.

The above low ratio means that the electrodes of the apparatus, between which the fluid solidifies, must usually be of high mutually opposed surface area and be close together.

As noted above, many such fluids have a relatively high d.c. conductivity, and associated relatively low breakdown potential gradient.

The aforementioned relatively high electrode surface areas and relatively small inter-electrode distances coupled with the relatively high fluid d.c. conductivity results in undesirably high electrical power consumption. This high power consumption in turn leads to excessive heating of the apparatus (the electrical energy being converted to heat).

ER apparatus, eg ER clutches and dampers, may often have a moderately high operational temperature (eg in excess of 50 $^{\circ}$ C), owing to

a) electrical heating, and

b) in the case of dampers, to the conversion of absorbed mechanical energy to heat.

The electrical d.c. conductivity of ER fluids increases markedly and even exponentially with temperature, leading in practical use to a continuing cycle of further power consumption and increased apparatus temperature.

Typically, such fluids in a d.c. apparatus exhibit a so called doubling temperature. This is the operating temperature increment which causes the conductivity of the fluid to double, and may typically be as low as about 6 $^{\circ}$ C.

An equilibrium temperature below the long-term degradation temperature of the fluid may not be reached at an acceptable level of power consumption.

If this does not occur below breakdown conditions for the fluid, d.c. conductivity and power consumption increases until the capacity of the power source is exceeded and/or the apparatus and/or the fluid fails.

The foregoing disadvantages are avoided by the apparatus of the present invention.

The present invention provides an ER apparatus comprising means containing an ER fluid, two electrodes in contact with the fluid, and means for applying an electrical potential between the electrodes, characterised in that the means for applying an electrical potential is capable of applying a cyclically variable potential, and the fluid has a d.c. conductivity at 25 $^{\circ}$ C below 5 x $10^{-8}$ ohm$^{-1}$.cm$^{-1}$.

Typically, ER fluids used in the present apparatus exhibit a d.c. conductivity between the electrodes of conventional ER apparatus of the order of 5 x $10^{-9}$ ohm$^{-1}$.cm$^{-1}$ at 25 $^{\circ}$ C.

The operational potential gradient between the electrodes (which may be the same as or different from that applied to the ER fluid) in the apparatus of the present invention may conveniently be in the range of 1 to 20, eg 2 to 15 kV $mm^{-1}$.

The applied potential may be varied in any manner which is cyclical. Thus it may be an a.c. potential varying about earth potential in any wave-form, including sinusoidal, square or saw-tooth (triangular) waves.

The potential applied to the fluid may also be a positive or negative potential with respect to earth, similarly varying, eg pulsed d.c. at any mean potential with respect to earth.

However, it is preferred that the applied varying potential is a.c. rather than pulsed d.c. of the same magnitude and wave-form at any mean potential with respect to earth, in view of the observed ER behaviour of any given ER fluid.

The observed ER effect increases not only with the applied potential gradient, but also with the power put in at a given maximum input potential. Thus, for a given maximum applied potential, the observed ER effect increases as the wave form is changed from triangular to sinusoidal to square.

Suitable frequencies for the cyclically variable potential will depend greatly on the type of the present ER device. Thus, eg engineering problems associated with medium and higher frequencies (described further below) may be acceptable in some specialist dampers, but not in automotive applications.

In general, the frequency may suitably be in the range of 1 to 6,000 Hz, for example 1 to 2,000 Hz.

However, at medium and higher frequencies the problems associated with the skin effect, inductance, pick up and transmission, inteference, and the consequent need for rigorous screening of all electrical parts of the apparatus, are greatly increased.

Generally applicable frequencies are therefore often in the range of 1 to 600, eg 1 to 300 Hz, favourably 3 to 250, and preferably 5 to 150 Hz.

Such frequencies may also be in the ranges of 1 to 200, eg 3 to 250, or 5 to 100 Hz.

For some systems, for a given applied potential the ER effect shows a frequency related maximum at a readily determined frequency ('the Optimal Frequency').

This frequency will depend not only on the ER fluid used in the apparatus, but also on the dimensions and materials of the apparatus, and other materials used in the apparatus. This factor may well be another factor determining the desired operating frequency of the present apparatus, and indeed may be used in controlling the apparatus response.

Typically, those ER fluids defined hereinbefore as forming part of the present apparatus which exhibit a relatively lower d.c. conductivity between the electrodes of conventional ER apparatus tend to exhibit a sharper maximum ER effect at an Optimal Frequency in the preferred frequency range of 5 to 150 Hz mentioned hereinbefore, in particular where the applied potential is varied in an a.c. sinusoidal waveform.

At least one of the electrodes may be insulated. The favoured operating frequencies for uninsulated electrodes tend to lie towards the lower end of the abovementioned ranges.

For insulated electrodes they tend to lie towards the higher end.

Each electrode will typically be of metal. Suitable metals include iron, cobalt, nickel, titanium and copper and alloys thereof, including stainless steels and low carbon steels.

The present apparatus offers a number of advantages over the ER apparatus of the prior art.

Thus, eg the fluid in such apparatus has good dynamic performance, in that the shear stress increases slightly, and possibly even significantly with increasing shear rate.

Such apparatus is clearly of use in applications such as ER dampers, where good dynamic performance is required.

Also, as noted above, the conductivity of most ER fluids increases with their operating temperature, to the extent that many cannot be put to practical use under every-day working conditions.

In the present apparatus, the typical doubling temperature of many fluids is increased markedly, typically from about 6 to 9 to about 30 to 50 °C, thus greatly increasing the practical operating temperature range which is accessible by many conventional fluids.

Fluids whose conductivity at moderately elevated temperatures would normally be too high for practicable use in conventional ER apparatus, but which may have other desirable characteristics such as a fast energisation response time, may be used, without excessive power consumption.

Further, as noted above, the frequency-related maximum of the ER effect of some systems may be used in controlling and tuning the desired apparatus response.

The present apparatus appears to offer a number of further advantages over known d.c. apparatus.

The breakdown potential gradient of many conventional ER fluids tends to lower in longer term use of the fluid, probably due to the longer term electrochemical degradation of the fluid under repeated application of d.c. potentials and with the transmission of d.c. currents.

In the present apparatus the net current transmitted and power applied for a given ER effect will often

be substantially lower, especially if the apparatus is operated at the Optimal Frequency as hereinbefore defined, so that this effect will be lowered.

Where the potential applied in the present apparatus is an a.c. potential, there will be no net d.c. current transfer through the fluid, so that any electrochemical effects will be minimised.

In a particular embodiment of the present apparatus, at least one electrode comprises an electrically insulating surface coating.

By 'insulating surface coating' herein is meant any coating on such an electrode which gives an apparent d.c. conductivity of an ER fluid in the apparatus of less than $5 \times 10^{-10}$ $ohm^{-1}.cm^{-1}$ at 25° C.

If this embodiment of the present apparatus is used with a steady applied (d.c.) potential (and thus steady field) between the electrodes, no ER effect is observed.

When a steady d.c. potential is applied, the resistance of the insulating layer on at least one electrode is the current-limiting factor, and the negligible conduction through the fluid is insufficient to produce the ER effect.

Without prejudice to the generality of the present invention, it appears surprising that, when a cyclically varying potential is applied between the mutually insulated electrodes, the current induced in the ER fluid is sufficient to give rise to an ER effect.

It is all the more surprising that such an effect occurs notwithstanding the high limiting series resistance of the insulating coating on at least one electrode.

At the practical field frequencies used (discussed above) the ER effect is comparable to that achieved with the same d.c. potential under the same conditions.

This embodiment of the present apparatus offers a number of advantages over the ER apparatus of the prior art. Thus, although an apparent current flows through the fluid in use, its magnitude is limited by the impedance of the apparatus rather than by the d.c. resistance of the fluid.

Power consumption for an equivalent shear stress will therefore generally tend to be reduced. Additionally, ER fluids with an advantageous dynamic behaviour but a disadvantageously high d.c. conductivity may be used without excessive power consumption and consequent risk of overheating and breakdown.

Such fluids may also be driven to higher yield or shear stress values by applying higher potential gradients, without the risk of such potential gradients causing fluid breakdown.

The insulation on the electrode(s), by reducing the risk of fluid breakdown, will render the apparatus safer in practical use.

Conventional ER apparatus entails the application of a high potential across an ER fluid usually contained in a metal housing, which for safety must be earthed and insulated. Where both of the present electrodes are insulated, this is unnecessary and the apparatus is considerably safer than the conventional apparatus.

Convenient and cheap liquid vehicles for ER fluids include organohalogens, such as chlorinated aliphatics.

Where both electrodes are insulated in this embodiment of the present apparatus the range of convenient and cheap fluid and electrode materials which may be used is conveniently extended, eg to cover such vehicles.

In conventional ER apparatus, where such a fluid is in contact with the (generally metal) electrodes, there may be a risk of longer term corrosion of the electrode, unless it is made of a (generally more expensive) corrosion resistant metal, such as a stainless steel.

There is thus also a risk of consequent contamination by metal ions and/or particles and degradation of the fluid.

The above extension of the range of suitable electrode and fluid materials is brought about because most of the insulator coatings in this embodiment of the present apparatus (described further below) which sheath the electrodes tend to be inert to such fluids.

Turning to the features of this embodiment of the present invention, it will be appreciated that the coated electrode may be a single coated electrode in the present apparatus. It may also be one of a plurality of coated electrodes in a multielectrode apparatus.

The or each coated electrode will typically be of metal, such as described hereinbefore.

The present insulating coating may be any that fulfils the criteria given hereinbefore.

Such materials will generally be present as a coating on a metal electrode, for example to a thickness in the range of 1 to 5000 micron, such as 50 to 4000 micron. The thickness will however depend greatly on the resistivity, dielectric constant and other physical properties of the insulator material.

The insulator will often have a resistivity in the range of $10^{10}$ to $10^{15}$, eg $10^{10}$ to $10^{13}$ ohm $m^{-1}$, and a dielectric constant in the range of 2 to 8. Within these ranges, it is often favoured that the relevant constant

be as high as possible.

The insulator may for example comprise an organic plastics polymer or an inorganic material such as ceramic, a glass or a glass-ceramic.

Preferably, the insulator will have a softening or decomposition temperature at least 50 ° C, preferably at least 100 ° C, above the operational temperature of the present apparatus, although this may vary considerably with the specific application.

When a polymer, the insulator may be any type of homo- or co-polymer on polycondensate, including random, block and graft co-polymers. The polymers may be cross-linked or not. The polymer will seldom be a pure compound, but will often consist of a molecular weight cut of a mixture of congeners.

The polymer may suitably be a polyester, such as poly(ethylene terephthalate); or a polyolefin, such as polyethylene or polypropylene. The polymer may also suitably be a polyfluoroolefin, such as polytetrafluoroethylene; a polyvinylic, such as pclyvinylchloride; or polyacetal.

The polymer may further suitably be a copolymer of any of the foregoing, such as a cross-linked ethylene - vinyl acetate (EVA) or ethylene - propylene - diene monomer (EPDM) rubber.

One suitable class of polymers which fulfils the above criterion for preferred polymers includes homo- and co-polymers of dienes, such as butadiene, isoprene, 1,5-cyclooctadiene, optionally with acrylics, including acrylonitrile. A particularly suitable class of diene copolymers are those with styrene, such as the Cariflex series (Shell).

Other suitable classes of polymers are believed to include polyaromatics such as polyphenylene, polyamides and polyimides. Especially suitable polyaromatic polymers are believed to be those polyaromatics with a high aromatic content, and other high-temperature polymers, such as PES, PEK and PEEK from ICI.

A yet further suitable class is believed to include resins, such as thermosetting epoxy resins (eg the reaction product of epichlorhydrin and bisphenol A, together with curing agents) and acrylics resins.

Mixtures of all the foregoing materials may be used (insofar as they are mutually compatible).

Preferred polymers include polyesters, such as poly(ethylene terephthalate); polyolefins, such as polyethylene or polypropylene; polyfluoroolefins, such as polytetrafluoroethylene; and polyvinylics, such as polyvinylchloride.

The insulator may also be a ceramic, glass or glass-ceramic.

Where the insulator coating is a ceramic it may be one selected from the group consisting of beryllia, aluminia, titania, zirconia, silica, aluminium nitride, silicon carbide and silicon nitride.

It may also be one selected from the group consisting of strontium nitride, barium titanate and barium zircotitanate.

Suitable glasses for the insulator coating include respectively medium and high-softening or melting barium and lead borosilicate and aluminosilicate and other barium glasses and medium and high-softening or melting glass containing dissolved metal oxides (eg melting or softening in the range of 500 to 900 ° C).

The insulator may also be a low softening or melting glass, such as a soda glass.

Suitable glass-ceramics include medium-softening or melting lead borosilicate and aluminosilicate silicate glasses containing dispersed particulate ceramics.

Suitable such ceramics include metal oxides, such as beryllia, alumina and zirconia.

Suitable such ceramics also include silica, aluminium nitride, silicon carbide, silicon nitride, strontium nitride, barium titanate and barium zircotitanate.

Mixtures of all the foregoing materials may be used.

For ease of application (see below) glass or glass ceramic insulators derived from devitrifying glasses and glass ceramics respectively may be favoured.

It is of course preferred and advantageous that the coating is cohesive and non-porous, and has no pinprick defects, which could lead to electrical breakdown of the coating.

Preferred coating materials will be those which also have better abrasion resistance and other relevant strength properties than other equivalent insulators.

For these reasons, preferred insulator polymer compositions tend to be crosslinked and to contain conventional strengthening, such as a filler.

The best materials to ensure this will be known to the skilled man, or may readily and routinely determined by him without undue experimentation.

The ex situ formation of a solid insulator coating and its application to the electrode, eg with a suitable adhesive, is often preferred.

It may be the only practicable means of applying a cohesive insulator coating eg where it is of refractory ceramic, or the most convenient means where it is a polymer composition, eg as an adhesive polymer tape.

Alternatively, a precursor composition for the insulator (often comprising a precursor of the insulator itself together with a vehicle) may be applied to the electrode, and converted to the insulator in situ.

The best method of application for any given insulator material will be known to the skilled man, or may readily and routinely determined by him without undue experimentation.

In all cases, the choice between the insulator or of any precursor will often be made on the basis of suitability to be formulated in a manner known to the skilled man into a composition which is suitable for application to the electrode.

Any precursor composition will generally comprise the insulator as appropriate as a melt, or a solution or particulate dispersion in a fluid vehicle.

For example, a polymer precursor composition may be a typical polymer paint, comprising the polymer in solution, gel and/or dispersion in an organic vehicle.

A glass or glass ceramic precursor composition may be a commercially available firable dielectric composition.

The composition may be applied to the relevant electrode surfaces as appropriate, eg by dipping, painting, curtain or roller application, printing, or by masking and spraying. The precursor may then be converted into the insulator, also in a manner known to the skilled man, eg by allowing an applied melt to solidfy.

In the case of a polymer, the applied fluid precursor (which may contain curing agents) may be dried off and cured. In the case of a glass or glass-ceramic, the coated electrode may be fired to produce the fused coating on the electrode.

Suitable process parameters, including temperatures and heating profiles in such cases, will be apparent to the skilled man. For example, for a dielectric composition, the firing is preferably carried out a towards 900 ° C, optionally first applying a dwell time at about 500 ° C.

In all cases the coating and conversion steps may be repeated as often as is desired.

In an example of this embodiment of the apparatus of the present invention, one of the electrodes may conveniently be in the form of a conventional optionally insulated electrical wire or cable.

Such a wire or cable, if insulated, must of course be rated for the magnitude of operational potentials for the present apparatus mentioned above.

In a convenient, simple and cheap ER valve of the present invention, such an electrode is mounted centrally in a metal tube, which may if desired be insulated similarly on its inner surface.

The tube is used as a second electrode. A high-voltage signal generator is connected across the electrodes.

In use, a conventional ER fluid is pumped through the tube. (The tube may form a passageway in an otherwise conventional damper, and the fluid will then be pumped through the tube by the action of the damper in use).

On application of a variable potential of the type described hereinbefore, the ER fluid lying in the tube between the tube and the wire will solidify, thereby cutting off flow through the tube.

The operational potential gradient applied to the ER fluid in the apparatus of the present invention may conveniently be in the range of 1 to 20, eg 2 to 15 kV $mm^{-1}$.

The varying potential may be applied by any suitable means which is capable of generating the necessary potentials, frequencies and wave-forms.

In general the impedance is relatively high, taking into account the factors mentioned above, so that a large power source is not generally crucial in most practical ER applications which can be envisaged. An industrial high-voltage signal generator will often be suitable.

For use in the apparatus of the present invention, suitable electrorheological fluid compositions are any which fulfil the conductivity criteria given hereinbefore.

Suitable fluids include those comprising a dispersion of a high alumina exchanger aluminosilicate optionally comprising water in an electrically highly resistive fluid vehicle.

The term 'exchanger aluminosilicate' herein means any inorganic material comprising

a) a moiety of empirical formula

$(Al_2O_3)b\ (SiO_2)c$

where b and c are any numerical values provided that the ratio of b/c never exceeds 1, and

b) mono- or divalent main group metal cations, hydrogen ions or optionally substituted ammonium ions.

In some of these materials the ions are exchangeable. The term embraces crystalline inorganic materials for example zeolites, micas and vermiculites. These materials may be natural or synthetic and commercially available, or derivable from such materials e.g. by ion exchange. The term extends to

materials in which the cations are an infinitely variable mixture of two or more such species.

'High alumina' herein means any exchanger aluminosilicate in which the ratio of b:c lies in the range of 1:1 to 1:9.

Crystalline materials are preferred.

Zeolites within the scope of the aluminosilicates which are suitable for use in the apparatus of the present invention include crystalline inorganic materials of which the empirical formula is

$$M_aO(Al_2O_3)_{b'}\ (SiO_2)_{c'}\ (H_2O)_d \qquad (I)$$

where

M is a mono or divalent main group metal cation or hydrogen or ammonium ion,

a is 1 where M is divalent and 2 where M is monovalent, and

b', c'and d' are any numerical values, save that the ratio of b'/c' can never exceed 1:1 and c' is never less than 1,

and thus include natural and commercially available zeolites, and materials derivable therefrom.

Such materials may be derived from commercially available materials by ion exchange of $M_a$ or by removal of water (Zeolites are known ion exchange and hygroscopic minerals).

The definition extends to materials in which $M_aO$ is an infinitely variable mixture of two or more species falling within the definition of $M_aO$.

ER fluids which are suitable for use in the apparatus of the present invention tend to have good ER properties, where such properties include for example a good yield stress to applied voltage ratio, preferably with a low conductivity.

Suitable high alumina exchanger aluminosilicate in the present fluids include those wherein the or one cationic species is ammonium or a Group IA or IIA metal. Examples include lithium, sodium, potassium, magnesium or calcium, and mixtures thereof, and in particular potassium or ammonium, preferably potassium.

In such materials which are suitable for use in the apparatus of the present invention the cations generally form 1 to 50% w/w of the disperse phase.

In one group of exchanger aluminosilicates of interest the ratio of b:c lies in the range of 1:1 to 1:5, in particular 1:1 to 1:3.

Typically any optional water content is pure, but it may also be an aqueous solution of a polar solid, such as an inorganic salt, for example salts of any of the cations listed above with sulphuric, hydrochloric or organic carboxylic or sulphonic acids.

The water is adsorbed, coordinated and/or adsorbed into the aluminosilicate structure. The precise physical state of this 'water' is not always clear.

However, the term 'water' herein extends to all physical states of the water in the present aluminosilicates, as is conventional e.g. for zeolites with a water content.

Any water comprised in the aluminosilicate will generally be 0.05 to 10% w/w of the disperse phase, although it may vary widely up to larger values, e.g. up to 30% w/w. Even above a certain water content (about 10% w/w, all other parameters being fixed), good values of yield stress to applied voltage ratio tend to be retained for corresponding ER fluids.

However, we have found the conductivity of such fluids, and hence the power consumption tend to increase disadvantageously. For example power consumption may increase by more than 50%, and there will typically be an increased tendency to electrical breakdown at lower applied voltages in commercial use.

It is therefore preferred that the total water content of the disperse phase exchanger aluminosilicate is less than 10% w/w, more preferably less than 5% w/w.

In the case of preferred lithium-based materials, it is preferably less than 1% w/w, more preferably less than 0.5% w/w. It will be appreciated that the last named materials are essentially anhydrous.

However each suitable or the optimum water content may vary widely with the particular adsorbate and the specific ER fluid vehicle but may be determined routinely.

Higher water contents may be permissible where the water and/or each relevant disperse phase particle and/or exchange aluminosilicate component of the phase or particle is encapsulated from the rest of the ER fluid.

The particle may be encapsulated e.g. by a hydrophobic fluid, gel or wax which is insoluble in the vehicle of the corresponding ER fluid.

The water content is often exchangeable, and may be adjusted by

a) equilibration of a water-free material with water or with air at a desired non-aqueous water partial vapour pressure or

b) (less often) equilibration as the disperse phase or a component thereof of an ER fluid with the vehicle of the fluid having a controlled water content in mutual admixture with the rest of the vehicle.

Generally however, the water content is adjusted by controlled (at least partial) desiccation under heat and/or reduced pressure, optionally in the presence of a desiccant such as $P_2O_5$.

Particles of 0.1 to 20 micron mean cross-dimension (corresponding to particular particles which are suitable for use in the apparatus of the present invention) are preferred.

This is because of their shorter desiccation equilibration times compared with larger particles.

Particular high alumina exchanger aluminosilicates which are suitable as disperse phase materials for the ER fluids for use in the apparatus of the present invention thus include zeolites such as those derivable from Zeolites A and X (Union Carbide) and Y (Strem).

Such zeolites may be derived for example by controlled reduction of water content and optionally conventional ion exchange of $M_a$.

Thus for example in derivatives of the A series $M_a$ may be inter alia potassium, $K_2$ (from Zeolite 3A), sodium, $Na_2$ (from Zeolite 4A), or calcium, Ca (from Zeolite 5A). Similarly, the $Na_2$ in Zeolite X derivatives may be optionally exchanged with the same cations.

$M_a$ may of course be exchanged with two or more ions to give a 'mixed' zeolite within the scope which are suitable for use in the apparatus of the present invention.

These zeolites have cubic particle morphology.

For reproducible and controllable operational parameters, and good yield stress to applied voltage ratio with low power consumption and a high breakdown voltage in the corresponding ER fluids, favoured exchanger aluminosilicate disperse phases or exchanger aluminosilicate components for the disperse phase of the fluid include those with a low conductivity.

In addition to those with a low water content generally (which is similar to that indicated hereinbefore as desirable), these include in particular those zeolites of formula (I) wherein $M_aO$ is CaO, $(NH_4)_2O$, MgO or $K_2O$, especially Zeolites 5A (calcium) derivatives.

Another group of favoured exchanger aluminosilicates ER fluid disperse phases or exchanger aluminosilicate components of disperse phases include those with a good yield stress to applied voltage ratio at elevated temperatures, for example over 40 °C, such as 50 to 100 °C or 50 to 150 °C.

A good ratio at such elevated temperatures, rather than at ambient temperatures, e.g. below 40 °C, may be advantageous since some typical working environments and/or the fluid itself (owing to heat generated in the fluid in use, eg as a clutch fluid) may often have such elevated temperatures in use.

Such present materials include those zeolites of formula (I) wherein $M_aO$ is $K_2O$, or $Li_2O$ especially Zeolite 3A (potassium) derivatives, having a low to negligible water content similar to that indicated hereinbefore as desirable.

The conductivity of ER fluid disperse phases tends to increase with temperature, leading to higher power consumption and a lower breakdown voltage.

A preferred group of the present materials thus includes those with a good yield stress to applied voltage ratio and a low conductivity at elevated temperatures. Such materials again include those wherein $M_aO$ is $K_2O$, especially Zeolite 3A derivatives.

Another group of favoured exchanger aluminosilicates disperse phases or zeolite components of disperse phases include those with a good yield stress to applied voltage ratio over a wide temperature range, for example 0 to 100 °C or 0 to 150 °C, for use in a wide variety of working environments.

Such materials include

a) those single zeolite materials of formula (I) wherein $M_aO$ is a mixture of two or more species falling within the definition of $M_aO$, and

b) mixtures of two or more single such materials in each of which $M_aO$ is a single species.

In either type of mixture, two species of $M_aO$ will often be used, chosen such that one has a good performance towards the lower end of the desired temperature range and the other towards the upper end.

The choice will however also be dependent at the upper end of the range, however, on the thermal stability of both materials.

The choice of such materials will be determined by the particular application profile required but include single and two species in which $M_aO$ is CaO and $K_2O$, eg a Zeolite A derivative containing both CaO and $K_2O$, or a mixture of derivatives of Zeolites 5A and 3A.

In the case of such materials which contain two $M_aO$ species, the two may each be present as 1 to 99% and 99 to 1% w/w respectively of the total $M_aO$ content, depending on the exact performance against temperature profile desired and the specific ions or materials used.

Where the different $M_aO$ species are present in different zeolite exchanger aluminosilicates in the present ER fluid disperse phases, they may each be present in each particle of the ER fluid disperse phase in mutual admixture and/or as a coating of at least one on at least one other.

As an alternative, the disperse phase may consist of a mixture of sets of particles, the particles in each set being essentially homogenous and of one zeolite exchanger aluminosilicate species.

In all such species, the total water content of the disperse phase is desirably similar to those values indicated as favoured or preferred for the aluminosilicate hereinbefore.

Additionally, however any of the foregoing disperse phases may advantageously consist of at least one exchanger aluminosilicate and another material.

Again, such materials may be in mutual admixture in the same particles and/or as a coating of at least one component on at least one other, that is concentrated at and/or near the core surface.

In both cases, the other material may be any material compatible with the exchanger aluminosilicate(s) and such that the resultant disperse phase is compatible with the properties of the vehicle and desired properties of the corresponding ER fluid.

In the latter regard it may often be desirable that the alumina content and any water content of the total disperse phase are similar to those indicated hereinbefore as suitable, favoured or preferred for the exchanger aluminosilicate itself.

The exchanger aluminosilicate content will generally be much greater than that of other components (eg those named hereinafter) for example 90 to 100% w/w of the disperse phase. Often the exchanger aluminosilicate(s) will be present as 100% of the disperse phase and particles. However, the optimum aluminosilicate (e.g. zeolite) proportion may vary widely from this figure with the specific ER fluid and the specific desired ER effect, but this optimum may be readily ascertained by routine trial.

Higher water contents are also possible, but are however much less preferred as they tend to make the corresponding ER fluid more conducting to a disadvantageous extent.

Among suitable other materials in mutual admixture in each disperse phase particle of the present ER fluids are

a) conductors, eg carbon, which are however much less preferred as they tend to make the ER fluid disadvantageously conductive, and

b) conventional inert coating and core materials such as cellulose derivatives, alumina and silica.

Again, the disperse phase may consist of a mixture of any of the foregoing with other particles.

In such case, the other particles are preferably also capable of imparting ER properties to the fluid. Suitable materials in the other particle species include organic ion-exchange resins.

Such other particle species may of course also comprise water or a different polar adsorbate; any such adsorbate is often water. A total water content in the disperse phase which is similar to that indicated herein as preferred for the exchanger aluminosilicate itself is preferred.

Where the particles of a disperse phase comprise a labile water content, it is desirable that the water content of the disperse phase is essentially homogeneous for operational stability of the corresponding ER fluid.

The disperse phase may of course consist essentially of any of the foregoing other materials which also capable of imparting ER properties to the fluid. Suitable materials include organic ion-exchange resins, eg the Amberlite series (Rohm & Haas), such as Amberlite IRP 88 (potassium ion resin) and derivatives of Amberlite 64 by ion exchange, the Dowex series (Dow Chemical) and the Duolite series (Diamond Shamrock).

Such other particle species may of course also comprise water or a different polar adsorbate; any such adsorbate is often water. A total water content in the disperse phase which is similar to that indicated herein as preferred for an exchanger aluminosilicate disperse phase is preferred.

The proportion of disperse phase in the ER composition is determined by the particular application of the composition, and the particular disperse phase and vehicle used, since these will determine the desired or acceptable viscosity. The desired proportion may thus be determined routinely.

In general a weight fraction of the total composition of 15 to 65% will be suitable for most applications, and, depending on the vehicle, 25 to 60% by weight will be pumpable in use.

In general the appropriate weight fraction of the total composition for an inorganic disperse phase will be higher than that for an organic disperse phase. 35 to 65% by weight will be suitable for most inorganic disperse phase applications, and, depending on the vehicle, 15 to 40% by weight for organic disperse phases.

For some applications higher or lower viscosities and hence higher or lower fractions respectively may be tolerable or necessary.

Higher fractions may be used if the disperse phase is surface treated, or the vehicle has a fairly low

viscosity, or if high temperature operation is envisaged.

Higher fractions may, however, only be used provided that the (solids content-related) no-field viscosity of the fluid is not thereby increased to a disadvantageous or impractical extent.

A lower weight fraction, eg of 15 to 25%, may be suitable where high yield stresses at relatively low voltage gradients and/or current densities can be achieved (as with preferred fluids for use in the apparatus of the present invention, eg those wherein the disperse phase has a low polar fluid content).

The disperse phase particles of the compositions which are suitable for use in the apparatus of the present invention may suitably have a mean cross-dimension of 0.1 to 50 microns, in particular 0.1 to 20 microns.

This is dependent at the upper end of the size range, however, on the minimum field gap in which the composition is to be used, which should be at least 10 times the largest particle cross-dimension.

Particle cross-dimensions below 0.1 micron are best avoided, both because of the effect on the physical properties of the corresponding ER fluids and because of the generally higher potential toxicity of the dry disperse phase compared with that of larger particles.

For reproducible and controllable operational parameters of the corresponding ER fluids which are suitable for use in the apparatus of the present invention, a narrow size distribution is advantageous.

Favoured vehicles or components therefor include halogenated higher aliphatics such as chlorinated $C_{10-30}$ paraffins. These typically will be hydrocarbon cuts such as $C_{10-13}$, $C_{14-17}$, $C_{18-23}$ and $C_{24-30}$.

Typically these will have a chlorine content of 25 to 60% w/w, for example 29 to 33% and 49 to 53%. Examples include the Cereclor series (registered trade mark, ICI).

Similar materials include halogenated vinylic polymers, eg poly(trifluorovinylchloride) (eg Fluorolube FS-5; Hooker) and perfluoro polyethers such as Fomblin (Montedison).

Optionally halogenated lower aliphatic derivatives such as cyclohexane, carbon tetrachloride and chloroform are also suitable as vehicle components.

Silicones, especially polydialkylsiloxanes, polydiaralkylsiloxanes and substituted aromatic silicones such as bis(chlorinated phenyl) silicones are preferred as vehicles or vehicle components.

The dispersion may also be optimised by using a surface-treated e.g. surfactant-treated disperse phase, and including a gellant in the vehicle.

The gellant and its proportion in the ER fluid is choosen such that the ER fluid composition has a rest viscosity which works against settling out of the disperse phase yet has a sufficiently low dynamic viscosity for an ER fluid.

The composition may also comprise a fluidiser such as sorbitan mono- or sesqui-oleate, although it is preferred to adjust the ER fluid viscosity as hereinbefore described.

The present invention also provides the use of any of the foregoing compositions as an ER fluid in an applied electric field in the apparatus of the present invention. Typical apparatus of the present invention includes hydraulic ER clutches and dampers.

The preparation and use of such compositions as ER fluids is conventional.

The exchanger aluminosilicates for the ER fluid compositions which are suitable for use in the apparatus of the present invention may be prepared as in the following Description 1.

The ER fluid compositions themselves may be prepared as in the following Description 2.

In general in the Descriptions the aluminosilicates are prepared by equilibrating a water-containing aluminosilicate at ambient relative humidity, temperature and pressure.

This is optionally followed by partial or total dessication of the foregoing equilibrated product. If necessary the starting auminosilicate may be prepared from a commercially available ion-exchange aluminosilicate by conventional ion exchange followed by washing.

Description 1

Preparation of disperse phases for ER fluids of the present invention is described in the following Table I. The following Zeolites are denoted by the Union Carbide reference numbers.

TABLE I

| For Composition | Zeolite/ Resin | Treatment |
|---|---|---|
| 1, 1a | 5A(Calcium) | 150°C for 4 hr, then vacuum cool, treated with stream of damp nitrogen gas |
| 2 | 5A(Calcium) | 175°C for 7 hr in vacuo, cooled in dessicator |
| 3 | 5A(Calcium) | 25°C for 48 hr in ambient air |
| 4, 5, 6 | Amberlite IRP 88 | bead-milled to <20 micron particle size |

Description 2

The following compositions were prepared by conventional dispersion of the disperse phase in the vehicle.

Additionally, compositions 3a and 3b were derived from 3 respectively by heating at 120° C and 140° C in 5 mbar vacuum for 40 hr.

TABLE II

| Composition | Percent w/w | |
|---|---|---|
| | Disperse Phase | Vehicle<br>a = Silicone Oil C111/50<br>b = Silicone Oil C111/30 |
| 1 | 47.5 | a 52.5 |
| 1a | 54 | a 46 |
| 2 | 60 | a 40 |
| 3 | 50.8 | b 49.2 |
| 4 | 33 | a 60 |
| 5 | 27 | a 63 |
| 6 | 30 | a 70 |

Example 1

The performance of an ER apparatus of the present invention was dynamically tested.

The apparatus was in the form of an ER clutch, comprising a pair of coaxially mounted cylindrical electrode clutch members, the outer stationary, the inner rotated. The inner member was a solid copper cylinder optionally covered with an insulating coating, and housed within the outer member, which was a hollow steel cylinder axially coterminous with the inner.

With an ER fluid between the two electrodes, the inner member was rotated with a variable speed motor with feedback control through a torque transducer.

The following results were obtained with

a) apparatus of the following dimensions, with the following optional insulators on one or both electrodes, and

b) at the following field potential gradient, frequencies and shear rate across the electrodes:

TABLE III

ER Fluid: 1

Disperse Phase Particle Size, micron: 1 - 5

Apparatus Dimensions:

Inner Electrode,

Radius, mm: 25.3

Circumferential Area, $mm^2$: 8130

Radial Interelectrode Gap, mm: 0.5

Insulator: none

Run Temp 30°C Mean Field 4.0 kV $mm^{-1}$ rms

Frequency, Hz 50 Waveform: sinusoidal

| Shear Rate, $s^{-1}$ | Shear Stress, kPa |
|---|---|
| 53.2 | 2.271 |
| 106.4 | 2.213 |
| 212.8 | 2.179 |
| 425.6 | 2.276 |

At the same d.c. applied potential the shear stress in the above apparatus fell with increasing shear rate from 0.600 to 0.339 KPa.

TABLE IV

| | | | |
|---|---|---|---|
| ER Fluid | | | 2 |
| Disperse Phase Particle Size, micron: | | | 1 - 5 |
| Apparatus Dimensions: | | | |
| Inner Electrode, | | | |
| Radius, mm: | | | |
| Circumferential Area, $mm^2$: | | | 8130 |
| Radial Interelectrode Gap, mm: | | | 0.5 |
| Insulator: | | | none |
| Run Temp, °C | 30 | Mean Field kV $mm^{-1}$ rms: | 2.0 |
| Frequency, Hz | 50 | Waveform: | sinusoidal |

| Shear Rate, $s^{-1}$ | Shear Stress, kPa |
|---|---|
| 53.2 | 1.463 |
| 106.4 | 1.642 |
| 212.8 | 1.797 |
| 425.6 | 2.325 |

TABLE V

| | |
|---|---|
| ER Fluid | 1a |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: | 25.3 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: | 0.5 |
| Insulator: | none |
| Shear Rate, $s^{-1}$ | 425.6 |
| Mean Field kV $mm^{-1}$ rms: | 2.0 |
| Frequency, Hz | 50 |
| Waveform: | sinusoidal |

TABLE V (CONTD)

| Run Temp, °C | Shear Stress, kPa | Doubling Temp, °C |
|---|---|---|
| 30 | 3.457 | |
| 60 | 2.271 | 46 |

With a comparable d.c. applied potential, the doubling temperature was 9°C.

TABLE VI

ER Fluid: 3

Disperse Phase Particle Size, micron: 1 - 5

Apparatus Dimensions:

Inner Electrode,

Radius, mm: (uninsulated) 24.8

Circumferential Area, $mm^2$: 8130

Radial Interelectrode Gap, mm: (insulated) 0.5

Insulator: heat-shrink fluorinated ethylene/ propylene polymer (FHS 45, Adtech Ltd) on inner electrode only

Run Temp, °C 30

Mean Field kV $mm^{-1}$ rms: 7.4

Waveform: sinusoidal

Shear Rate, $s^{-1}$ 106.4

| Frequency, Hz | Shear Stress, kPa | |
|---|---|---|
| 160 | 0.484 | (The d.c. conduct- |
| 120 | 0.489 | ivity of this fluid |
| 80 | 0.489 | at 3 kV/mm is |
| 50 | 0.479 | 0.027 $mA/cm^2$.) |
| 30 | 0.460 | |
| 20 | 0.431 | |
| 14 | 0.392 | |
| 10 | 0.354 | |

TABLE VII

| | |
|---|---|
| ER Fluid | 3a |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: (uninsulated) | 24.8 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: (insulated) | 0.5 |
| Insulator: | heat-shrink fluorinated ethylene/ propylene polymer (FHS 45, Adtech Ltd) on inner electrode only |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 7.4 |
| Waveform: | sinusoidal |
| Shear Rate, $s^{-1}$ | 106.4 |

| Frequency, Hz | Shear Stress, kPa |
|---|---|
| 200 | 0.503 |
| 160 | 0.595 |
| 120 | 0.532 |
| 80 | 0.513 |

(The d.c. conductivity of this fluid at 3 kV/mm is 0.005 $mA/cm^2$.)

TABLE VIII

| | |
|---|---|
| ER Fluid | 3b |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: (uninsulated) | 24.8 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: (insulated) | 0.5 |
| Insulator: | heat-shrink fluorinated ethylene/propylene polymer (FHS 45, Adtech Ltd) on inner electrode only |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 7.4 |
| Waveform: | sinusoidal |
| Shear Rate, $s^{-1}$ | 106.4 |

| Frequency, Hz | Shear Stress, kPa |
|---|---|
| 200 | 0.741 |
| 160 | 0.736 |
| 120 | 0.818 |
| 80 | 0.823 |
| 50 | 0.794 |
| 30 | 0.775 |
| 20 | 0.726 |
| 14 | 0.697 |

(The d.c. conductivity of this fluid at 3 kV/mm is 0.001 $mA/cm^2$.)

TABLE IX

| | |
|---|---|
| ER Fluid | 3 |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: | 25.3 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: | 0.5 |
| Insulator: | none |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 3.0 |
| Waveform: | sinusoidal |
| Shear Rate, $s^{-1}$ | 106.4 |

| Frequency, Hz | Shear Stress, kPa |
|---|---|
| 200 | 2.058 |
| 160 | 2.111 |
| 120 | 2.193 |
| 80 | 2.252 |
| 50 | 2.281 |
| 30 | 2.203 |
| 20 | 2.169 |
| 14 | 1.864 |

(The d.c. conductivity of this fluid at 3 kV/mm is 0.027 $mA/cm^2$.)

TABLE X

| | |
|---|---|
| ER Fluid | 3a |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: | 25.3 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: | 0.5 |
| Insulator: | none |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 3.0 |
| Waveform: | sinusoidal |
| Shear Rate, $s^{-1}$ | 106.4 |

| Frequency, Hz | Shear Stress, kPa |
|---|---|
| 200 | 1.356 |
| 160 | 1.457 |
| 120 | 1.636 |
| 80 | 1.733 |
| 50 | 1.937 |
| 30 | 1.985 |
| 18 | 2.010 |
| 14 | 1.695 |

(The d.c. conductivity of this fluid at 3 kV/mm is 0.003 mA/$cm^2$.)

TABLE XI

| | |
|---|---|
| ER Fluid | 3b |
| Disperse Phase Particle Size, micron: | 1 - 5 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: | 25.3 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: | 0.5 |
| Insulator: | none |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 3.0 |
| Waveform: | sinusoidal |
| Shear Rate, $s^{-1}$ | 106.4 |

| Frequency, Hz | Shear Stress, kPa |
|---|---|
| 200 | 0.484 |
| 160 | 0.566 |
| 120 | 0.716 |
| 80 | 0.920 |
| 50 | 1.138 |
| 25 | 1.380 |
| 20 | 1.293 |
| 14 | 1.191 |

(The d.c. conductivity of this fluid at 3 kV/mm is 0.001 $mA/cm^2$.)

TABLE XII

| | |
|---|---|
| ER Fluid | 4 |
| Disperse Phase Particle Size, micron: | <20 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: | 24.72 |
| Circumferential Area, $mm^2$: | 8130 |
| Radial Interelectrode Gap, mm: | 1.08 |
| Insulator: | none |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 2.8 |
| Waveform: | sinusoidal |

| Shear Rate, $s^{-1}$ | Frequency, Hz | Shear Stress, kPa |
|---|---|---|
| 48.2 | 200 | 0.343 |
| | 160 | 0.382 |
| | 120 | 0.423 |
| | 80 | 0.473 |
| | 40 | 0.544 |
| | 20 | 0.554 |
| 96.4 | 200 | 0.353 |
| | 160 | 0.382 |
| | 120 | 0.413 |
| | 80 | 0.453 |
| | 40 | 0.513 |
| | 20 | 0.534 |
| 192.8 | 200 | 0.423 |
| | 160 | 0.443 |
| | 120 | 0.464 |
| | 80 | 0.483 |
| | 40 | 0.513 |
| | 20 | 0.534 |

TABLE XIII

ER Fluid 4

Disperse Phase Particle Size, micron: <20

Apparatus Dimensions:

Inner Electrode,

Radius, mm: (uninsulated) 24.84

Circumferential Area, $mm^2$: 4000

Radial Interelectrode Gap, mm: (insulated) 0.96

Insulator: self-adhesive PVC tape 0.12 mm thick on inner electrode only

Run Temp, °C 30

Mean Field kV $mm^{-1}$ rms: 2.8

Waveform: sinusoidal

| Shear Rate, $s^{-1}$ | Frequency, Hz | Shear Stress, kPa |
|---|---|---|
| 48.2 | 160 | 0.302 |
| | 120 | 0.322 |
| | 80 | 0.342 |
| | 40 | 0.362 |
| | 20 | 0.312 |
| | 2 | 0.091 |
| 96.4 | 160 | 0.322 |
| | 120 | 0.342 |
| | 80 | 0.362 |
| | 40 | 0.362 |
| | 20 | 0.302 |
| | 2 | 0.091 |
| 192.8 | 160 | 0.372 |
| | 120 | 0.393 |
| | 80 | 0.393 |
| | 40 | 0.403 |
| | 20 | 0.363 |
| | 2 | 0.121 |

TABLE XIV

ER Fluid 5

Disperse Phase Particle Size, micron: <20

Apparatus Dimensions:

Inner Electrode,

Radius, mm: (uninsulated) 23.8

Circumferential Area, $mm^2$: 7552

Radial Interelectrode Gap, mm: (insulated) 2

Insulator: self-adhesive tape (3M Scotch (R) brand tape, ref. 375-G, USA code series 18-9221 on inner electrode only

Run Temp, °C 30

Mean Field kV $mm^{-1}$ rms: 2.0

Waveform: sinusoidal

| Shear Rate, $s^{-1}$ | Frequency, Hz | Shear Stress, kPa |
|---|---|---|
| 25 | 80 | 0.406 |
| | 40 | 0.434 |
| | 20 | 0.451 |
| | 8 | 0.440 |
| | 2 | 0.384 |
| 50 | 80 | 0.445 |
| | 40 | 0.461 |
| | 20 | 0.479 |
| | 8 | 0.472 |
| | 2 | 0.417 |
| 100 | 80 | 0.523 |
| | 40 | 0.540 |
| | 20 | 0.540 |
| | 8 | 0.540 |
| | 2 | 0.473 |

TABLE XV

| | |
|---|---|
| ER Fluid | 5 |
| Disperse Phase Particle Size, micron: | <20 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: (uninsulated) | 23.8 |
| Circumferential Area, $mm^2$: | 7552 |
| Radial Interelectrode Gap, mm: (insulated) | 2 |
| Insulator: | self-adhesive tape (3M Scotch (R) brand tape, ref. 375-G, USA code series 18-9221 on inner electrode only |
| Run Temp, °C | 60 |
| Mean Field kV $mm^{-1}$ rms: | 2.0 |
| Waveform: | sinusoidal |

| Shear Rate, $s^{-1}$ | Frequency, Hz | Shear Stress, kPa |
|---|---|---|
| 25 | 80 | 0.440 |
| | 40 | 0.462 |
| | 20 | 0.451 |
| | 8 | 0.406 |
| | 2 | 0.273 |
| 50 | 80 | 0.445 |
| | 40 | 0.484 |
| | 20 | 0.467 |
| | 8 | 0.417 |
| | 2 | 0.289 |
| 100 | 80 | 0.472 |
| | 40 | 0.506 |
| | 20 | 0.490 |
| | 8 | 0.434 |
| | 2 | 0.312 |

TABLE XVI

| | |
|---|---|
| ER Fluid | 5 |
| Disperse Phase Particle Size, micron: | <20 |
| Apparatus Dimensions: | |
| Inner Electrode, | |
| Radius, mm: (uninsulated) | 23.8 |
| Circumferential Area, $mm^2$: | 7552 |
| Radial Interelectrode Gap, mm: (insulated) | 2 |
| Insulator: | self-adhesive tape (3M Scotch (R) brand tape, ref. 375-G, USA code series 18-9221 on both electrodes |
| Run Temp, °C | 30 |
| Mean Field kV $mm^{-1}$ rms: | 2.0 |
| Waveform: | sinusoidal |

| Shear Rate, $s^{-1}$ | Frequency, Hz | Shear Stress, kPa |
|---|---|---|
| 25 | 80 | 0.412 |
| | 40 | 0.428 |
| | 20 | 0.434 |
| | 8 | 0.412 |
| | 2 | 0.362 |
| 50 | 80 | 0.417 |
| | 40 | 0.434 |
| | 20 | 0.440 |
| | 8 | 0.417 |
| | 2 | 0.362 |

## Claims

1. An ER apparatus comprising means containing an ER fluid, two electrodes in contact with the fluid, and means for applying an electrical potential between the electrodes, characterised in that the means for applying an electrical potential is capable of applying a cyclically variable potential, and the fluid has a d.c. conductivity at 25° C below $5 \times 10^{-8} ohm^{-1}.cm^{-1}$.

2. An ER apparatus according to claim 1 characterised in that the conductivity of the ER fluid is less than $5 \times 10^{-9}$ $ohm^{-1}.cm^{-1}$ at 25° C.

3. An ER apparatus according to claim 1 characterised in that the operational potential gradient between the electrodes is 2 to 15 kV $mm^{-1}$.

4. An ER apparatus according to claim 1 characterized in that the applied potential is an a.c. potential.

5. An ER apparatus according to claim 4 characterized in that the potential wave-form is sinusoidal.

6. An ER apparatus according to claim 1 characterised in that the frequency of the applied potential is in the range of 5 to 250 Hz.

7. An ER apparatus according to claim 1 characterised in that the ER effect shows a frequency related maximum.

8. An ER apparatus according to claim 1 characterized in that least one of the electrodes is insulated.

9. An ER apparatus according to claim 1 characterized in that the fluid is used in dynamic shear.

10. An ER apparatus according to claim 1 characterized in that the ER fluid comprises a dispersion of an aluminosilicate in an electrically highly resistive fluid vehicle, which aluminosilicate is a crystalline zeolite of which the empirical formula is

$$M_aO(Al_2O_3)_{b'}\ (SiO_2)_{c'}\ (H_2O)_d \qquad (I)$$

where
M is lithium, sodium, potassium, magnesium or calcium,
a is 1 where M is divalent and 2 where M is monovalent, and
b', c'and d' are any numerical values, save that the ratio of b'/c' is in the range 1:1 to 1:3, and c' is never less than 1,
or a materials in which $M_aO$ is an infinitely variable mixture of two or more species falling within the definition of $M_aO$.

European Patent Office

# EUROPEAN SEARCH REPORT

Application Number

EP 90 31 3585

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int. Cl.5) |
|---|---|---|---|
| X | EP-A-0 100 201 (NATIONAL RESEARCH DEVELOPMENT CORP.)<br>* Claims 1-4,18,19 * | 1-7,9 | C 10 M 171/00 |
| X | US-A-3 105 379 (L.E. ELLISON)<br>* Claims 1-6; column 2, line 13 - column 3, line 54 * | 1-9 | |
| X | US-A-3 990 93 (WARNER ELECTRIC BRAKE & CLUTCH CO.)<br>* Page 1, line 66 - page 2, line 23; page 3, line 70 - page 4, line 104 * | 1-4,8 | |
| X | EP-A-0 191 585 (NATIONAL RESEARCH DEVELOPMENT CORP.)<br>* Page 2, lines 1-29; page 5, line 29 - page 6, line 3; figure 1; page 6, line 18 - page 7, line 10 * | 1,2 | |
| X | US-A-3 047 507 (W.M. WINSLOW)<br>* column 6, lines 24-44 * | 1,2 | |
| X | EP-A-0 313 351 (THE BOARD OF REGENTS ACTING FOR AND BEHALF OF THE UNVERSITY OF MICHIGAN)<br>* Claims 1-6; page 8, lines 1-13 * | 1-10 | TECHNICAL FIELDS SEARCHED (Int. Cl.5)<br>C 10 M |
| X | EP-A-0 219 751 (BAYER)<br>* Claim 1; page 13, line 22 - page 14; page 19, table 2; page 1, lines 28-33 * | 1,3,4,6,9, 10 | |
| X | JOURNAL OF ELECTOSTATICS, vol. 17, no. 2, July 1985, pages 181-191, Amsterdam, NL; N.G. STEVENS et al.: "The influence of pulsed D.C. input signals on electrorheological fluids"<br>* Whole article * | 1-3,6,7,9 | |

-/-

The present search report has been drawn up for all claims

| Place of search | Date of completion of search | Examiner |
|---|---|---|
| The Hague | 30 May 91 | ROTSAERT L.D.C. |

CATEGORY OF CITED DOCUMENTS

X: particularly relevant if taken alone
Y: particularly relevant if combined with another document of the same catagory
A: technological background
O: non-written disclosure
P: intermediate document
T: theory or principle underlying the invention

E: earlier patent document, but published on, or after the filing date
D: document cited in the application
L: document cited for other reasons

&: member of the same patent family, corresponding document

European Patent Office

# EUROPEAN SEARCH REPORT

Application Number

**EP 90 31 3585**

## DOCUMENTS CONSIDERED TO BE RELEVANT

| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int. Cl.5) |
|---|---|---|---|
| P,X | EP-A-0 350 167 (CASTROL LTD)<br>* Claims 1-15; page 3, lines 8-13 * | 1-10 | |
| P,X | EP-A-0 395 453 (TONEN CORP.)<br>* Claims 1-8; page 3, lines 2-4; page 7, lines 11-24 * | 1,8 | |
| P,X | EP-A-0 381 198 (TOKAI RUBBER IND.)<br>* Claims 1,6,7-10 * | 1,8 | |
| | | | TECHNICAL FIELDS SEARCHED (Int. Cl.5) |

The present search report has been drawn up for all claims

| Place of search | Date of completion of search | Examiner |
|---|---|---|
| The Hague | 30 May 91 | ROTSAERT L.D.C. |

CATEGORY OF CITED DOCUMENTS

- X: particularly relevant if taken alone
- Y: particularly relevant if combined with another document of the same catagory
- A: technological background
- O: non-written disclosure
- P: intermediate document
- T: theory or principle underlying the invention
- E: earlier patent document, but published on, or after the filing date
- D: document cited in the application
- L: document cited for other reasons

&: member of the same patent family, corresponding document