Sept. 6, 1966 R. M. HAINES ET AL 3,270,672

PUMP APPARATUS

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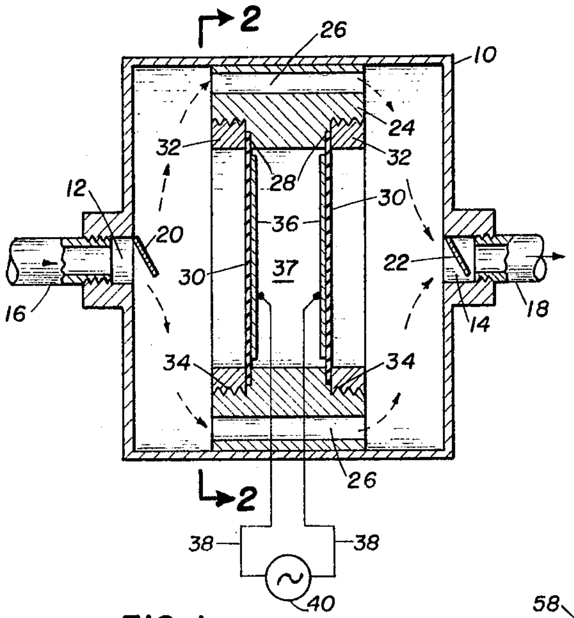

FIG. 1

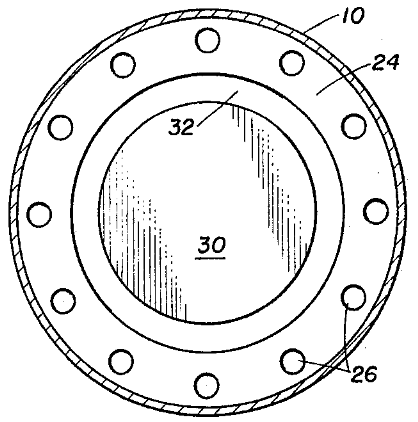

FIG. 2

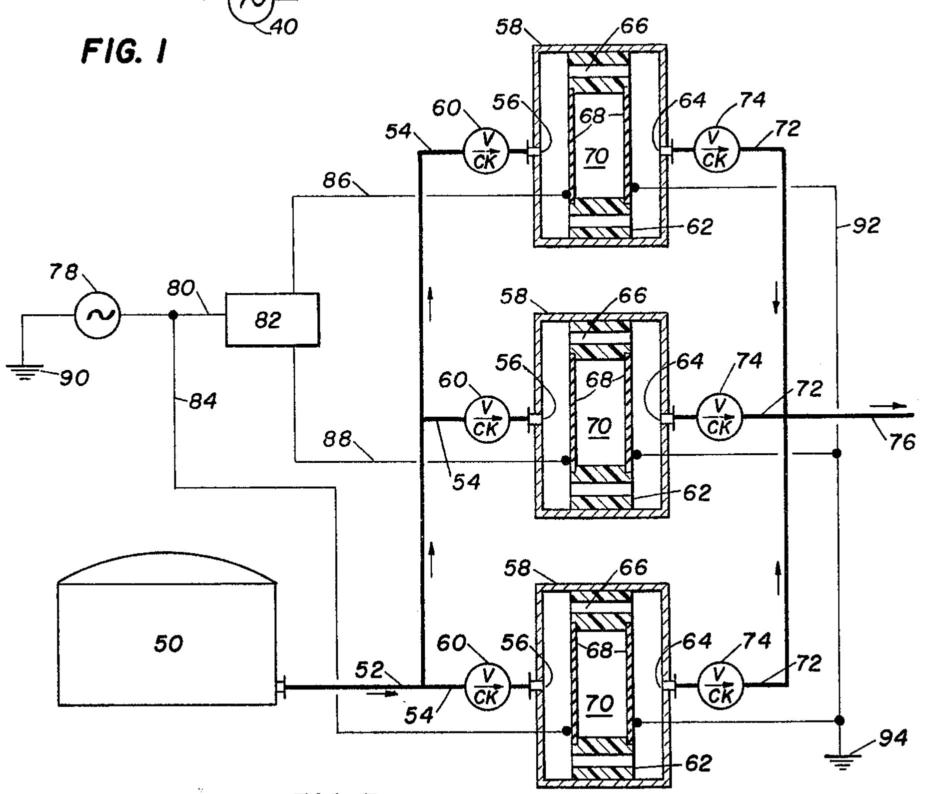

FIG. 3

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PUMP APPARATUS

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This invention relates to a fluid pump and, more particularly, to a fluid pump utilizing an electrostrictive transducer. Electro-viscous fluids are especially useful as the electrostrictive transducers in the pumps of this invention.

Certain fluids, which have been designated electro-viscous fluids and are sold under the trademark of Electro Fluid, respond to the influence of an electric potential by evidencing an apparent and pronounced increase in bulk viscosity. This phenomenon is reversible and the compositions revert to their initial viscosity when the electric field is removed. Such fluids are described in U.S. Patents 2,661,825, 2,886,151, and 3,047,507. Electro-viscous fluids are commonly used in clutches, wherein the fluid is disposed between the surfaces of two electrically conductive members, and an electric potential is imposed across the two members. The electro-viscous fluid responds to the application of an electric potential by instantaneously, but reversibly, changing in apparent bulk viscosity. In strong fields, the fluid thickens into a solid or semi-solid condition whereby torque can be transmitted between the surfaces of the clutch members. Certain electro-viscous fluids exhibit a similar change in bulk viscosity when exposed to an alternating electric field, even though the fluid is not in contact with the potential-carrying electrodes. This phenomenon is used in chucking devices to secure objects with a film of an electro-viscous fluid.

Electro-viscous fluids have also been found to be electrostrictive, that is, they respond to the influence of an electric potential by exhibiting an increase in volume. Application Serial Number 336,098, filed Dec. 26, 1963, is directed to transducers which utilize the electrostrictive properties of an electro-viscous fluid for converting electrical energy to mechanical energy. The transducers of said copending application consist of two spaced members having opposing electrically conductive surfaces, with at least one of the members being a flexible diaphragm. Confined between the two members is an electro-viscous fluid which is responsive to a transient electric potential, viz., a potential of changing magnitude. The quantity of the electro-viscous fluid confined between the two spaced members is such as to completely fill the space between the two members, and preferably is sufficient to put the flexible diaphragm (or diaphragms) under a slight degree of tension in the absence of an electric field. As the electro-viscous fluid is subjected to a transient electric field applied between the two electrically conductive surfaces, the electro-viscous fluid continuously changes in volume in response to the changing electric field to impart a vibratory motion to the flexible diaphragm (or diaphragms).

This invention is based on a pump utilizing an electrostrictive transducer, under the influence of a transient electric fluid. The transducer is preferably (but not limited to) the electro-viscous fluid transducer of said copending application. Briefly, the pump of this invention comprises a pump chamber having inlet and outlet openings in fluid communication with each other and the customary check valves at the inlet and outlet openings. The pumping action is obtained by utilizing in the pump housing at least one flexible diaphragm which is pulsated in the manner that the diaphragms of the transducers of the copending application are pulsated. Two or more such pumps can be used together such that the fluid is pumped in parallel. When two or more pumps are used together, the electric input to each of the pumps is preferably out of phase with the other pumps to provide overlapping pump cycles and a more constant pump outlet pressure with less pulsation of the flexible diaphragms in each of the pumps.

It is therefore an object of this invention to provide a pump utilizing an electrostrictive transducer. Another object of this invention is to provide a pump utilizing an electrostrictive liquid. Another object of this invention is to provide a pump utilizing the electrostrictive property of electro-viscous fluids. Still another object of this invention is to provide a pump and method of pumping wherein the pumping action is obtained from a flexible diaphragm pulsated either by an electro-viscous fluid or by another electrostrictive transducer under the influence of a transient electric field. These and further objects of this invention will become apparent or be described as the description thereof herein proceeds and reference is made to the accompanying drawings in which:

FIGURE 1 is an elevational view, partly in section and partly schematic, of a pump fabricated in accordance with this invention,

FIGURE 2 is a sectional view in the plane 2—2 of FIGURE 1, and

FIGURE 3 is a diagrammatic view, partly in section and partly schematic, of a system using a plurality of parallel-connected pumps.

Referring to FIGURES 1 and 2, the reference numeral **10** designates the pump housing having inlet opening **12** and outlet opening **14**. Openings **12** and **14** are preferably internally threaded to secure inlet conduit **16** and outlet conduit **18**, respectively, thereto. Inlet conduit **16** is connected to a source of the fluid to be pumped and outlet conduit **18** is connected to the destination of the fluid being pumped. Housing **10** is provided with check valves **20** and **22** to permit the flow of fluid through the pump housing **10** in one direction only, i.e., check valve **20** is provided at inlet opening **12** to permit only the entry of fluid from inlet conduit **16** into housing **10**, while check valve **22** is provided at outlet opening **14** to permit only the exodus of fluid from housing **10** into outlet conduit **18**.

Disposed within housing **10** is annular member **24**, which divides the interior of housing **10** into two sections communicating with each other through apertures **26**. Annular member **24**, which is disposed so that inlet opening **12** and outlet opening **14** are located in different sections, is formed with internal shoulders **28** against which flexible diaphragms **30** are held by rings **32**. Rings **32** are held in place by threads **34**. Flexible diaphragms **30** are fabricated of a resilient, fluid-impermeable, electrically non-conductive material, such as rubber, various organo-plastic materials, etc. Flexible diaphragms **30** are provided, as by vacuum evaporation of a suitable metal, with opposing electrically conductive coatings **36** in electrically insulating relationship. Alternatively, diaphragms **30** may be of thin flexible metallic members electrically insulated from annular member **24** and rings **32** as by O-rings, etc. An electrostrictive liquid, e.g. an electro-viscous fluid, is confined in space **37** between electrically conductive surfaces **36**. The amount of the electro-viscous fluid between electrically conductive surfaces **36** is such as to completely fill space **37** with the exclusion of any gases and may or may not be sufficient to place diaphragms **30** (and surfaces **36**) under a slight degree of tension in the absence of an applied electric field.

Electrically connected to electrically conductive surfaces **36** by lead wires **38** is a source of transient electric potential **40**. By this is meant a potential of changing magnitude. Thus, as the term is used in this specification, transient electric potentials include varying potentials of positive voltage as well as alternating potentials. For purposes of convenience, it is preferred to employ alternating potentials.

In operation, potential source **40** is used to apply an electric field of varying magnitude across the electro-viscous fluid confined between surfaces **36** so that the expansion and contraction of the fluid in a direction perpendicular to the diaphragms **30** changes in response to the varying electric field. The expansion of the electro-viscous fluid will be at a maximum when the applied potential is of maximum magnitude, irrespective of sign, and at a minimum when the applied potential is of minimum magnitude. The pumping action is obtained by the continuous pulsation of diaphragms **30** which is caused by the expansion and contraction of the transducer. More specifically, with inlet conduit connected to a source of fluid to be pumped, the outward deflection of diaphragms **30** at the time of maximum magnitude of the applied potential will keep check valve **20** closed and force a portion of the fluid within housing **10** through open check valve **22** into outlet conduit **18**. Then, as the applied potential is reduced in magnitude, diaphragms **30** will relax to increase the fluid capacity of housing **10**, thereby drawing fluid through open check valve **20** while keeping check valve **22** closed. The magnitude of the applied potential is then increased to repeat the described sequence of operation.

The field strength of the transient electric field which is utilized to activate the electrostrictive transducer, e.g., the electro-viscous fluid, may be either fixed or varied during the operation of the pump. Similarly, the frequency of the transient electric field may be either fixed or varied. The field strength and the frequency of the transient electric field can be varied in conjunction with, or independent of, each other by manual, predetermined automatic, continuously programmed, or any other means. A wide range in pumping conditions can be obtained from the pump by changing the frequency and amplitude of the applied field. The frequency change results in changes in both pumped fluid discharge rate and fluid pressure fluctuation rate, while changing the amplitude of the field results in increased or decreased pump displacement per cycle. It is obvious to one skilled in the art that the combining of these two different effects produces a wide range of pumping flexibility.

Although the pump of this invention has been described with relation to a specific embodiment, it will be apparent that obvious modifications may be made by one skilled in the art without departing from the intended scope of this invention. It will be evident that structures other than the described structure including two flexible members fabricated of an electrically non-conductive material having opposing electrically conductive surfaces may be used. The pump may be constructed with only one of diaphragms **30** being a flexible member or with more than two flexible diaphragms. If desired, the flexible diaphragm (or diaphragms) may form one or more interior surfaces of the pump housing rather than being disposed in the pump so as to divide the interior thereof into a plurality of sections. If a fluid of high electrical resistivity is pumped, the diaphragms may be conductive provided that the diaphragms are maintained in electrically-insulated relationship, or the diaphragms may be non-conductive members with energizing electrodes disposed externally of the electro-viscous fluid. Check valves **20** and **22** may be located in the inlet conduit **16** and outlet conduit **18**, respectively, rather than being located in the pump housing. Electrically conductive coatings **36** will generally be spaced about 0.005 to 0.030 inch apart, although other spacings may be used. The maximum magnitude of the applied electric field when using electro-viscous fluid transducers will generally be about 6000 volts at 0.030 inch spacing and 1000 volts at 0.005 inch spacing, although higher voltages may be used. Although the pump and method of this invention have been described using an electrostrictive liquid such as an electro-viscous fluid as the transducer, it will be obvious that conventional electrostrictive transducers such as piezoelectric crystals may be used. Examples of piezoelectric crystals which may be used include Rochelle salt, polycrystalline metallic titanates derived from barium, strontium, lead and other metals, etc. At least one electrostrictive transducer is supported in physical contact with, or is mechanically connected to, the flexible diaphragms so that the deformation of the transducers resulting from the applied transient electric field will impart a vibratory motion to the flexible diaphragms. When such conventional transducers are employed, substantially lower maximum potentials are required than when electro-viscous liquids are used.

Referring to FIGURE 3, which depicts a system including a plurality of pumps, the reference numeral **50** designates a reservoir of fluid to be pumped by the system. Extending into a reservoir **50** is main inlet conduit **52** connected to branch inlet conduits **54** which are connected to inlet openings **56** of pump housings **58**. Each of branch inlet conduits **54** includes a check valve **60** to permit the flow of fluid therethrough only in the indicated direction.

Disposed in pump housings **58** are annular members **62** which are disposed so as to divide the interiors of pump housings **58** into two sections with inlet openings **56** and outlet openings **64** located in different sections. Annular members **62** are fabricated of an electrically insulating material, such as Teflon, nylon, etc., and are similar in construction to annular member **24** depicted in FIGURES 1 and 2 so that the separated sections of pump housings **58** communicate with each other through apertures **66**. Annular members **62** support electrically conductive, flexible diaphragms **68** at opposite sides thereof. Confined in space **70** between diaphragms **68** is an electrostrictive fluid, e.g., an electro-viscous fluid. Connected to each of outlet openings **64** is a branch outlet conduit **72** containing a check valve **74** to permit the flow of fluid only in the indicated direction. Branch outlet conduits **72** are connected to main outlet conduit **76**.

The electro-viscous fluid confined between each pair of flexible diaphragms **68** is subjected to a transient electric field from potential source **78**, which may be for example a 60 c.p.s. single phase alternating current source. Lead wire **80** from potential source **78** is connected to phase shifter **82** and lead wire **84**, which is in turn connected to a diaphragm **68** disposed in one of pump housings **60**. Phase shifter **82** has two output leads **86** and **88** carrying current 120° and 240° out of phase with the current in lead wire **84**. Lead wires **86** and **88** are each connected to a diaphragm **68** in the other two pump housings **58**. The circuit is completed by connecting the second output lead of potential source **78** to ground **90** and connecting the second diaphragms **68** of each pair through lead wire **92** to ground **94**.

The operation of the individual pumps in the system illustrated in FIGURE 3 is the same as the hereinbefore described operation of the pump depicted in FIGURES 1 and 2. It will be apparent that the current input to each of the pumps in the system, being out of phase with the current inputs to the other pumps, will result in overlapping pump cycles and a more constant pump output with less pulsation of the diaphragms in the individual pumps.

Although the multi-pump system has been described as containing three pumps with the current input to each of the pumps being 120° out of phase with the inputs to the other pumps in the system, it will be apparent that any number of pumps can be used. The phase difference in the current input to the pumps of a multi-pump system will necessarily depend upon the number of pumps in the system. For example, if four pumps are used, the current input to each of the pumps will be a multiple of 90° out of phase.

In the absence of an applied electric field, the electro-viscous fluids may be either readily flowing compositions of relatively low viscosity or compositions of relatively high viscosity, i.e., of a grease-like consistency. In general, the electro-viscous fluids are comprised of about 5 to 50% by volume of particulate non-conducting materials dispersed in a non-polar oleaginous vehicle, which is weakly absorbed by the particulate material and has a dielectric constant less than about 5. The non-conducting particles are of a piezoelectric or non-piezoelectric material, have an average size in the range of about 0.1 to 5.0 micron diameter, and include, as for example, finely-divided silica, calcium titanate, barium titanate, aluminum octoate, aluminum stearate, crystalline D-sorbitol, and zinc stearate. The oleaginous vehicle is preferably a refined mineral oil fraction having a viscosity within the range of about 50 to 300 SUS at 100° F. and an initial boiling point greater than about 500° F. However, a wide variety of non-polar oleaginous vehicles which are weakly absorbed by the non-conducting particles can be employed, such as white oils, transformer oils, synthetic oils resulting from the polymerization of unsaturated hydrocarbons, fluorinated hydrocarbons in the lubricating oil viscosity range, tributyl phosphate, etc. Where relatively large volumes of the non-conducting particles are incorporated in the electro-viscous fluid, it is usually necessary to add a material to fluidize the mixture and keep the viscosity of the product electro-viscous fluid at a reasonable level. For this purpose, up to about 25% by volume of a neutral surfactant, such as polyoxyalkylene ethers, glycerol mono-oleate, sorbitan sesquioleate, etc., can be incorporated to maintain a mixture of the particles and vehicle as a fluid. Specific examples of such compounds include butyl amine, hexyl amine, ethanol amine, 2-amino-ethyl amine, diethyl amine, pyridine, diethanol amine, triethyl amine, triethanol amine, and tripropanol amine. A variety of polar materials, including water and lower hydroxy-substituted hydrocarbons may be used in an amount of about 1 to 15% by volume to activate the electro-viscous fluid. Reference is made to U.S. Patent 3,047,507, which is hereby incorporated by reference, for a further description of the electro-viscous fluids.

The embodiments of the invention in which an exclusive property or privilege is claimed are defined as follows:

1. A pump comprising a vessel having communicating inlet and outlet openings, a flexible diaphragm exposed to the interior of said vessel, an electrostrictive transducer, comprising an electrostrictive liquid confined between two spaced members having opposing surfaces, adapted to be deformed upon the application of an electric field thereto and cause movement of said diaphragm upon the deformation thereof, and means for applying a transient electric field to said electrostrictive transducer.

2. A pump in accordance with claim **1** in which said opposing surfaces are electrically conductive.

3. A pump in accordance with claim **1** in which at least one of said members is a flexible diaphragm exposed to the interior of said vessel.

4. A pump in accordance with claim **3** in which both

of said members are flexible diaphragms exposed to the interior of said vessel.

5. A pump in accordance with claim **4** in which the interior of said vessel is divided by said members into two sections communicating with each other through at least one opening.

6. A pump in accordance with claim **5** in which each of said sections includes one of said members and one of said inlet and outlet openings.

7. A pump in accordance with claim **6** in which said members are fabricated of a resilient, electrically non-conductive material and have electrically conductive coatings on the opposing surfaces thereof.

8. A pump in accordance with claim **6** in which both said members are flexible metallic diaphragms.

9. A multi-pump system comprising a plurality of pumps, each of said pumps including a pump housing having communicating inlet and outlet openings, a flexible diaphragm exposed to the interior of said vessel, and an electrostrictive transducer, comprising an electrostrictive liquid confined between a pair of spaced members, adapted to be deformed upon the application of an electric field thereto and cause movement of said diaphragm upon the deformation thereof, the inlet openings of each of said pumps being connected to a first common conduit, the outlet openings of each of said pumps being connected to a second common conduit, check valves adapted to only permit the entry of a fluid into said pumps through said inlet openings and the exodus of a fluid from said pumps through said outlet openings, and means for applying a transient electric fluid to said electrostrictive transducers.

10. A multi-pump system in accordance with claim **9** in which at least one of the members of each pair is a flexible diaphragm exposed to the interior of the respective vessel.

11. A multi-pump system in accordance with claim **10** in which both of the members of each pair are flexible diaphragms exposed to the interior of the respective vessel.

12. A multi-pump system in accordance with claim **11** in which the interiors of said housings are divided by the respective pairs of members into two sections communicating with each other through at least one opening.

13. A multi-pump system in accordance with claim **12** in which each pair of said members have opposing electrically conductive surfaces and said means for applying a transient electric field is adapted to apply a field between the opposing surfaces of each pair of members which is out of phase with the field applied between the opposing surfaces of the other pairs of members.

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