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(54) **Title**: ELECTRO-OSMOTIC PUMP

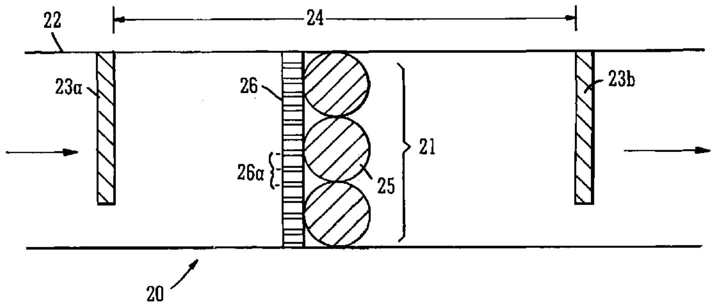

FIG. 2A

(57) **Abstract**: A pump for inducing liquid movement by means of polarisation electro-osmosis, comprising a passageway forming a flow path for fluid transport, at least one polarisable means located within said passageway so as to form at least one pore through said passageway, the at least one polarisable means being shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the passageway, the pump further comprising a non-conductive porous membrane positioned across the flow path and in close proximity to the at least one polarisable means, the membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the at least one pore formed by the polarisable means.

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Electro-osmotic Pump

This invention relates to an improved electro-osmotic pump which uses polarisation electro-osmosis, for example electro-osmosis of the second kind, to generate fluid movement, particularly within the field of microfluidics.

Electro-osmosis is a well known phenomenon and is used in many different fields. It relates to the motion of polar liquid through a porous structure under the influence of an applied electric field. Most surfaces possess a negative charge due to surface ionisation. When an ionic fluid is placed in contact with the surface, a layer of cations builds up near the surface to screen this negative charge and maintain the charge balance. This creates an electric double layer (EDL). When an electric field is applied across the surface, the ions in the EDL are attracted towards the oppositely charged electrode, dragging the surrounding medium with them due to viscous forces. This causes the fluid to move towards the negatively charged electrode.

Therefore, electro-osmosis can be used to control the movement of fluid. This has particular benefits in the field of microfluidics. Microfluidic structures, or microsystems, consist of a series of microchannels and reservoirs, at least one dimension of which is generally in the micro- or nano-meter range and not greater than 1-2 mm. Fluids can be directed through these microchannels and subjected to a variety of actions such as mixing, screening, detection, separation, reaction etc. Such microstructures are of growing importance in chemical and biotechnical fields as they allow tests and analysis to be carried out on a very small scale, thus reducing the amount of sample and reagents consumed in each operation. This means work can be carried out quickly and at less expense than previously, with the production of fewer waste materials. Such microsystems are often referred to as "lab-on-a-chip", or Micro-Total-Analysis Systems (μTAS).

The use of microfluidic actuators which utilise electro-osmosis is considered a promising technology for many microsystem applications, as these actuators are relatively simple to fabricate and a good performance can be obtained for a wide range of ionic concentrations.

However, the above described form of electro-osmosis, known as classical or ordinary electro-osmosis (EO1), normally requires a direct electric field component to be present in order to obtain directed liquid transport. This can result in several side effects, such as gas evolution at the electrodes and the establishment of pore concentration profiles along the pore axis, which reduces the efficiency and reliability of the system. These side effects can be reduced, although not eradicated, by using a pulsed current.

Several other forms of electro-osmosis exist which do not require a direct electric field component to be present in order to operate. These phenomena are referred to herein collectively as "polarisation electro-osmosis" and include induced charge electro-osmosis (ICEO) and electro-osmosis of the second kind (EO2). Polarisation electro-osmosis can be driven by either an alternating or direct current. Unlike classical electro-osmosis, in which the charge (the EDL) is already present and is simply set in motion by the application of an electric field, in polarisation electro-osmosis the electric field also induces the charge which is then set in motion.

Induced charge electro-osmosis results from the action of an electric field on its own induced diffuse charge near a polarisable surface. US2003/0164296 describes the use of ICEO to drive microfluidic pumps and mixers. This phenomenon is sometimes referred to as AC electro-osmosis (ACEO), especially in situations in which ICEO is used to pump liquids using flat asymmetric electrodes and an AC voltage.

Electro-osmosis of the second kind acts on ions within a space charge region (SCR) associated with the surface. Transport by EO2 is 10-100 times faster than for classical electro-osmosis at the same electric field strength. Consequently, fast transport of liquid can be achieved at relatively low potentials. Microfluidic pumps utilising electro-osmosis of the second kind are described in WO2004/007348.

In both of these types of polarisation electro-osmosis, the surface used to generate the diffuse charge layer or SCR is provided by one or more polarisable elements, usually spherical particles. The surface must be polarisable in order to create a build up of the charge imbalance necessary for the electric field to act upon. When these polarisable elements are immersed in electrolyte fluid (the fluid to be transported) and subjected to a suitable electric field, the necessary diffuse charge or SCR will be generated and the fluid will move via polarisation electro-osmosis. For ICEO, symmetrical flow patterns will be obtained on each side of a spherical particle, resulting in zero net flow, which is useful for mixing purposes. ICEO can be used for directed pumping by shielding one side of the spherical particle, or by adapting the shape of the polarisable element in order to create a greater charge imbalance on one side. In EO2 the flow is generated only or mainly at one side of the particle.

The velocity of the flow generated by polarisation electro-osmosis is proportional to the size of the polarisable elements used. When placed within a microchannel, or other fluid passageway, these polarisable elements reduce the cross sectional flow area through the passageway and effectively create pores, formed by the spaces between the polarisable elements, through which fluid can flow. The size of polarisable elements required in order to generate sufficient flow speeds creates a relatively large pore size and hence limits the pumping pressure of the device.

For example, when creating a EO2 pump it is necessary to use polarisable elements with a characteristic diameter, D_{char}, of at least 10μm. The characteristic diameter is defined as the diameter of the polarisable element(s) measured parallel to the direction of the electric field applied during operation.

This results in a trade off between the benefits of polarisation electro-osmosis (which increases with the size of the polarisable elements) and the pump pressure.

One option to mitigate this trade off is to use polarisable elements in the shape of cigars or cylinders. These still provide a curved surface, which can induce polarisation electro-osmosis, but can be packed closer together, hence reducing the pore size within the passageway. However, such polarisable elements are difficult to produce, especially at the small sizes which would be required to generate a high pressure in many microfluidic applications. For example, often the pore size should be below one micrometer.

Viewed from a first aspect the present invention provides a pump for inducing liquid movement by means of polarisation electro-osmosis, comprising

a passageway forming a flow path for fluid transport,

at least one polarisable means located within said passageway so as to form at least one pore through said passageway,

the pump further comprising

a non-conductive porous membrane positioned across the flow path and in close proximity to the at least one polarisable means, the membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the at least one pore formed by the

polarisable means, whereby, in use, an electric field generated across the polarisable means in the longitudinal direction of the passageway will cause fluid in the passageway to flow under the action of polarisation electro-osmosis.
the at least one polarisable means being shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the passageway,

Therefore, the invention lies in the realisation that existing polarisation electro-osmosis pumps can be improved by the addition of a porous membrane acting in combination with the polarisable means of the pump.

All polarisation electro-osmotic pumps require polarisable means as these provide the surfaces at which the charge imbalances necessary to induce movement by polarisation electro-osmosis, such as the diffuse charge layer or SCR, can form. Placing a porous membrane in close proximity to the polarisable means allows the generated charge to extend into the pores of the membrane. This occurs because the charge flow parallel to the membrane surface is inhibited by the porous structure of the membrane, and hence the charge layer grows thicker. In other words, lateral drift of the induced charge is reduced by the porous membrane.

Increasing the thickness of the generated charge layer increases its effect. Therefore, when a porous membrane is used in accordance with the present invention, both the polarisable means and this membrane can generate polarisation electro-osmotic flow. Flow can be increased for a given electric field.

In order to achieve this the porous membrane must be in close proximity to the polarisable means, as the induced charge layer which forms around this means is very thin. Therefore, the membrane should be no more than 5 micrometres from the polarisable means.

The possibility of enhancing EO2 by extending a generated SCR into a porous structure was suggested in an article by Mishchuk et al, "Electroosmotic Transport of Fluid through a Diaphragm-Resin System" (Journal of Water Chemistry and Technology, Vol. 26, No. 4, pp.21-32, 2004). This article relates to the use of EO2 in electrofiltration processes. These processes are used in order to, for example, extract impurities from water and to remove heavy metals from soils. In such processes a charged porous diaphragm can be used to induce electro-osmotic movement through the diaphragm, leaving the unwanted particles behind. Although highly theoretical, this article hypothesises that by coating the diaphragm in an ion exchange resin the SCR generated by the resin granules will extend into the diaphragm, thus increasing the electro-osmotic effect. It is suggested that flow through a charged porous diaphragm could be enhanced by using this in combination with an ion exchange resin or that an uncharged diaphragm could be used in combination with the resin to provide electrofiltration processes.

The inventors of the present invention have realised that this technique could also have advantages in relation to polarisation electro-osmosis pumps. In addition, it has been appreciated that the use of a porous membrane can offer further advantages.

The use of a porous membrane in accordance with the present invention has the further benefit of enabling the effective pore size of the passageway to be reduced. By using a separate component to control the pore size of the pump, the polarisable means can be designed solely with a view to providing the desired level of polarisation electro-osmotic effect. The polarisable means can therefore be made larger without sacrificing the pumping pressure, as the porous membrane can be used to keep the pore size of the pump small.

The "pores" formed by the polarisable means can comprise pores or interstices within the means itself but also the spaces formed between the passageway walls and the polarisable means. In other words, the pores formed by the polarisable means are the areas through which fluid flowing through the passageway can pass by or through the polarisable means. Therefore it is not necessary for the polarisable means to contain pores itself. Instead this can act to partially block the passageway such that the remaining spaces act as pores.

In accordance with the present invention, the porous membrane must contain pores of a smaller size than the pores formed by the polarisable means. The pore size of the pores formed by the polarisable means is, for the purposes of the present invention, taken to be the same as the pore size of a membrane with straight cylindrical pores having the same length and porosity as the pores provided by the polarisable means, and with the same void volume to surface area ratio. Such a calculation of equivalent pore sizes is frequently done when considering fluid flow, see W.L. McCabe, J.C. Smith, and P Harriot. Unit operations of chemical engineering. McGraw-Hill, Singapore, 1993, page 152-153.

The membrane is preferably positioned across the entire flow path such that it would block the passageway if it were not porous. This ensures that the whole of the flow path is affected by the pore size of the membrane.

It is not necessary for all of the pores of the membrane to be the same size, or indeed the same orientation. It is possible for example, for the porous membrane to comprise a first set of pores extending in a first direction and a second set of pores extending in a second direction which is perpendicular to the first. Alternatively the membrane may comprise a first set of pores having one size and a second set of pores having a different size. Preferably however the membrane comprises uniform pores which are unidirectional.

It is necessary for at least some of the pores of the membrane to extend in a direction at least partially parallel to the longitudinal axis of the passageway, such that fluid flowing through these pores will exit the membrane at a point longitudinally remote from the point at which it entered the membrane.

Preferably the pores of the membrane are substantially parallel to the longitudinal axis of the passageway.

The pore size of the membrane will be determined in part by the function of the pump. In situations in which a very low flow rate is required but at high pressure, pores as small as 30nm could be used. On the other hand, when a higher flow rate is desired, for example for electronic cooling, larger pores, e.g. up to 10μm would be beneficial.

Within the field of microfluidic systems, it has been found that the use of membranes having a pore size of between 0.1 - 1 μm produces a noticeable increase in pumping ability.

However, more generally the pores of the porous membrane are preferably at least ten, most preferably at least one hundred, times smaller than the length of the polarisable means when measured in a direction parallel to the longitudinal axis of the passageway.

Ideally, the thickness of the membrane should be of a similar magnitude to the enhanced diffuse charge layer, SCR or other charge concentration that will be induced. This ensures that all of the extended diffuse charge layer, SCR etc is utilised without introducing any additional length which would simply add resistance to the system.

However, finding this preferred thickness in practice would be time consuming and difficult. A membrane thickness of 100μm has produced good results in microfluidic systems. More generally, a membrane thickness of between 10 and 1000μm is preferred, more preferably between 50 and 200μm.

A single membrane may be used, or plural membranes may be used. It may be desirable to use more than one membrane, for example in order to achieve the desired overall membrane thickness. Where plural membranes are used they will normally be in face to face contact. The membrane thickness as referred to herein means the overall thickness, i.e. the thickness of a single membrane or the combined thickness of plural membranes. In certain embodiments two membranes are used.

The membrane is non-conductive as the use of a conductive membrane would short circuit the electro-osmotic effect.

Although the membrane can have the opposite or no surface charge, it is preferable for the membrane to have a surface charge of the same sign, and preferably the same surface groups, as the polarisable means. Different charges will lead to a braking effect on the electro-osmotic flow, whereas using two different surface groups might lead to undesired electrochemical reactions.

Preferably the membrane comprises a hydrophobic polymer. This prevents the occurrence of a soaked membrane matrix, which would not contribute significantly to liquid transport, while leading to increased current and power consumption. This type of membrane also has the advantage that it does not retain liquid after the liquid within the pores is removed by liquid transport.

Preferably the hydrophobic membrane material is selected from polymer materials such as polypropylene, polytetrafluoroethylene (PTFE) or (ultra high molecular weight) polyethylene. Preferably the hydrophobic membrane is treated during manufacture with a hydrophilising surface treatment. This treatment could, for example, introduce sulfonic acid groups, onto the pore surface. As mentioned above, these groups are preferably the same as the surface groups of the polarisable means.

As mentioned previously, the porous membrane must be placed in close proximity to the polarisable means so that the induced charge imbalance generated on the surface of the polarisable means can extend into the membrane. In order to achieve the best results it is preferable that the porous membrane is in direct contact with the polarisable means.

The polarisable means can be in any form suitable for inducing polarisation electro-osmotic movement. Such means are known from prior art polarisation electro-osmotic pumps.

In certain preferred embodiments, the at least one polarisable means is shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the passageway. Thus the pores formed by the polarisable means may have walls which are curved or inclined with respect to the generated electric field, which is typically parallel to the longitudinal axis of the passageway in the vicinity of the polarisable means. The field within the pores will then have both normal and tangential components, thus the normal electric field component induces a charge on the polarisable surface, and the tangential component sets the charge in motion resulting in liquid movement along the surface. Thus polarisation electro-osmotic flow is achieved.

In these embodiments, it is not necessary for the entire pore wall to be curved or inclined. In some cases the passageway may have straight sides and these may form one or more sides of a pore. However each pore should preferably contain at least a section of pore wall, formed by the polarisable means, which is curved or inclined with respect to the longitudinal axis of the passageway. Although the passageway may, in its entirety, contain bends and changes in direction, the polarisable means will generally be positioned in a straight segment of the passageway along which an electric field can be applied. Therefore all reference to the longitudinal axis or direction of the passageway refers to the section of passageway containing the polarisable means.

The at least one polarisable means may have a portion having a surface in close proximity to the porous membrane and substantially perpendicular to the longitudinal direction of the passageway. Under the effect of an electric field a charge will be generated on this surface and so a generated charge layer is formed. The generated charge layer will tend to extend into the pores of the membrane and across the pores of the polarisable means, with the result that flow will be generated. The polarisable means of such embodiments may additionally have curved or inclined walls, but these are not necessary. Therefore, in certain embodiments the at least one polarisable means has only surfaces which are substantially perpendicular to the longitudinal direction of the passageway and surfaces which are substantially parallel to the longitudinal direction of the passageway. An example is a polarisable means with straight cylindrical pores arranged parallel to the longitudinal direction of the passageway. The polarisable means may be a membrane with such pores, i.e. a second membrane.

For the embodiments having a surface in close proximity to the porous membrane and substantially perpendicular to the longitudinal direction of the passageway, the relationships between the thickness and pore size of the porous membrane and the polarisable means are the same as those described above.

In one embodiment the polarisable means comprises at least one polarisable particle. When placed in the passageway this restricts the flow and hence forms a pore. This pore has the same length as the particle as measured in the longitudinal direction of the passageway. The addition of more particles can change the shape of the pore or create a plurality of pores.

Preferably the polarisable particle is substantially spherical, as these are relatively simple to manufacture. However, many other shapes are possible, for example, cylindrical, oval, parallelogram, triangular, kite-shaped, frustro-conical etc.

When individual polarisable particles are placed in contact with one another a single charge is produced and the electro-osmotic effect is increased. Therefore preferably the polarisable means comprises a plurality of adjoining polarisable particles.

The adjoining polarisable particles may be arranged in rows or grids within the passageway, or simply be randomly packed or clustered together. Increasing the number of particles positioned "side by side" in a plane substantially perpendicular to the longitudinal axis of the passageway increases the number of pores while increasing the thickness of the polarisable means by adding particles in the longitudinal direction increases the pore length. Having adjoining layers of polarisable particles adds to the strength of the generated polarisation electro-osmotic effect but only up to a certain threshold, whereupon the addition of further layers will not affect the flow rate obtained.

In embodiments in which the polarisable means comprises a plurality of adjoining polarisable particles, it is preferred that the porous membrane is in close proximity to or contacts more than one polarisable particle. For example, when the polarisable particles are arranged in the same plane across the passageway it is preferable for the porous membrane to contact each polarisable particle, i.e. the entire outer surface of the polarisable means.

It is also possible in some embodiments for a single porous membrane to contact, or to be in close proximity to, more than one polarisable means. This can occur when two or more polarisable particles are attached to the wall of the passageway at radially spaced intervals in the same cross sectional plane. Together these polarisable means restrict the flow path and create a pore.

When the polarisable means comprises one or more polarisable particles it is preferable that the pores of the porous membrane are at least ten times smaller than the length of a single polarisable particle as measured in the longitudinal direction of the passageway. Most preferably the pore size is at least one hundred times smaller than this length.

Preferably the porous membrane has a thickness of between 0.5 and 3 times the size of one polarisable particle measured in the longitudinal direction of the passageway.

Alternatively, the polarisable means may be provided in the form of a polarisable membrane (in some embodiments having pores which are curved or inclined with respect to the longitudinal axis of the passageway, or in other embodiments having straight cylindrical pores). In this case, the non-conductive membrane pore size should preferably be at least ten and more preferably at least 100 times smaller than the thickness of the membrane constituting the polarisable means as measured in the longitudinal direction of the passageway.

As mentioned previously, electro-osmosis of the second kind (EO2) provides fast flow rates at relatively low voltages compared to classical electro-osmosis. Therefore, in a preferred embodiment the pump is arranged to induce liquid movement by electro-osmosis of the second kind.

In order to achieve this, it must be possible to generate an SCR at the surface of the polarisable means. This is accomplished by using a unipolar conducting material. So that the generated SCR can be used to provide directed movement of the fluid the surface of the unipolar conducting means should be uniform. By uniform it is meant that any surface irregularities must be less than 5% of the characteristic diameter of the polarisable means (the characteristic diameter being the dimension of the polarisable means measured parallel to the direction of the generated electric field). The polarisable means may comprise regular structures (such as grooves) in the flow direction. However, preferably the polarisable means has a smooth surface, i.e. all surface discrepancies are less than 5% of the characteristic diameter. Preferably any surface discrepancies are less than 100nm, regardless of diameter.

Although it is possible to construct the present invention with any unipolar conducting means, preferably the polarisable means should have one or more of the following properties: an ionic conductor, made from polymer, have strongly acidic ion exchange groups (e.g. sulfonic acid groups), conductivity 10 or more times that of the fluid medium, bulk conductivity (the member could have a non-polarisable core, but the diameter of this should preferably be significantly smaller that that of the conductive outer layer, more preferably zero), lowest possible porosity and pore-size (ideally zero). In particular it is preferable that the unipolar conducting means comprises a strongly acidic ion-exchanger. Sulfonated polystyrene-divinylbenzene is a particularly preferred material, although sulfonated acrylic could also be used, especially for applications where reduced protein binding is beneficial. When the polarisable conducting means is a membrane with conical pores, sulfonated polyether ether ketone (sPEEK) mixed with polyethersulfone (PES) is a preferred material. Such a membrane can be produced by casting the dissolved polymer mixture onto a surface having protrusions representing the negative of the pore shape. This surface can be made of polydimetylsiloxane (PDMS) replicated from an etched silicon master.

Metal, semiconductor, metallic polymers and other ion-exchangers could be used for special applications, but are generally less preferred.

By unipolar conductor is meant a material for which the conductivity is higher for either negative or for positive charges, preferably at least 4 times higher, more preferably at least 15 times higher.

When the pump is arranged to operate via ICEO the polarisable means can comprise a dielectric material. However, preferably a conducting material is used. Therefore, in both EO2 and ICEO pumps the polarisable means is preferably a conducting means.

To ensure a suitably high conductivity ratio between the conducting means and the fluids likely to be used within the pump it is preferable for the conducting means to have a specific conductivity of greater than 0.01S/cm, more preferably between 0.01-1S/cm and most preferably greater than 1 S/cm.

When the polarisable means comprises a conducting means, the porous membrane can be considered to be non conductive if it has a specific conductance at least 5 times lower than the conducting means.

When the pump is arranged to operate via EO2, it is preferable for the porous membrane to be provided such that it is in close proximity to or contacts the unipolar conducting means on the surface on which, in use, the SCR is generated. However, in addition it has been surprisingly shown that placing the membrane on the opposing side of the polarisable means, or placing porous membranes on both sides, also enhances the pumping effect.

This benefit is also found in pumps which operate using other forms of polarisation electro-osmosis. Therefore, in one embodiment, the pump further comprises a second porous membrane in close proximity to, preferably in contact with, the opposing surface of the polarisable means to the porous membrane, the second porous membrane having pores which extend in a direction at least partially parallel to the longitudinal direction of the passageway. Preferably the pores of the second porous membrane are larger than the pores formed by the polarisable means. This lowers the flow resistance created by this additional membrane.

The use of a second porous membrane can serve the additional purpose of fixedly securing polarisable particle(s) in place within the passageway when these are used to form the polarisable means. This is advantageous as it negates the need for a bonding agent or precision engineering to hold the polarisation means in place.

It is not necessary for a second porous membrane to be used for this function. Instead it is also possible for the polarisable means to be contained between the porous membrane and another porous structure, for example an open grid. Therefore, preferably the polarisable means is fixedly located within the passageway between the porous membrane and a porous sealing element, such as a second membrane, net or grid. Preferably the pores of the sealing element are larger, most preferably at least 3 times larger, than the pores formed by the porous membrane.

A further option is for the porous membrane to be provided in the form of a porous plug, which encases the polarisable means. This has the advantage that it would be easier to manufacture, although would produce less electro-osmotic effect.

Alternatively, the porous membrane may comprise a porous film over the surface of the polarisable means, which can be applied through conventional spraying techniques.

As mentioned above, when polarisable particles are used, increasing the number of adjoining particles only results in a corresponding increase in polarisation electro-osmotic effect up to a certain threshold. Preferably therefore a plurality of polarisable means are provided spaced apart in the longitudinal direction of the passageway. In this way, the pump can, in effect, contain a number of separate pumping sections. The plurality of polarisable means can each be individual particles, adjoining particles, membranes or a combination thereof.

When a plurality of polarisable means are used, it is preferred that the pump further comprises a plurality of porous membranes, such that each polarisable means is in close proximity to, or in contact with, a porous membrane having pores at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the pores formed by the polarisable means.

This allows each polarisable means to enhance the polarisation electro-osmotic flow by extending the charge concentration, e.g. the SCR, into the pores of a membrane.

In certain preferred embodiments, the pump comprises a pair of non-conductive porous membranes, one on each side of the at least one polarisable means and each in close proximity to the at least one polarisable means. With such an arrangement the pump is bidirectional.

In some embodiments, each polarisable means is further in contact with a porous sealing element on the opposing surface to the porous membrane so as to fixedly locate the polarisable means. This sealing element could be a second porous membrane, grid, net etc.

All of the membranes used within the pump may have the same thickness, pore sizes and material properties as discussed above. Thus where a second porous membrane is used it can serve both the mechanical function of locating the polarisable means, as well as enabling the pump to be operated bidirectionally.

It is possible for the porous membrane of a second, downstream polarisable means to be in contact with a first, upstream polarisable means. In other words, the longitudinally spaced polarisable means can be separated only by a porous membrane which contacts both groups. In such embodiments the porous membrane itself acts as a sealing element.

Alternatively, the gap between longitudinally spaced polarisable means could be filled by a sealing element having a pore size much greater, e.g. at least 5 times, preferably 10 times the pore size of the porous membrane. This sealing element may comprise e.g. a second porous membrane or grid.

In embodiments in which the membrane comprises a porous plug, this plug can enclose one or more polarisable means or separate plugs can be used in respect of each longitudinally spaced polarisable means within the pump.

The pump can be produced without electrodes. However, these must be present in use in order to produce an electric field across the polarisable means. These can be added to the pump once this is in place within an operating system but could also be an integral part of the pump. Therefore, preferably, the pump further comprises electrodes positioned on either side of the polarisable means in the longitudinal direction of the passageway which, in use, are arranged to generate an electric field across the polarisable means so as to cause fluid to flow under the action of polarisation electro-osmosis.

The electrodes can encompass a plurality of longitudinally spaced polarisable means or alternatively each longitudinally spaced polarisable means may have its own pair of electrodes. Each electrode may be spaced from a respective non-conductive porous membrane or it may be in direct contact therewith so as to cover its surface. Good results can be achieved with the electrode in contact with the porous membrane. In embodiments where a single porous membrane is provided in close proximity to the polarisable means, the electrode on that side of the polarisable means may be in contact with the porous membrane, whilst in embodiments where a pair of porous membranes are provided, one on each side of the polarisable means, an electrode on one side of the polarisable means may be in contact with the porous membrane on that side and the electrode on the other side of the polarisable means may be in contact with the porous membrane on that other side.

Palladium is a preferred material for the electrodes.

Preferably the electrodes comprise a surface area directed towards the polarisable means. Such electrodes could be porous metal grids parallel to and covering (part of or the entire) passageway cross section. They could also be threedimensional structures, such as pillars, extending from the channel walls. Such electrodes will provide a more even current distribution. This is particularly important when using EO2 in order to ensure an SCR is generated in all parts of the polarisable means.

Alternatively, the electrodes can comprise a metal or conducting polymer layer deposited onto the porous membrane and/or sealing element on either side of the polarisable means. For example, gold or other metals could be deposited by sputtering or evaporation, and conducting polymers could be deposited by coating with a dissolved polymer. The conducting material should be deposited in a controlled way in thin layers, so they form thin conducting layers on top of the membranes and sealing elements, rather than rendering the bulk of the sealing elements and membranes conducting. This form of electrode is beneficial when the polarisable means are positioned between membranes or other sealing elements such as grids. Making use of the existing structure of the pump to form electrodes in this manner is cost effective.

Therefore, preferably the porous membrane(s) and sealing element(s) comprise an electrode layer deposited on their outer surface.

The electric signals required to generate polarisation electro-osmotic movement are known in the art.

Due to the larger induced charge which is built up when using a porous membrane in close proximity to the polarisable means, liquid velocities will typically be higher than the velocities obtained in a pump which does not comprise a porous membrane at a given field strength. The velocity of an EO2 pump can be increased by up to ten times and the pressure can increase by more than 10 times. It is therefore possible to reduce the voltage used to operate the pump. This brings several advantages, including reduced problems with electrochemical reactions and gas formation, simpler control electronics and power supply and increased portability.

According to theory, during the short period of charge build-up in an EO2 pump in accordance with the present invention, the liquid velocity (v) is expected to depend on the electric field strength E, size of conductive means a, membrane pore size a_m and bulk ionic concentration C as follows:

$$v \sim E^{\frac{5}{3}} a^{\frac{2}{3}} a_m^2 C_0^{\frac{2}{3}}$$

However, after charge build-up, the following relation is assumed to hold for the case of an inert (i.e. non-conductive) membrane with straight cylindrical pores parallel to the direction of the electric field:

$$v \sim E^{\frac{2}{3}} a^{\frac{2}{3}} a_m^2 C_0$$

This means that the overall pump shows a sub-linear velocity – electric field strength relation for this extreme case (i.e. pores parallel to the direction of the electric field). Most porous materials will have porosity also in the direction perpendicular to the electric field, allowing for flow of liquid and charge in this direction, although still inhibited.

Although the exact flow - voltage relation can vary with the porosity and possibly other properties of the inert porous material, the entering of the charge into this more finely porous material and the concomitant thickening of the charged layer will lead to a large increase in flow rate and pressure compared to the situation without such inert porous material.

The pump can be operated using an asymmetric square pulse signal with an offset or zero DC component, as is frequently used for EO2 and ICEO. For systems with a sub-linear relationship between pressure / flow and the electric field, the weak pulse will determine the flow direction, whereas for a super-linear relation the strong pulse determines the direction.

For asymmetric pumps (with a finely porous membrane only at one side of the polarisable means) symmetrical AC signals can be used to obtain directed transport. DC signals can also be used.

As the use of a porous membrane increases the electro-osmotic effect, the electrodes can be positioned further from the polarisable means than in previous pumps. In some embodiments this may be beneficial as the electrodes can create unwanted side effects.

In certain embodiments, therefore, a spacer layer is provided between the porous membrane and the electrodes in order to reduce electrical resistance and unwanted bubble formation. Preferably, this spacer is in the form of an ion exchange membrane, which allows the electrical charge to be transmitted to the polarisable means but prevents any bubbles from passing. It is further possible to provide polarisable means in contact with this ion exchange membrane. This will produce an electro-osmotic convection effect and reduce the undesired polarisation on the spacer membranes (which would lead to increased electrical resistance and hence the need for higher voltages). However, for dilute ionic solutions (up to 0.1 to 1 millimolar) the lower voltage and the possibility to use AC for the present invention will usually make this measure unnecessary.

The pump of the present invention can be provided within a microchannel of a microfluidic system. In such embodiments the passageway of the pump preferably forms part of a microchannel. The electrodes for providing the electric field can be positioned within the microchannel on either side of the polarisable means, thus defining a pumping segment within the channel. Multiple pumps could be placed in the same system or even the same microchannel, as desired.

Therefore, viewed from a further aspect the present invention provides a microfluidic system comprising:

a microchannel;

electrodes positioned within said microchannel, defining between them a pumping segment;

at least one polarisable means located within said pumping segment as so to form at least one pore through said pumping segment;

a non-conductive porous membrane positioned across the pumping segment and in close proximity to the at least one polarisable means, the membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the pumping segment and having a pore size smaller than the at least one pore formed by the polarisable means; and

the pumping segment being arranged such that, in use, the electrodes generate an electric field across the polarisable means so as to cause fluid in the microchannel to flow under the action of polarisation electro-osmosis.

In certain preferred embodiments, the at least one polarisable means is shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the pumping segment. Alternatively the at least one polarisable means may have only surfaces which are substantially perpendicular to the longitudinal direction of the passageway and surfaces which are substantially parallel to the longitudinal direction of the passageway.

However, it is also possible for the pump of the present invention to be free standing. This allows the pump to be manufactured and sold independently so that this can then be used in a variety of applications. For example, a free standing pump could be connected to the inflow conduit of a microfluidic "lab-on-a-chip" system. In this way, the pump could still be used to pump fluid through a microsystem without the complexity of incorporating this in to the microsystem itself.

In such embodiments the passageway is preferably a through hole within a housing. The polarisable means preferably comprises a plurality of adjoining polarisable particles packed within the through hole between said porous membrane and a porous sealing element. In this way the plurality of polarisable particles are contained within the through hole. In a preferred embodiment the sealing element is a second membrane having pores which extend in a direction at least partially parallel to the longitudinal direction of the passageway. It is preferred that the pores of the second membrane are larger than the pores formed by the polarisable means. Alternatively the sealing element may comprise a grid or net.

The use of a free standing pump is considered inventive in its own right and therefore, viewed from a further aspect the present invention comprises a pump for inducing liquid movement by means of polarisation electro-osmosis, comprising a housing containing a through hole therein, said through hole forming a passageway; porous sealing elements sealing at least a section of the through hole; a plurality of adjoining polarisable particles packed between said sealing elements, the polarisable particles creating pores through said passageway; wherein one of said sealing elements comprises a non-conductive porous membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the pores created by the polarisable particles.

The polarisable particles may be shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the through hole. Alternatively they may have only surfaces which are substantially perpendicular to the longitudinal direction of the passageway and surfaces which are substantially parallel to the longitudinal direction of the passageway.

The second sealing element may comprise a further membrane or a grid as described above.

The free standing pump may also comprise electrodes positioned on either side of the polarisable particles. These can be located outside the through hole or alternatively the electrodes may be positioned within the through hole on either side of the polarisable particles. This could be achieved by creating a through hole, filling this with polarisable particles, sealing the through hole using porous membranes and then extending this through hole by the addition of annular rings on either side of the housing.

Several embodiments of the invention shall now be described, by way of example only, with reference to the accompanying figures, in which:

FIG 1A shows a cross section through a microchannel containing a prior art pump;

FIG 1B shows a cross section along line B-B of FIG 1A;

FIG 2A shows a pump according to the present invention;

FIG 2B shows another pump according to the present invention

FIG 3A shows the principle of EO2 on a single polarisable particle;

FIG 3B shows the principle of EO2 on a single polarisable particle in contact with a porous membrane;

FIG 4A shows another version of the pump according to the present invention;

FIG 4B shows another version of the pump according to the present invention;

FIG 4C shows another version of the pump according to the present invention;

FIG 5 shows a further version of the present invention;

FIG 6 shows a further embodiment of the present invention;

FIG 7 shows an embodiment of the present invention in which the pump is free standing;

FIG 8 shows a further embodiment of the present invention;

FIG 9 shows a schematic representation of a porous polarisable membrane for use in the present invention;

FIG 10 shows another embodiment of the pump of the present invention; and

FIG 11 shows an enlargement of the part show as "X" in FIG 10.

FIG 1A shows a prior art pump 10 within a microchannel 12. This pump 10 is arranged to operate via electro-osmosis of the second kind. Electrodes 13a, b extend into microchannel 12 and define a pumping segment 14 within the microchannel 12. Within this pumping segment 14 a number of spherical polarisable particles 15 are arranged to form a polarisable means 11. These particles 15 are made of a unipolar conducting material and are curved with respect to the longitudinal axis of the microchannel 12 and the electric field provided by electrodes 13a, b. When the microchannel is filled with an electrolyte, such as methanol, and electrodes 13a, b are operated to provide a suitable electric field across the polarisable means 11, this induces movement of the surrounding fluid via electro-osmosis of the second kind. Therefore, this pump allows fluid to flow through the microchannel 12 in the direction indicated by the arrows.

A cross section through microchannel 12 is shown in FIG 1B. This cross section is taken along line B-B, i.e. through the polarisable means 11. As can be seen, the polarisable means 11 partially blocks the microchannel 12 and forms pores 17 through the channel. The shape of the polarisable particles 15 is such that they provide the pores 17 with curved walls. In this instance the microchannel 12 itself also forms a curved pore wall, however this is unnecessary and in other embodiments the microchannel may be square or rectangular in cross section. The charge imbalance required to generate polarisation electro-osmotic movement will be induced at the surface of the polarisable means 11 and this which creates a curved or inclined pore wall. Due to the required size of the polarisable particles 15 the pores 17 created between these are relatively large, which limits the pump pressure.

The pump of the present invention, an embodiment of which is shown in FIG 2A, overcomes this problem. The pump 20 includes a porous membrane 26 positioned across the microchannel 22 such that it contacts the polarisable means 21, which consists of spherical polarisable particles 25. The membrane 26 comprises narrow pores 26a which are parallel to the longitudinal axis of the microchannel 22. Apart from this addition, pump 20 comprises identical components to prior art pump 10.

A variation is shown in Figure 2B. In this embodiment, the electrode 23a is in contact with the porous membrane 26. The electrode 23a may be a laser perforated foil, or a mesh or grid, of metal or other conductive material.

The porous membrane 26 affects the pump 20 in two beneficial ways. Firstly, it reduces the effective pore size of the pump 20, as the membrane is selected such that its pores 26a are narrower than the pores formed by the polarisable means 21. This allows the pumping pressure to be increased. Secondly the electro-osmotic effect is increased. This is due to the effect that the membrane 26 has on the space charge region (SCR) generated around the polarisable means 21 upon application of a suitable electric field. The principles of SCR are explained below with reference to FIGs 3A and B.

An SCR is induced on the polarisable means 21 if the generated electric field is strong enough to give a strong concentration polarisation. The polarisation zone then consists of a diffusion zone at the boundary with the bulk liquid, an SCR layer closer to the polarisable surface, and possibly an EDL closest to the surface. However, despite the possibility of an EDL at the polarisable particle surface it is important to note that the SCR is established independently of this layer. The notion of "electro-osmosis of the second kind" indicates the similarity to EO1 by having its source in a thin charged zone, the SCR, which is different from electric effects working on the bulk liquid (electro-hydrodynamic effects). Such polarisation phenomena have been described for both ionically and electronically conducting materials.

The polarisation phenomenon can be described most simply with reference to a permselective (cat)ion conducting material in some liquid of lower conductivity. This phenomenon is well known, and will be described briefly here. By directing an electric field towards the material, cations are transported towards and through the solid material, while no anions are allowed to pass in the opposite direction, due to permselectivity (i.e. the transport number of one charge is significantly larger than that of the other). At a steady state, the electro-diffusional flux of co-ions away from the material is compensated by a diffusional flux in the opposite direction. Thus, a diffusion zone with concentration decreasing towards the material is observed. Upon increasing the electric field strength, the current increases while the concentration decrease becomes larger. A limit is reached at zero ion concentration near the material. At this point, no current increase is observed upon further increasing the voltage, thus the term "limiting current".

However, while the limiting current represents a plateau in the voltage-current curve, a further increase in current takes place if the voltage is high enough.

One feature of this strong concentration polarisation is the appearance of the SCR close to the material (between the material and the diffusion zone).

One reason for the appearance of over limiting current is the appearance of EO2 eddies (circular flows, sometimes referred to as electroconvection) in the polarisation zone, adding to diffusional ion transport. Even at a flat membrane, EO2 eddies are observed.

FIG 3A shows the SCR produced on a single unipolar conducting particle in some liquid of lower conductivity and in a strong electric field, indicated by arrow E. The curved surface of the particle creates two components to the main electric field, tangential component E_{tan} and normal component E_{norm}. The normal component induces a thin SCR layer, while the tangential component acting on this layer results in ion and liquid transport - electro-osmosis of the second kind. As shown in this figure, the SCR generated is very thin. However, when multiple polarisable particles are grouped together a single, combined SCR is produced.

The SCR can be further increased by the provision of a porous membrane 36 contacting the particle. As shown in FIG 3B, the SCR extends into the pores 36a of the membrane. This occurs as the free space between the particle and membrane is not large enough to allow for unrestricted electro-osmotic flow. Therefore, the polarisation region thickens and extends into the membrane. A larger layer of SCR produces a larger EO2 effect.

This explanation relates to EO2. However, weaker (not involving over limiting current) polarisation phenomena such as induced charge electro osmosis (ICEO) can be enhanced in the same way.

Consequently a pump 20, having a porous membrane 26 will produce a greater electro-osmotic effect and in addition the reduced effective pore size of the pump 20 will increase the pumping pressure. This allows electrodes 23a, b to be positioned further from the polarisable means 21, thus increasing the stability of the pump 20.

Due to the unipolar nature of the polarisable means 21, an SCR only builds up on one side of the particles. Therefore the membrane 26 is usually placed on the side of the polarisable means 21 on which, in use, the SCR will be induced. However, benefits can also be obtained by placing the membrane 26 on the opposing side of the polarisable means, or having a membrane on each side.

FIG 4A shows an embodiment of the pump 40 in which a further membrane 47 is included on the opposing side of the polarisable means 41. This membrane 47 acts as a sealing element which, together with porous membrane 46, fixedly locates the polarisable means 41 within the passageway 40. Membrane 47 has larger pores in order to reduce the hydrodynamic resistance. Membrane 46 is positioned on the side of the polarisable means 41 on which, in use, the SCR is generated. In an alternative version of this embodiment, it is possible for electrodes 43a, 43b to be formed by a layer of metal or conducting polymer deposited on the membranes 46, 47.

In a variation shown in Figure 4B, a pair of membranes 46 with fine pores is provided, one on each side of the polarisable means 41. This arrangement provides a bidirectional pump. Although the pump involves a greater hydrodynamic resistance than the pump of Figure 4A, due to the presence of a finely porous membrane on the downstream side of the polarisable means 41, it has the advantage that it can be operated in either direction.

In an alternative version, shown in Figure 4C, the electrodes 43a and 43b are provided each in contact with a respective membrane 46. Each electrode 43a, 43b may be a laser perforated foil, or a mesh or grid, of metal or other conductive material.

FIG 5 shows a further embodiment in which pump 50 has two polarisable means 51 a, b comprising a plurality of polarisable particles 55 for generating electro-osmotic movement. Both of these means 51 a, b are in contact with a separate porous membrane 56a, b positioned so as to enhance the generated SCR.

It is also possible for the polarisable means 51a, b to be positioned closer together, or for membrane 56b to be thicker, so that this membrane 56b also contacts the first polarisable means 51a. Further polarisable means 51 could also be included as desired.

The embodiment shown in FIG 5 further includes an alternative passageway configuration in which electrodes 53a, b are situated in compartments 54 off the main passageway 52. Flow through the passageway 52 by-passes these compartments 54, as indicated by the arrows. Ion exchange membranes 58 are located close to the electrodes 53a, b and separate the compartments 54 from the main passageway 52. These ion exchange membranes 58 do not block the electric field but they do prevent bubbles from reaching the polarisable means 51a, b. Such bubbles can form when, for example, a direct current is used to power the pump 50. The compartments 54 could hold a lower pressure than the passageway 52. For example, they could be open to the atmosphere or contain a lid making it possible to exchange (buffer) solution and let out electrolytic gases.

FIG 6 shows another embodiment of the invention. Here the pump 60 comprises a plurality of polarisable means 61 a, b, each being contacted by a porous membrane 66a, b and a second sealing membrane 67a, b so that the same advantages as discussed in relation to FIG 4 are achieved. Compartments 64 and ion exchange membranes 68 are again used to prevent bubbles from interfering with the operation of the pump 60. In this embodiment however additional polarisable means 69 are placed in contact with these membranes 68. These additional polarisable means 69 create electro-osmotic convection which reduces the undesired polarisation effects of the ion exchange membranes 68.

The above embodiments all relate to pumps formed within microchannels. While the pump of the present invention is particularly suited to use in microsystems, it can also be used in many other fields.

FIG 7 shows a free standing pump 70 in accordance with the present invention. This pump can be attached to many different fluid systems, such as electronic cooling circuitry, or a feeder inlet to a microsystem. In this latter application the pump 70 can still be used to operate a microsystem without the complexity of integrating this within the system itself.

Pump 70 is created within housing 71. A passageway 72 is drilled through this housing 71 and tightly packed with polarisable particles 75 such that every particle is in contact with another particle, thus forming a single polarisable means. This ensures that a single, combined SCR is generated during use. Having multiple layers of polarisable particles 75 increases the electro-osmotic effect up to a certain depth, after which increasing the number of layers will not have any further effect on the generated SCR. Pump 70 has an excess number of layers, meaning that not all of these will further the electro-osmotic effect, however creating the pump 70 on this scale eases production.

The passageway 72 is sealed at each end by porous membranes 76, 77. These can be identical or the membrane which in use will not carry any of the generated SCR can have larger pores in order to reduce the resistance of the pump

70. In an alternative embodiment a grid could be used to seal this end of the passageway.

Spacer layers 78 are coated over the housing 71 and then electrodes 73a, b are attached to the outer side of these layers 78 by any suitable means.

Pump 70 can then be attached to flow channels as required.

Although the above embodiments have used spherical polarisable particles, other polarisable means are also possible. In some cases they also comprise a surface with is curved or inclined to the generated electric field.

FIG 8 shows a pump 80 in which the polarisable means 81 is in the form of a hollow cylinder having a tapering inner surface such that a frustroconical pore 87 is formed. The tapered inner surface provides an inclined surface for producing an SCR. Porous membrane 86 is placed in contact with the polarisable means 81 in order to reduce the effective pore size of the pumping segment and to enhance the electro-osmotic effect.

Alternatively the pore 87 of FIG 8 could be formed by a number of separate polarisable wedge-shaped particles radially spaced about the passageway wall. In such an embodiment each wedge would form a polarisable means.

In other embodiments the polarisable means can be a porous membrane, having pores of a shape similar to polarisable means 81. FIG 9 shows a schematic representation of a suitable pore shape for a polarisable membrane 90. Here, pore 91 comprises a sloped, inclined section 92 and a straight walled section 93. Therefore in this embodiment only a section of the pore wall is inclined with respect to the longitudinal axis of the passageway. Sloped section 92 is pyramidal in shape, while section 93 has a square cross section. The sloping section 92 is thicker then the straight section 93 in order to provide a larger surface for SCR generation. An example of suitable dimensions for the membrane 90 are $l1 = 50\mu m$, $l2 = 1\text{-}2\ \mu m$, $w1 = 5\ \mu m$, $w2 = 5\mu m$. The sloping section 92 can have an inclination of 54.7 degrees, and hence follow the crystal planes of silicon.

Such a membrane 90 could be used, for example, in textiles to provide a water transport function. In such embodiments, in line with the invention, a porous membrane could be placed in contact with one or both sides of the polarisable membrane.

It will be appreciated that the embodiments described above are preferred embodiments only of the invention. Thus various changes could be made to the embodiments shown which would fall within the scope of the invention. For example, although the above embodiments have been described with reference to the use of EO2, these could equally be adapted to provide movement via ICEO or any other form of polarisation electro-osmosis.

Another preferred embodiment is described with reference to Figures 10 and 11. This embodiment is similar to that of Figure 2 except that instead of using spherical polarisable particles it uses a polarisable membrane 27. The pump 20 includes a non-conductive porous membrane 26 positioned across a microchannel 22 such that it contacts the polarisable means, which consists of the polarisable membrane 27. Electrodes 23a, 23b extend into the microchannel 22.

The polarisable membrane 27 comprises straight cylindrical pores 28 which are parallel to the longitudinal axis of the microchannel 22. The polarisable membrane 27 has surfaces 29 in close proximity to the porous membrane 26 and which are perpendicular to the electric field. In fact, the polarisable membrane 27 and the porous membrane 26 are arranged in direct (face to face) contact and are shown slightly separated in Figure 11 for the purposes of illustration only.

The walls of the pores 28 of the membrane 27 are formed by surfaces 29a which are parallel to the direction of the electric field. Therefore, in this embodiment, the polarisable membrane 27 has only surfaces 29 which are substantially perpendicular to the longitudinal direction of the passageway and surfaces 29a which are substantially parallel to the longitudinal direction of the passageway. There are no surfaces which are curved or inclined with respect to the longitudinal direction.

The porous membrane 26 also comprises pores 26a which are parallel to the longitudinal axis of the microchannel 22, but these are narrower than the pores 28.

A charge layer is generated by an electric field on the surfaces 29 which are substantially perpendicular to the longitudinal direction of the passageway and covered by the non-conductive porous membrane 26. The generated charge layer will tend to extend into the pores 26a of the membrane 26 and across the pores 28 of the polarisable membrane 27. The charge induced on the surfaces 29 will overlap and form a continuous space charge region (SCR) extending fully or partly through the thickness of the non-conductive porous membrane 26. As the SCR extends across the pores 28 of the polarisable membrane 27, pressure and flow is generated. Therefore, in this embodiment, the combination of the polarisable membrane and the non-conductive membrane leads to flow under the action of polarisation electro-osmosis, without the polarisation membrane having any surfaces which are inclined or curved with respect to the longitudinal direction of the passageway. The effect provided by the combination of a polarisable membrane and a non-conductive membrane is also obtainable with other embodiments, and is not limited to this particular example.

Claims:

1. A pump for inducing liquid movement by means of polarisation electro-osmosis, comprising

a passageway forming a flow path for fluid transport,

at least one polarisable means located within said passageway so as to form at least one pore through said passageway,

the pump further comprising

a non-conductive porous membrane positioned across the flow path and in close proximity to the at least one polarisable means, the membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the at least one pore formed by the polarisable means, whereby, in use, an electric field generated across the polarisable means in the longitudinal direction of the passageway will cause fluid in the passageway to flow under the action of polarisation electro-osmosis.

2. A pump as claimed in claim 1, wherein the at least one polarisable means is shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the passageway.

3. A pump as claimed in claim 1 or 2, wherein the at least one polarisable means has a portion having a surface in close proximity to the porous membrane and substantially perpendicular to the longitudinal direction of the passageway.

4. A pump as claimed in claim 1, wherein the at least one polarisable means has only surfaces which are substantially perpendicular to the longitudinal direction of the passageway and surfaces which are substantially parallel to the longitudinal direction of the passageway.

5. A pump as claimed in any preceding claim, wherein the membrane comprises uniform pores which are unidirectional.

6. A pump as claimed in any preceding claim, wherein the pores of the membrane are substantially parallel to the longitudinal axis of the passageway.

7. A pump as claimed in any preceding claim, wherein the porous membrane is in direct contact with the at least one polarisable means.

8. A pump as claimed in any preceding claim, wherein the membrane has a pore size of between 30nm and 10 μm.

9. A pump as claimed in claim 8, wherein the membrane has a pore size of between 0.1 and 1 μm.

10. A pump as claimed in any preceding claim, wherein the pores of the porous membrane are at least ten times smaller than the length of the polarisable means when measured in a direction parallel to the longitudinal axis of the passageway.

11. A pump as claimed in any preceding claim, wherein the membrane has a thickness of between 10 and 1000μm

12. A pump as claimed in claim 11, wherein the membrane has a thickness of between 50 and 200μm.

13. A pump as claimed in any preceding claim, wherein the membrane has a surface charge of the same sign as the polarisable means.

14. A pump as claimed in claim 13, wherein the membrane has the same surface groups as the polarisable means.

15. A pump as claimed in any preceding claim, wherein the membrane is made of a hydrophobic polymer.

16. A pump as claimed in claim 15, wherein the membrane has a hydrophilic surface treatment.

17. A pump as claimed in any preceding claim, wherein the polarisable means comprises at least one polarisable particle.

18. A pump as claimed in claim 17, wherein the polarisable means comprising a plurality of adjoining polarisable particles.

19. A pump as claimed in claim 17 or 18, wherein the porous membrane has a pore size at least 10 times smaller than the size of one polarisable particle measured in the longitudinal direction of the passageway.

20. A pump as claimed in claim 17, 18 or 19, wherein the porous membrane has a thickness of between 0.5 and 3 times the size of one polarisable particle measured in the longitudinal direction of the passageway.

21. A pump as claimed in any of claims 1 to 16, wherein the polarisable means comprises a porous membrane.

22. A pump as claimed in any preceding claim, wherein the polarisable means is fixedly located within the passageway between the porous membrane and a porous sealing element having pores which extend in a direction at least partially parallel to the longitudinal axis of the passageway.

23. A pump as claimed in claim 22, wherein the pores of the sealing element are at least 3 times larger than the pores of the porous membrane.

24. A pump as claimed in any of claims 1 to 21, comprising a pair of non-conductive porous membranes, one on each side of the at least one polarising means and each in close proximity to the at least one polarising means.

25. A pump as claimed in any preceding claim, wherein the pump comprises a plurality of polarisable means spaced apart in the longitudinal direction of the passageway.

26. A pump as claimed in claim 25, wherein each polarisable means is in close proximity to a porous membrane comprising pores which extend in a direction at

least partially parallel to the longitudinal axis of the passageway, and having a pore size smaller than the pores formed by the polarisable means.

27. A pump as claimed in claim 26, wherein each polarisable means is further in contact with a porous sealing element on the opposing surface to the porous membrane.

28. A pump as claimed in any preceding claim, wherein the pump further comprises electrodes positioned on either side of the polarisable means in the longitudinal direction of the passageway which, in use, are arranged to generate an electric field across the polarisable means so as to cause fluid to flow under the action of polarisation electro-osmosis.

29. A pump as claimed in claim 28, wherein a spacer layer is provided between the porous membrane and the electrodes.

30. A pump as claimed in claim 29, wherein the spacer layer is in the form of an ion exchange membrane.

31. A pump as claimed in claim 28, wherein at least one of the electrodes is in direct contact with the porous membrane.

32. A pump as claimed in any preceding claim, wherein the polarisable means is a conducting means.

33. A pump as claimed in any preceding claim, wherein the pump is arranged to induce liquid movement by electro-osmosis of the second kind.

34. A pump as claimed in claim 33, wherein the polarisable means is unipolar ionic conductor.

35. A pump as claimed in claim 1, wherein the passageway comprises a through hole within a housing, and the polarisable means comprises a plurality of adjoining

polarisable particles packed within the through hole between said porous membrane and a porous sealing element.

36 A pump as claimed in claim 35, wherein the sealing element is a second porous membrane.

37. A microfluidic system comprising a pump as claimed in any of claims 1 to 36.

38. A microfluidic system comprising:

a microchannel;

electrodes positioned within said microchannel, defining between them a pumping segment;

at least one polarisable means located within said pumping segment as so to form at least one pore through said pumping segment;

a non-conductive porous membrane positioned across the pumping segment and in close proximity to the at least one polarisable means, the membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the pumping segment and having a pore size smaller than the at least one pore formed by the polarisable means; and

the pumping segment being arranged such that, in use, the electrodes generate an electric field across the polarisable means so as to cause fluid in the microchannel to flow under the action of polarisation electro-osmosis.

39. A microfluidic system as claimed in claim 38, wherein the at least one polarisable means is shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the pumping segment.

40. A pump for inducing liquid movement by means of polarisation electro-osmosis, comprising:

a housing containing a through hole therein, said through hole forming a passageway;

porous sealing elements sealing at least a section of the through hole;

a plurality of adjoining polarisable particles packed between said sealing elements, the polarisable particles creating pores through said passageway;

wherein one of said sealing elements comprises a non-conductive porous membrane comprising pores extending in a direction at least partially parallel to the longitudinal axis of the passageway and having a pore size smaller than the pores created by the polarisable particles.

41. A pump as claimed in claim 38, wherein the polarisable particles are shaped such that at least a section of the pore walls are curved or inclined with respect to the longitudinal axis of the through hole.

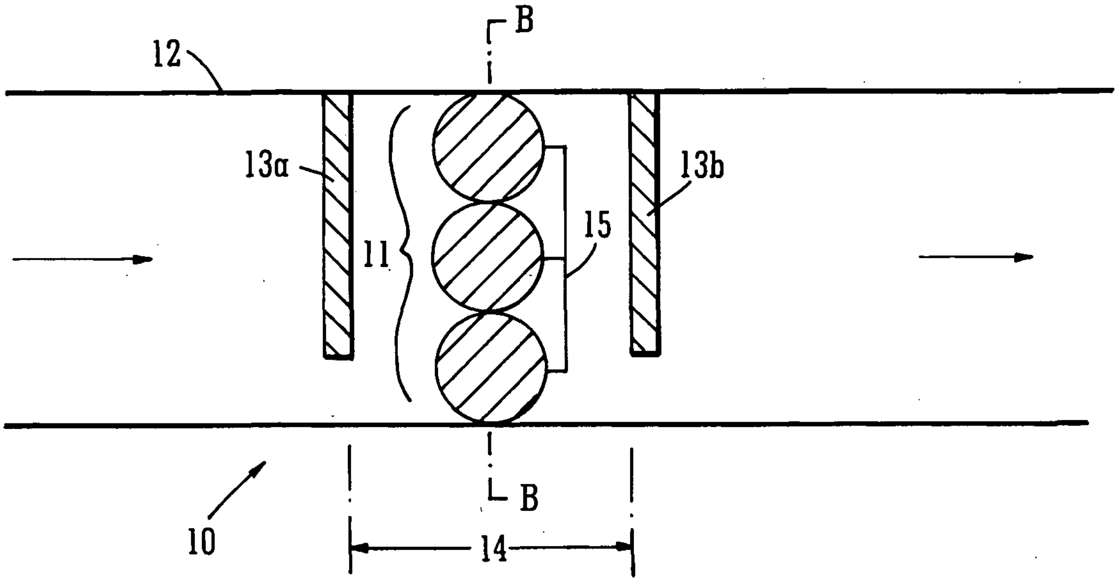


FIG. 1A

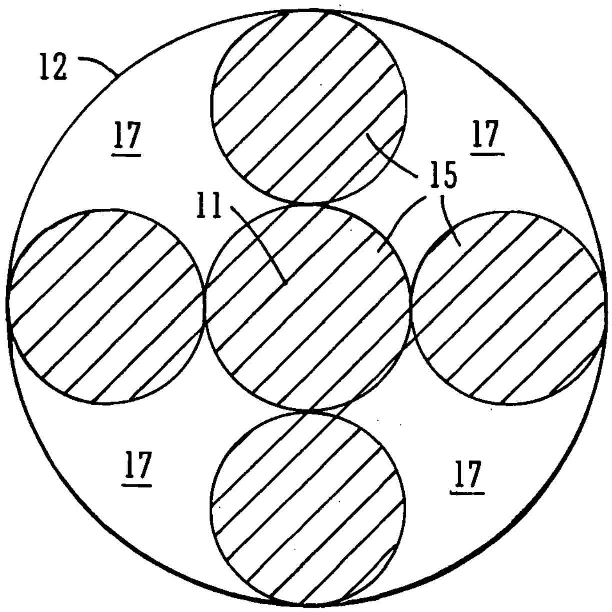


FIG. 1B

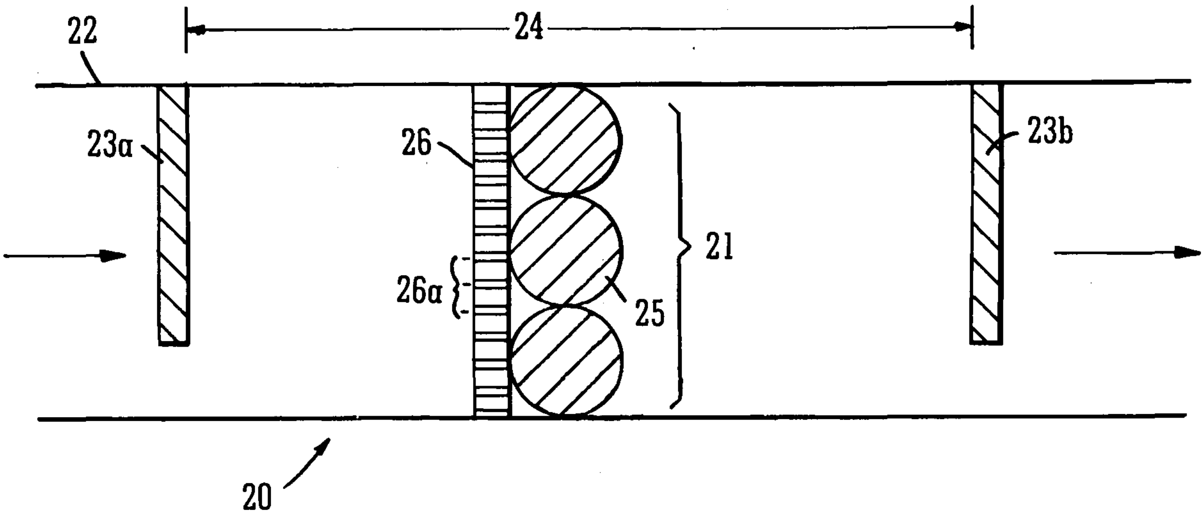


FIG. 2A

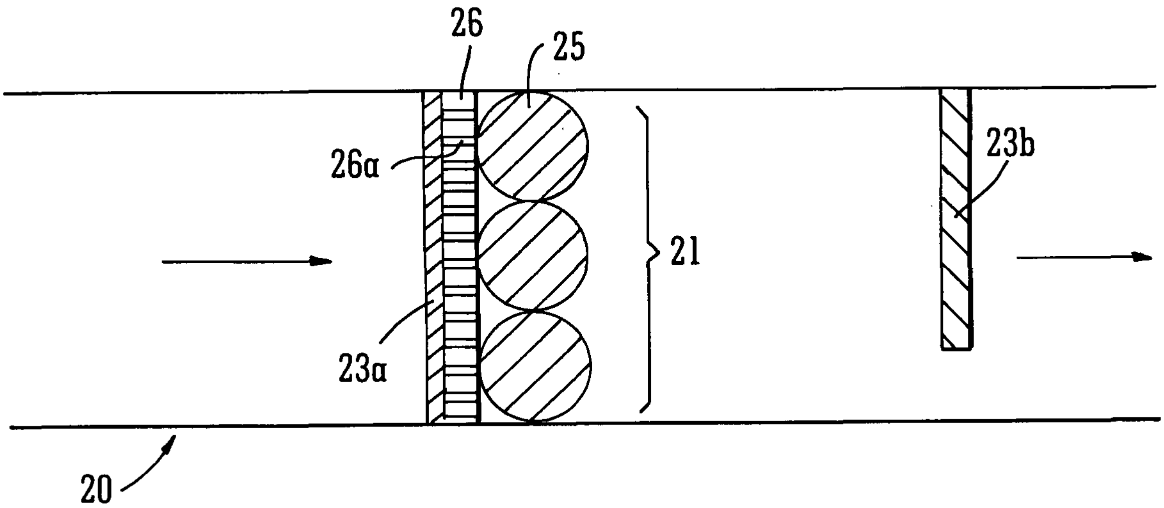


FIG. 2B

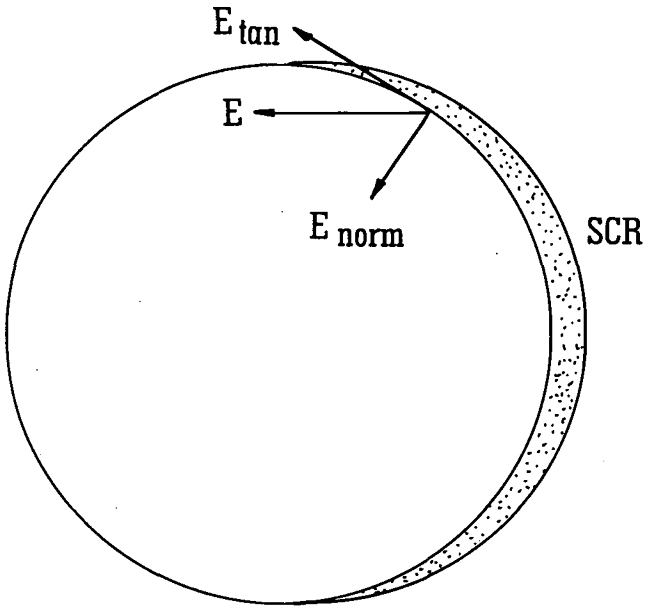


FIG. 3A

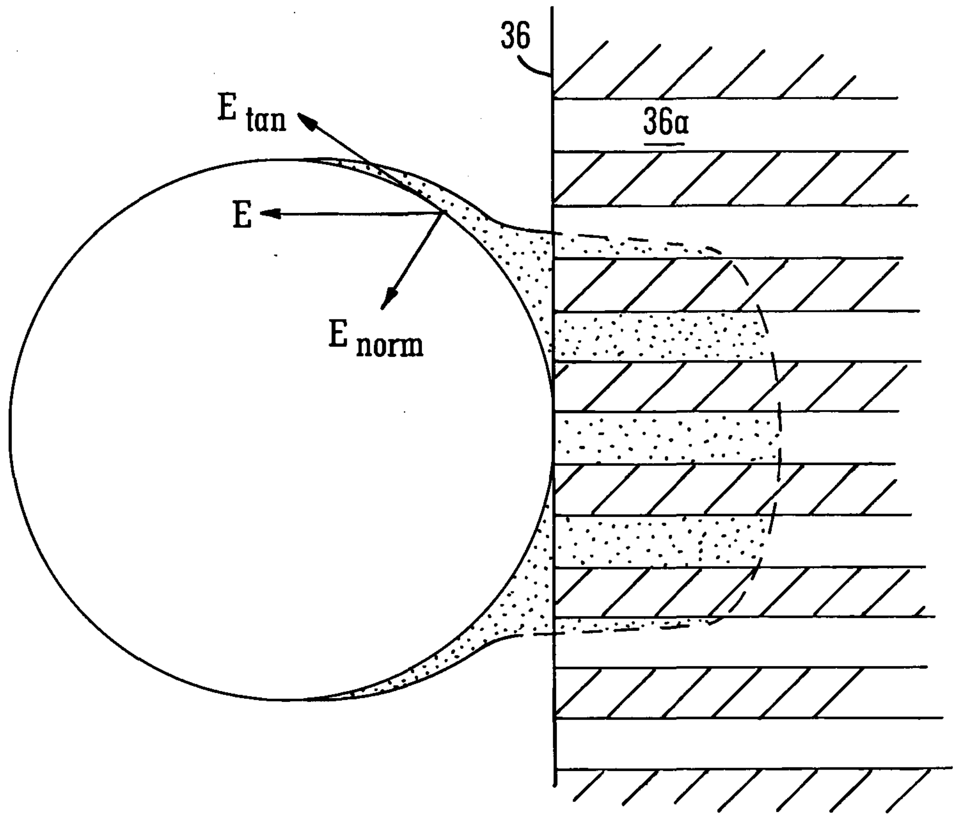


FIG. 3B

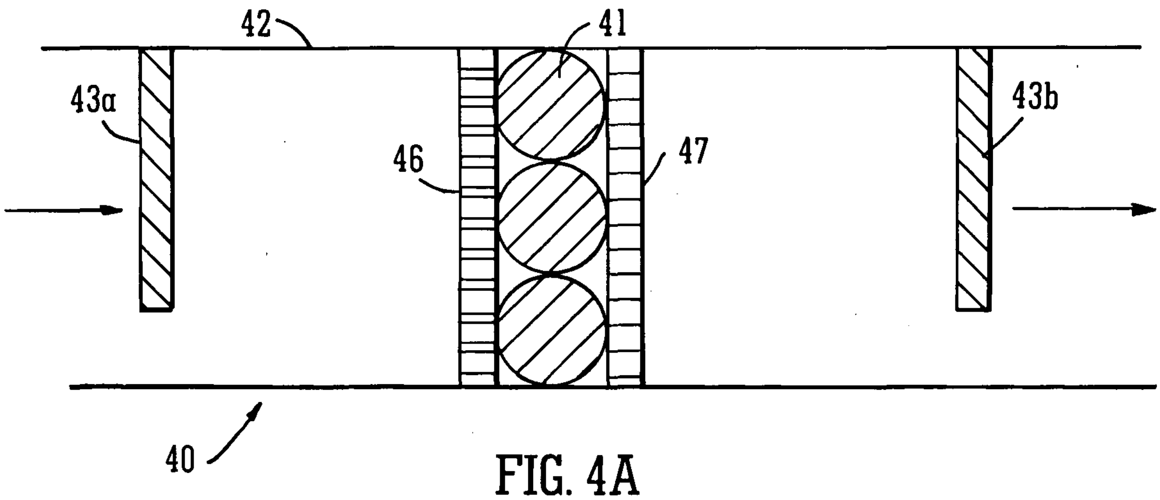


FIG. 4A

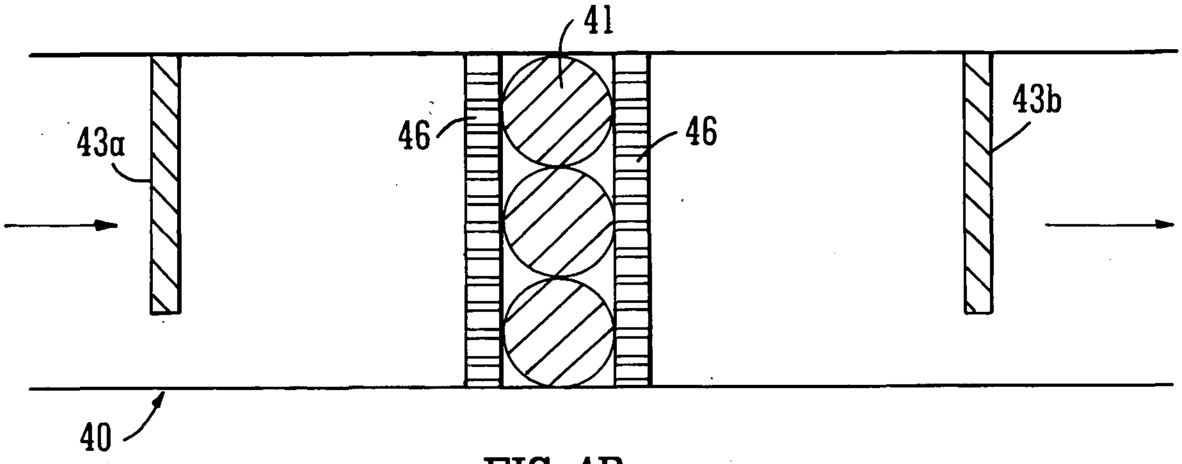


FIG. 4B

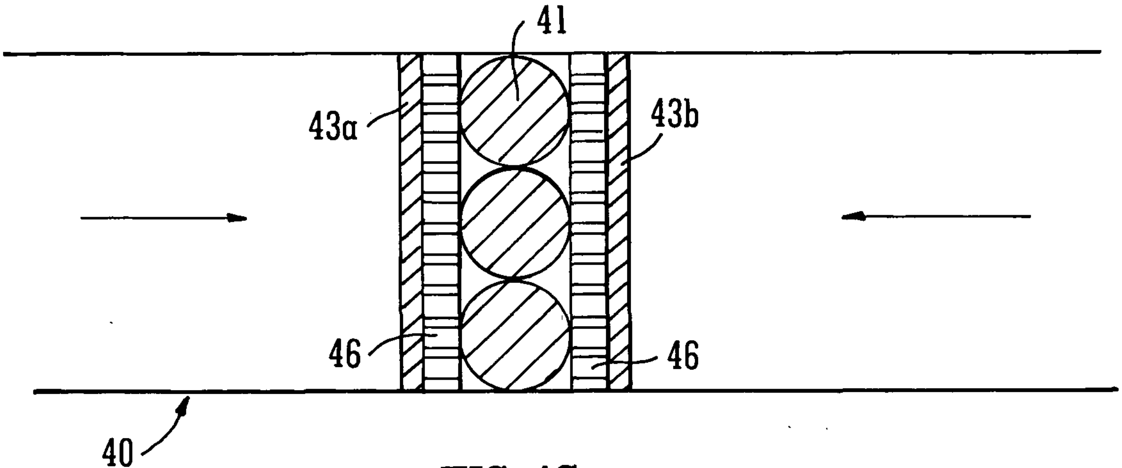
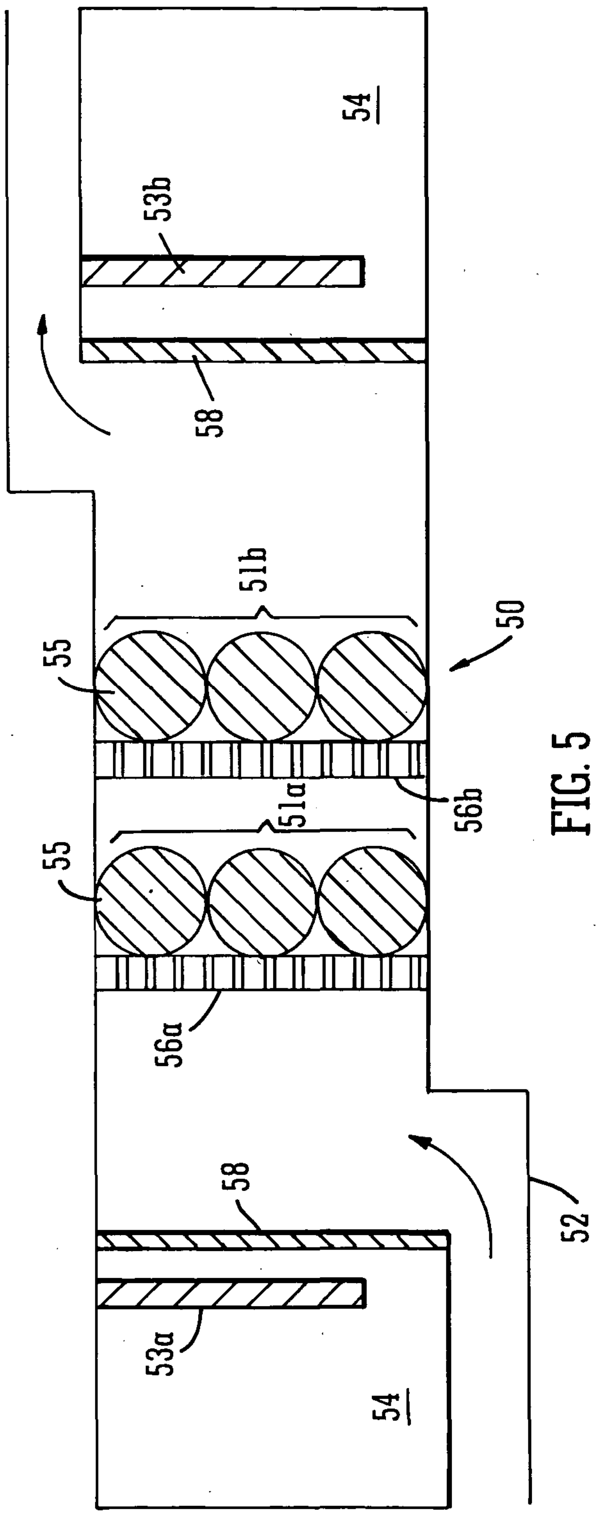


FIG. 4C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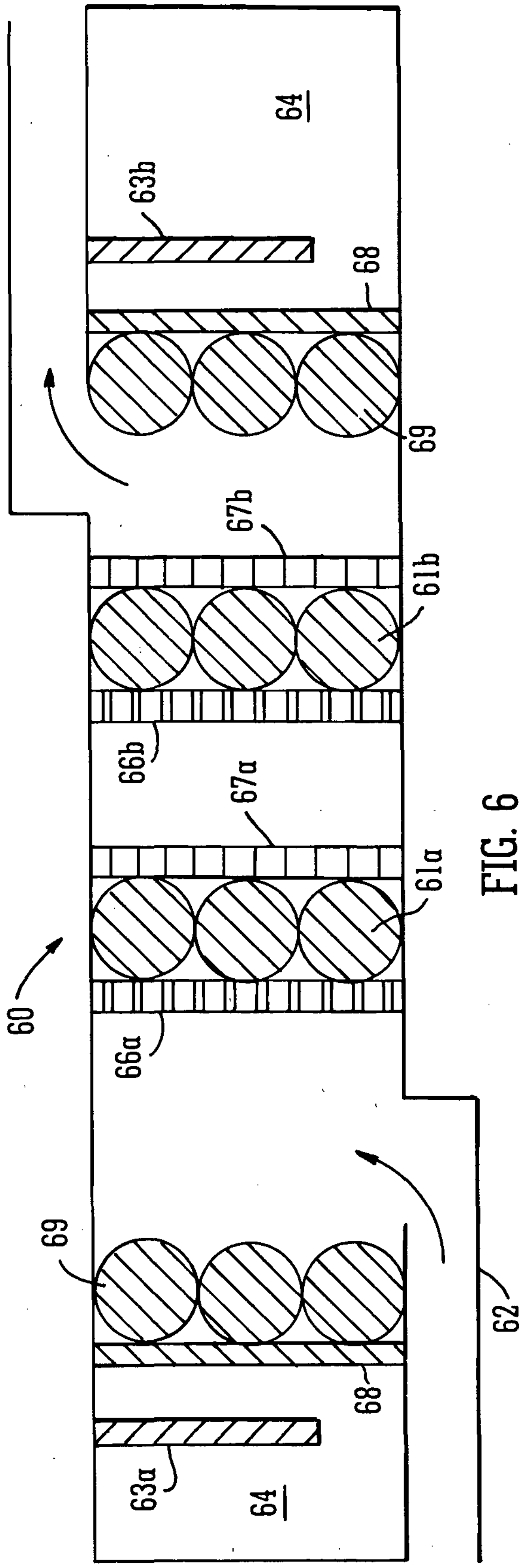
53a
54

FIG. 5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66a
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62
68
63a
64

FIG. 6

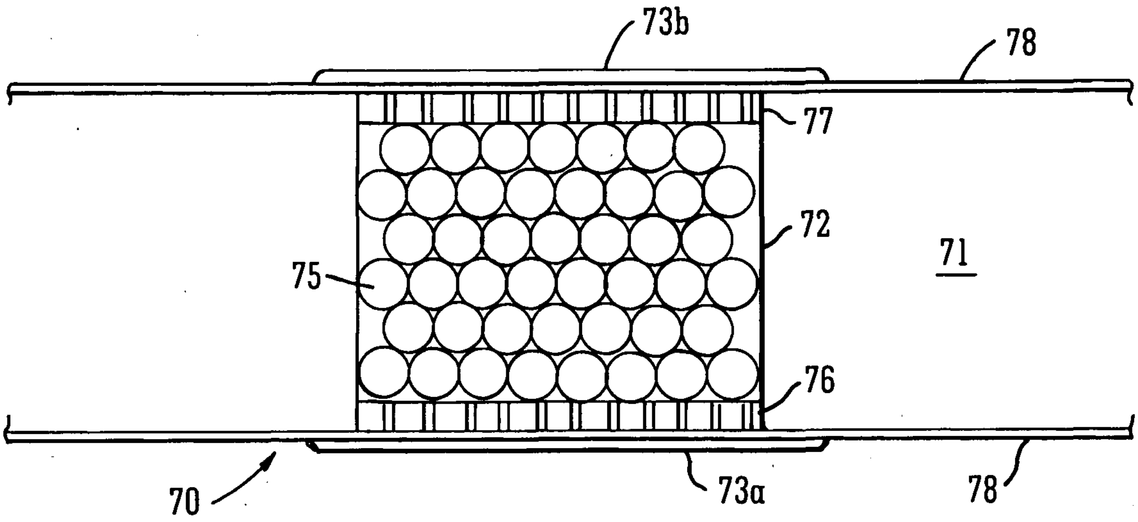

FIG. 7

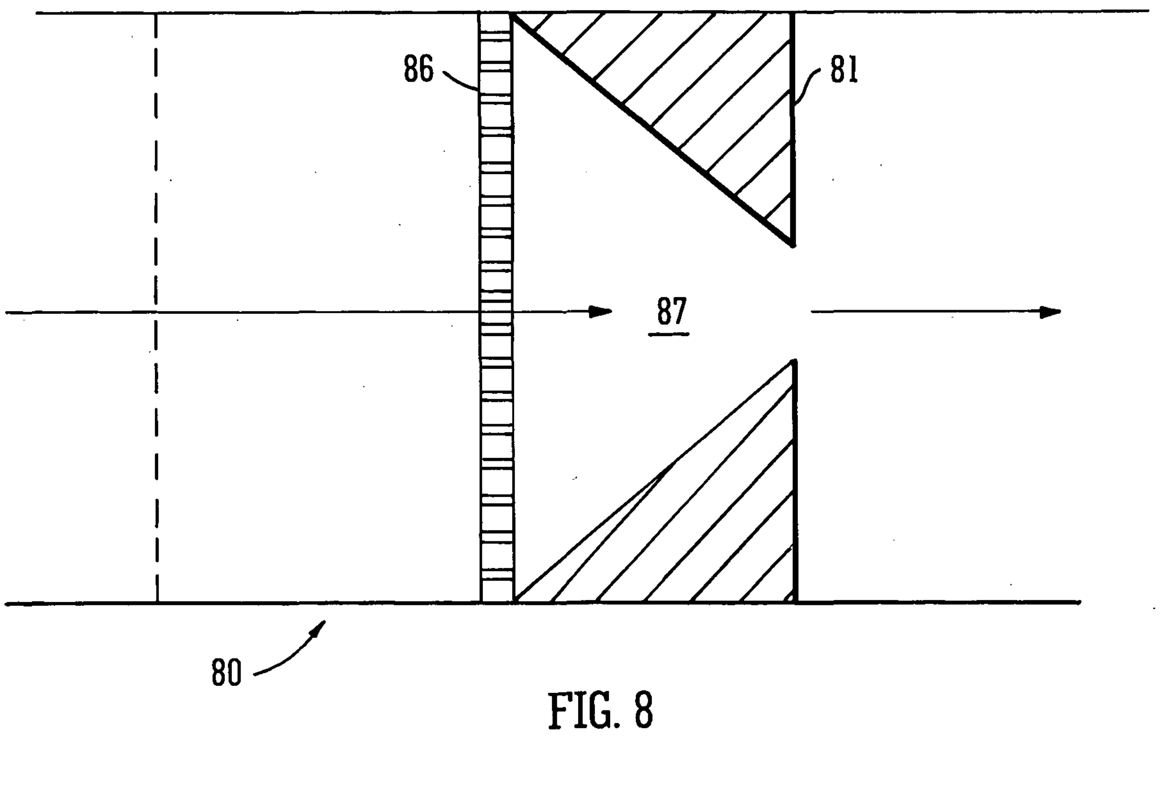

FIG. 8

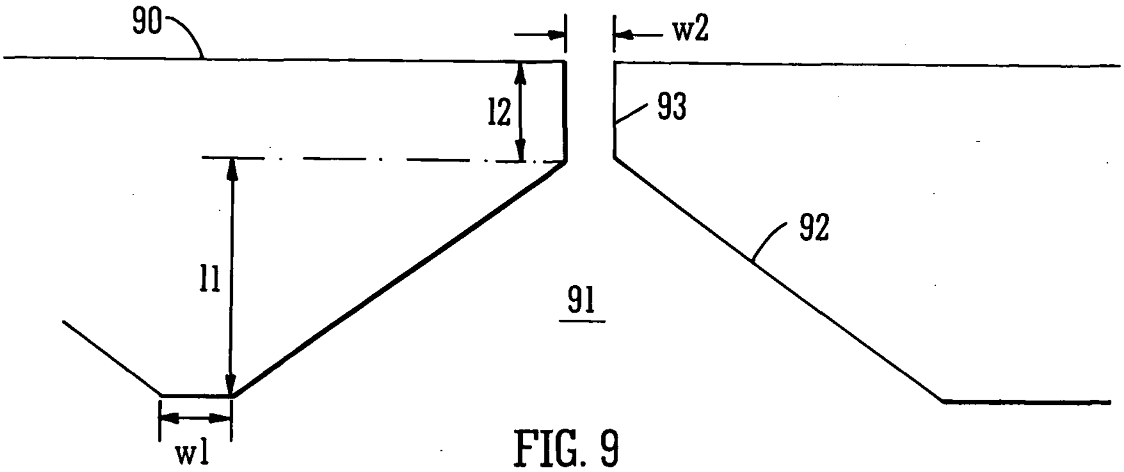

FIG. 9

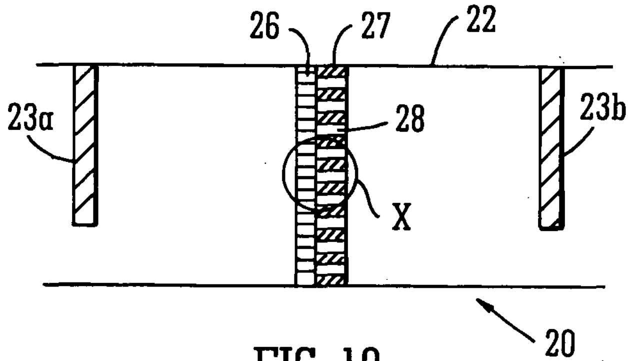

FIG. 10

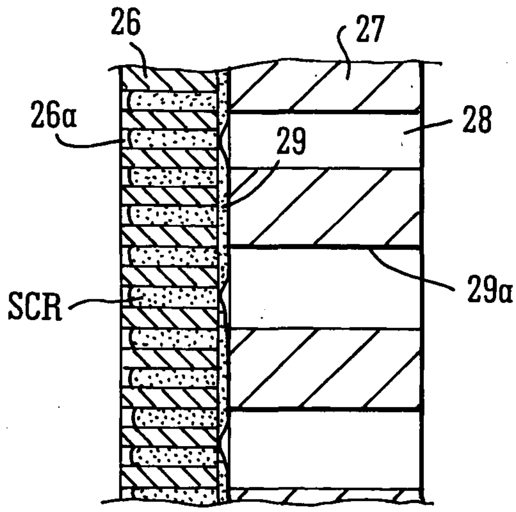

FIG. 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2009/000355

A. CLASSIFICATION OF SUBJECT MATTER
INV. F04B19/00 F04B43/04 B01D61/56

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 2004/007348 A (OSMOTEX AS [NO]) 22 January 2004 (2004-01-22) cited in the application page 1, line 5 - page 3, line 7 page 11, line 17 - page 12, line 28; claim 1 figures 4-11	1-41
A	US 2003/164296 A1 (SQUIRES TODD, M.; ET AL. [US]) 4 September 2003 (2003-09-04) paragraph [0002] - paragraph [0012] paragraph [0031] - paragraph [0040] figures 3,4	1-41

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 April 2009	07/05/2009

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Gnüchtel, Frank

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2003/062149 A1 (GOODSON KENNETH, E.; ET AL. [US]) 3 April 2003 (2003-04-03) paragraph [0135] - paragraph [0144] paragraph [0173] - paragraph [0178] claims 69-72 figures 11,15 -----	1-41
A	US 2006/275138 A1 (HONG KONG UNIV. OF SCIENCE AND TECHNOLOGY[CN] ET AL) 7 December 2006 (2006-12-07) paragraph [0001] - paragraph [0008] paragraph [0013] - paragraph [0016] paragraph [0026] - paragraph [0032] figure 1 -----	1-41
A	WO 2007/092253 A (MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US]) 16 August 2007 (2007-08-16) paragraph [0077] paragraph [0283] figures 19-21 -----	1-41
A	URBANSKI, J.P.; THORSEN, T.; LEVITAN, J.A.; BAZANT, M.Z.: "Fast AC electro-osmotic micropumps with nanoplanar electrodes" APPLIED PHYSICS LETTERS, vol. 89, 3 October 2006 (2006-10-03), pages 143508-1-143508-3, XP002524296 the whole document -----	1-41

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2009/000355

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			CA	2489437	A1	22-01-2004
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