LOW POWER ELECTROMAGNETIC PUMP

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ABSTRACT

An electromagnetic pump comprising an armature comprising a pole portion and plunger portion, the plunger portion sized to be received in a cylindrical passage formed in the housing and which guides the armature. The pump further comprises an electromagnet operatively associated with the armature, and the pump is driven during a forward pumping stroke by the partial discharge of a capacitor into the electromagnet. The case of the electromagnet is sized such that a ratio of the case diameter to the core diameter and a ratio of the case length to the case diameter provide for improved electromagnetic efficiency.
LOW POWER ELECTROMAGNETIC PUMP

FIELD OF THE INVENTION

[0001] The present invention relates to the field of electromagnetic pumps, and further relates to the use of low power electromagnetic pumps for use in implantable medical device applications.

BACKGROUND

[0002] Presently, small electromagnetic pumps are used for pumping liquids such as medicines, drugs, insulin, chemotherapy liquids, and other life critical drugs to a patient. These pumps are sometimes required to be quite small given the fact that they oftentimes will be implanted into the patient’s body. If the pump is implanted, it is desirable that it have a low power requirement so that the battery which powers the electromagnetic pump has a long life.

[0003] There exists a need for a low power electromagnetic pump to satisfy the various requirements. These requirements include a simpler construction to reduce costs, increased energy efficiency to increase the life of an implanted device, efficient operation of the pump at battery voltage, efficient operation at variable voltage as the battery is depleted, reduced MRI signature, and improved tolerance to bubbles in the flow. Also, the safety and accuracy of the pump should not be compromised.

[0004] Other requirements are that the pump have a simplified structure and method of assembly while simultaneously having improved performance. More requirements are that the pump operate in a manner preventing damage to fragile drugs, such as insulin, and that moving parts of the pump be resistant to wear, thus prolonging the useful working life of the pump.

[0005] It would therefore be desirable to provide a simpler electromagnetically operated pump that can be produced at reduced costs, which has increased energy efficiency to increase the life of an implanted device, which is safe, which operates efficiently at battery voltage, which operates efficiently at variable voltage as the battery is depleted, has a reduced MRI signature, and that has improved capability to pump bubbles in the flow. It would also be desirable for the pump to be compatible with drugs, such as insulin, or other liquids to be pumped, and to have a relatively simple structure and method of assembly, along with improved performance. It would be desirable if the pump could operate in a manner that prevents damage to fragile drugs being pumped, such as insulin, while at the same time resists the detrimental effects of the drugs, insulin, or other fluids being pumped. It would also be desirable for the pump to have wear resistant moving parts.

SUMMARY

[0006] The low power electromagnetic pump operates at an extremely low power, and it may be used in implantable drug delivery systems, although the principles of this invention can be variously applied. For example, the low power electromagnetic pump may be employed in applications external to a patient’s body.

[0007] The present invention provides an electromagnetic pump comprising a housing having an interior fluid containing region including a fluid receiving chamber in fluid communication with an inlet tube, a fluid output chamber in fluid communication with an outlet tube, and a check valve operatively associated with the fluid containing region for allowing fluid flow in a direction from the inlet tube toward the outlet tube and blocking fluid flow in a direction from the outlet tube to the inlet tube. An electromagnet is carried by the housing and located external to the fluid containing region, and a barrier of fluid impervious material isolates the electromagnet from the fluid chambers of the pump. An armature is positioned in the fluid containing region of the housing and comprises a pole portion located for magnetic attraction by the electromagnet, and the armature has a plunger portion extending from the pole portion. The armature is supported in the housing for movement from a rest position through a forward pumping stroke when attracted by the energized electromagnet to force fluid from the outlet chamber through the outlet tube, and for movement in an opposite direction through a return stroke back to the rest position when the electromagnet is de-energized.

[0008] A retainer element can be joined to the armature, and a main spring can be captured between the retainer element and a retainer plate. The main spring is for providing a biasing force during the return stroke. Guiding of the armature as it reciprocates is provided by the cooperation between the plunger portion and the adjacent housing of the pump, which is formed as a surrounding wall or cylinder in the pump housing.

[0009] The pump can be used for delivering an infusion medium to a patient. The pump also has an interior fluid containing region, and the inlet and outlet tubes are in fluid communication with that region. The electromagnet is located external to that fluid containing region of the housing, and is separated from the fluid containing region of the housing by a barrier. There is a gap in the fluid containing region of the housing between the pole portion and the electromagnet. The pole portion is located for magnetic attraction by the electromagnet, which results in movement of the armature to force fluid out of said region through said outlet.

[0010] The electromagnet can comprise a case and a core or coil spindle positioned inside the case. The case and core comprise a magnetic material. The case has a thickness, a length, and a diameter, and the core has a diameter and a length. The case surrounds the coil and core, the case being spaced from the coil so as to be in insulated relation to the coil for example by encapsulant material such as potting compound or epoxy. The ratio of the case diameter to the core diameter is in a range from about 2.5 to about 7, and the ratio of the case length to the case diameter is in a range from about 1.3 to about 2.3. Also, the case diameter can be less than about 0.28 inches so that the pump can be installed in an implantable drug delivery system.

[0011] The housing has a pump chamber which has a volume defined by a region within the housing surface bounded by the check valve, an axial end face of the plunger portion, and a bypass check valve. Also, a ratio of the volume of the pump chamber to a stroke volume is less than about 0.9 so as to enable the pump to move a liquid containing gas bubbles having a volume up to about 300 microliters against a pressure increase of at least five pounds per square inch.

[0012] The delivered stroke volume of the pump is between about 0.1 microliters to about 0.35 microliters. Also, the voltage supplied to the coil to energize the electromagnet ranges between about 1.5 volts to about 6.0 volts.
In one of the preferred embodiments, the voltage supplied to the coil is terminated at time intervals ranging between about 1 millisecond to about 6 milliseconds. This time range can longer or shorter in other embodiments.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0013] At the outset, it noted that like reference numbers are intended to identify the same structure, portions, or surfaces consistently throughout the figures.

[0014] FIG. 1 is a longitudinal sectional view of the pump according to a preferred embodiment of the invention.

[0015] FIG. 2 is a diagrammatic view of the pump at rest with gap exaggerated.

[0016] FIG. 3 is a diagrammatic view of the pump showing one stage of the forward stroke.

[0017] FIG. 4 is a diagrammatic view of the pump showing a more forward stroke than FIG. 3.

[0018] FIG. 5 is a diagrammatic view of the pump showing the return stroke.

[0019] FIG. 6 is a schematic of the circuitry of the electromagnetic pump.

[0020] FIG. 7 is a graph further illustrating operation of the electromagnetic pump.

[0021] FIG. 8 is an enlarged fragmentary sectional view further illustrating the main check valve of the electromagnetic pump.

**DETAILED DESCRIPTION OF THE INVENTION**

[0022] The present invention is for a low power electromagnetic pump of the type shown in, for example, U.S. Pat. Nos. 6,227,818 to Falk et al. for a Low Power Electromagnetic Pump issued May 8, 2001; and 6,264,439 to Falk et al. for a Low Power Electromagnetic Pump issued Jul. 24, 2001, the disclosures of which are hereby incorporated herein by reference.

[0023] FIG. 1 shows a longitudinal sectional view of the pump 10. The pump 10 comprises a body or housing 32 which may be embodied to have a cylindrical shape. The housing 32 is generally hollow and has a fluid receiving chamber 15 at its inlet 19 that is in fluid communication with an inlet tube 14. The housing 32 also has a fluid output chamber 17 at its outlet 21 that is in fluid communication with an outlet tube 20, and the fluid receiving and output chambers 15, 17, respectively, are in fluid communication with one another, as will be described presently. There is also provided a check valve 24 positioned in the pump 10. The check valve 24 is operatively associated with the fluid containing region of the pump 10 for allowing fluid flow in a direction from the inlet tube 14 through outlet tube 20, and blocking fluid flow in a direction from the outlet tube 20 through the inlet tube 14.

[0024] In the fluid circuit in which the pump 10 is employed, fluid (for example insulin, drugs, medications, chemotherapy drugs, and life critical drugs) enters the inlet tube 14, is moved through the pump 10, and exits the pump 10 through the outlet tube 20. FIG. 1 shows the pump 10 at rest, and the pumping cycle will be described in greater detail presently.

[0025] The inlet tube 14 receives incoming drugs, medicines, insulin, and other fluids to be moved by the pump 10. The pump 10 contains an armature 45 having a plunger portion 49. The inlet tube 14 is in fluid communication with and leads to a pump chamber 122 defined in the housing 32, that is the volume bounded by the inlet check valve 24, a bypass check valve 74, and an axial end face 53 of the plunger portion 49. An armature shaft chamber 124 is defined in the housing 32, and it is sized to accommodate the pump armature 45 therein. The armature shaft chamber 124 leads to and is in fluid communication with a main spring retainer chamber 126 having a diameter greater than the diameter of the armature shaft chamber 124. The main spring retainer chamber 126 is in fluid flow communication with and leads to a pole button chamber 128 having a diameter greater than the diameter the main spring retainer chamber 126. The pole button chamber 128 is in fluid flow communication with and leads to a flow passage 130, which is in fluid communication with the fluid output chamber 17.

Thus, an armature chamber 132 can be viewed as a combination of the armature shaft chamber 124, the main spring retainer chamber 126, and the pole button chamber 128. The armature chamber 132 is sized such that the pump armature 45 can be positioned therein.

[0026] The housing 32 further defines, between the armature shaft chamber 124 and pole button chamber 128, a fluid bypass chamber 136. A passage or orifice 44 defined in the housing 32 leads from the armature shaft chamber 124 to a plug chamber 134. The orifice 44 provides for fluid communication between the armature shaft chamber 124 and the plug chamber 134.

The orifice 44 may be of relatively small diameter made by drilling and the like. The plug chamber 134 leads to and is in fluid flow communication with bypass chamber 136. The bypass chamber 136 is in fluid flow communication with the pole button chamber 128. These chambers thus provide for a bypass path or passage in the pump 10.

[0027] The seat ferrule 56 shown in FIG. 1 is mounted to the housing 32 and joins to the inlet tube 14. It is noted that upstream of the seat ferrule 56 there is a reservoir of fluid to be pumped (not shown in the figures).

[0028] The pump armature 45 is located in the fluid containing region defined in the housing 32. The armature comprises a pole portion 48 located for magnetic attraction by the electromagnet 100. The plunger portion 49 is joined to and extends from the pole portion 48. The armature pole portion 48 is located for movement within the pole button chamber 128 as shown in FIG. 1. The armature 45 is movably supported in housing 32 for movement from a rest position through a forward pumping stroke when attracted by the electromagnet 100 to force fluid out through outlet 21, and for movement in an opposite direction through a return stroke back to the rest position. In FIG. 1, armature 45 is shown at rest.

[0029] Armature pole portion 48, which occupies a major portion of the pole button chamber 128 in which it is positioned, is in the general form of a disc. It has a lateral dimension as viewed in FIG. 1 which is several times greater than the longitudinal dimension thereof. Pole portion 48 comprises a solid, monolithic body of magnetic material having a first axial end face 50 that faces toward barrier or plate 51 and a second, opposite axial end face 52 that faces toward inlet tube 14.

Thus, the first and second axial end faces 50, 52, respectively, of the pole portion 48 are disposed substantially perpendicular to the direction of travel of armature 45, as shown.

[0030] In a preferred embodiment, the pole portion 48 comprises a magnetic material, such as a heat treated
chrome-molybdenum-iron alloy. Examples include 29-4 and 29-4C chrome-molybdenum iron alloy. These alloys have high corrosion resistance, and have adequate magnetic characteristics for use in the pump 10 when heat treated. The alloy is heat treated to provide it with a BH characteristic that yields the requisite level of magnetic flux density and a relatively low level of coercive force, wherein B is the flux density and H is the magnetic field. BH characteristics are well known to those having ordinary skill in the art. In addition, the alloy is sufficiently resistant to corrosive effects of insulin stabilized for use in implantable drug delivery systems and does not harm the insulin or other drug to be used in the system.

[0031] Thus, the armature pole portion 48 terminates at the first end face 50 and serves as a pole face that faces the electromagnet 100. The armature end face 50 together with electromagnet 100 define the magnetic circuit gap which is closed during the forward stroke of the armature 45. The first end face 50 is of a relatively large cross-sectional area as compared to the cross sectional area of the armature plunger portion 49.

[0032] The plunger portion 49 of the armature 45 is movably positioned within the interior region of housing portion 32 and extends axially from armature pole portion 48 in a direction toward the inlet tube 14. Plunger portion 49 is substantially cylindrically in shape having an outer diameter slightly less than the diameter of the interior passage in the housing 32 to allow reciprocal movement of plunger 49 within housing portion 32 during the forward and return strokes of armature 45. The plunger portion 49 terminates in an axial end face 53 that faces in a direction toward the tube 14.

[0033] The armature pole portion 48 and plunger portion 49 are joined together in the following manner. Plunger portion 49 has an enlarged, generally cylindrical formation 54 on the end adjacent pole portion 48 and which formation 54 has a diameter slightly greater than that of plunger portion 49. At the end of formation 54 adjacent pole portion 48 there is provided an annular head or enlargement 55. The second axial end face 52 of pole portion 48 is provided with a recess 57 bordered by an annular peripheral flange 58. The recess 57 is of a diameter sized to receive the outer end of the annular head or enlargement 55, and the recess 57 is surrounded by a flange 58. The flange 58 is sized such that it can be crimped onto and over formation annular head or enlargement 55, as shown in FIG. 1, thereby securely joining the armature plunger portion 49 and the armature pole portion 48.

[0034] The main check valve 24 is shown in FIG. 1, positioned at the end of the armature shaft chamber 124. In a manner to be described presently, the main check valve means 24 allows fluid from an upstream location, for example a reservoir, to enter the pump 10 when it is activated (the forward stroke of the pump 10). The check valve 24 comprises a retainer 29 joined to a check valve element 27. A weak check valve spring 25, as compared to a main spring 90 to be described presently, biases against the retainer 29 and the ferrule 56 to keep the check valve 24 closed, such that the check valve element 27 is biased into the valve seat 30. During a forward pumping stroke, to be described presently, the check valve 24 opens allowing fluid from an upstream location, such as a reservoir, to enter the pump 10 through the inlet tube 14. Before the electromagnet 100 is activated, the pump 10 is in the deactivated state, shown in FIGS. 1 and 2. When the pump 10 activates, the pump armature 45 is drawn to the electromagnet 100 as will be described in connection with FIG. 2 (this shows the forward stroke of the pump 10). The electromagnet 100 is isolated from the fluid being pumped by the barrier or plate 51. The plate 51 may be embodied as a thin plate-like diaphragm. The plate 51 prevents fluids being pumped from contacting the parts and components of the electromagnet 100, or in other words, provides a fluid seal between the electromagnet 100 and the pump interior. The electromagnet 100 serves to cyclically generate an electromagnetic field and is used to pull the armature 45 towards it when it is activated, which draws fluid into the pump 10. When the electromagnet 100 is deactivated, the armature 45 returns to its at rest state (FIG. 1). The check valve 24 is closed shortly after the armature 45 contacts plate 51. Thus, the check valve 24 prevents backflow out of the pump 10.

[0035] FIG. 1 also shows a retainer element 59. The retainer element 59 comprises an annular body 60 having a lip portion 61 that extends about its periphery. The retainer element 59 also defines a central opening or bore (not shown) into which the cylindrical formation 54 of the armature 45 is positioned. The retainer element 59 is joined to the cylindrical formation 54 by welding, laser welding, friction fit, or combinations thereof.

[0036] FIG. 1 also shows a retainer plate 80, which defines a bypass fluid chamber opening 82, an outlet opening 84, and a central opening 86. The central opening 86 is sized to receive a crimped flange 58 that surrounds the annular enlarged head 55. The retainer plate 80 also comprises an annular retainer plate flange 88 surrounding the central opening 86. There is provided a main spring 90. When the pump is assembled, as shown in FIG. 1, a first end 91 of the main spring 90 abuts the lip portion 61 of the retainer element 59, and the second end 92 of the main spring 90 abuts against the annular flange 88 of the retainer plate 80.

[0037] Also shown in FIG. 1, is the outer weld ring 94 of the pump 10. The outer weld ring 94 comprises an annular support protrusion or lip 95. The support protrusion 95 contacts a peripheral edge of the retainer plate 80. The retainer plate 80 is thus positioned between the housing 32 and the support protrusion 95, and becomes trapped therebetween upon welding or joining the outer weld ring 94 and the housing 32. This prevents movement of the retainer plate 80 as the pump 10 cycles. Due to this configuration, the retainer plate 80 itself need not be welded.

[0038] The electromagnet 100 comprises a case 101. A second weld ring 112 is provided on the case 101 adjacent the pump housing 32. The outer diameter of the second weld ring 112 is substantially equal to the outer diameter of the outer weld ring 94, such that the respective outer surfaces are substantially flush. The pump housing 32 and electromagnet case are placed in abutting relation on opposite sides of the barrier 51. The assembly is secured together by a weld joining the respective outer surfaces of the outer weld rings 94 and second weld ring 112.

[0039] As further shown in FIG. 1, the electromagnet case 101 houses a coil spindle or core 102. The case 101 and core 102 are made from a magnetic material. The case has a first case end 106 and a second case end 108. The first case end 106 is joined to the pump housing 32 as described above, such that the core 102 is separated from the fluid containing region of the pump housing 32 by the barrier 51.
A coil 104 comprising a wire or conductor is wound around the coil spindle or core 102. A locator 105 is provided and it is joined to the core 102 adjacent the first case end 106. A washer 107, also of magnetic material, is provided and it is joined to the other end of the core 102 adjacent the second case end 108. A locator 105 is provided, and one of the purposes of the locator 105 and washer 107 is to center the core 102 within the case 101 during the potting process that is used to form the electromagnet 100.

During this potting process potting compound, encapsulant material, or epoxy 109 is introduced into the case 101. The potting compound flows between the case 101 and coil 104, between the core 102 and coil 104, and between the conductors that make up the coil 104. Potting compound 109 is well known to those having ordinary skill in the art. After curing, the potting compound joins the coil 104 to the case 101, the coil 104 to the core 102, and the conductors of the coil 104 to one another. The cured potting compound 109 thus insulates and stabilizes the internal components of the electromagnet 100. In particular, potting compound 109 located between coil 104 and case 101 serves to space coil 104 from case 101 in an insulated manner. Such insulated spacing of case 101 from coil 104 can be accomplished by other means such as insulated spacer components positioned between coil 104 and case 101 or by having washers like washer 107 at each end of the assembly and provided with inwardly extending annular flanges positioned to space and support coil 104 and case 101 relative to each other.

In addition, a body of potting compound or a potting cap 110 can be joined to a second end 108 of the electromagnet 100. A pair of terminals 111 extends from the second end 108 of the electromagnet 100, and each of the terminals is surrounded by and insulated by the potting cap 110. As shown, a conductor 114 is joined to each of the pair of terminals 111. The conductors 114 lead to a battery powered charging circuit 115 which is depicted in FIG. 1 as a box, and is shown in greater detail in FIG. 6. The battery powered circuit 115 delivers pulses of energy to the pump in a manner to be described presently.

The pulses of energy energize the electromagnet pump 100, and this causes the pole portion 48 of the armature 45 to be drawn towards the electromagnet 100, as shown in FIGS. 3 and 4. When the pole portion 48 is so attracted, the armature 45 compresses the main spring 90 as it moves towards the electromagnet 100. At substantially the same time fluid is drawn into the pump 10. When the electromagnet 100 is de-energized, the main spring 90 expands, as shown in FIG. 5, and applies force on the retainer element 59, which moves the armature 45 back to its rest position in the pump 10 shown in FIG. 1.

Also, the efficiency of the pump 10 is increased by the electromagnet 100 and the magnetic components that make up the magnetic circuit, reducing the degree of saturation of the magnetic circuit at peak coil current. This is done by reducing the diameter, designated S in FIG. 1, of the core 102, to thus reduce the resistance of each coil turn, by increasing the clearance or distance, designated E in FIG. 1, between the coil case 101 and the core 102, to reduce the leakage of flux, and by shortening the length, designated C in FIG. 1, of the coil 104 which further reduces flux leakage. In addition to improving the efficiency of the coil 104 at constant current, these above-described features also reduce the inductance of the coil 104, which reduces the current rise time and the energy consumed by the coil 104 during the period when the magnetic force is too low to move the plunger portion 49.

Calculations have shown that for one of the preferred embodiments of the pump 10 configuration, the coil 104 length, designated C in FIG. 1, is about 0.35 inches, the coil spindle or core 102 diameter designated S is about 0.08 inches, and the coil case 104 thickness designated T is about 0.013 inches.

In another preferred embodiment, the case diameter CD is less than about 0.28 inches so that the pump can be installed in, for example, an implantable drug delivery system.

In all embodiments, the ratio of the case diameter, designated CD in FIG. 1, to the core diameter S is in a range from about 2.5 to about 7.0, and the ratio of the case length, designated CL in FIG. 1, to the case diameter CD is in a range from about 1.3 to about 2.3.

Additionally, a plug 42 is mounted to the housing 32 in a plug chamber 134. A bypass check valve 74 is positioned internal to the housing 32, between the orifice 44 and the bypass chamber 136. Spring 76 is located between check valve element 78 and the end 43 of the plug 42. The bypass check valve 74 controls fluid communication between the orifice 44 and bypass fluid chamber 136. That is, during the return stroke after the electromagnet 100 has been deactivated and the armature 45 begins to return to its starting position (rest position) shown in FIG. 1, the bypass check valve 74 opens. Fluid from the armature shaft chamber 124 moves through the orifice 44, forces on element 78 and opens the bypass check valve 74. The fluid then moves into the bypass chamber 136.

The pumping cycle of the pump 10 is diagrammatically shown in FIGS. 2-5. Since the internal volume of the pump 10 does not change either during the pumping stroke or the return stroke in the absence of air within the pump 10, the volume of an incompressible fluid leaving the pump 10 is always equal to the volume of fluid entering the pump. As shown, when the armature 45 is in its rest position, no fluid flow passes through the inlet tube 14, because check valve 24 blocks fluid flow through the pump 10.

Next, the electromagnet 100 is energized which creates a magnetic field in the vicinity of the plate barrier 51 (FIG. 3). The armature pole portion 48 is drawn towards the barrier 51. As this happens, movement of the armature 45 is to the left, as shown in FIGS. 3 and 4. That is, the armature 45 moves in the direction indicated by the arrow designated 140 in those drawings. This is generally called the forward pumping stroke. The main spring 90 is compressed between the lip 61 of the retainer element 59 and the retainer plate 80 during the forward pumping stroke.

As shown in FIG. 3, during the forward pumping stroke, fluid is pumped enters the pump 10 at the inlet tube 14, as shown by the fluid inflow arrow designated 138 in FIGS. 3 and 4. This happens because as the armature 45 moves towards the electromagnet 100, the check valve 24 opens and the fluid to be pumped enters armature shaft chamber 124. Fluid begins to move through the fluid circuit. Also during the forward pumping stroke, fluid exits the pump 10 through the passage 130 and out the outlet tube 20, which is indicated by outflow arrow 142 in FIGS. 3 and 4.

During the forward pumping stroke, fluid does not pass through the bypass check valve 74, because the bypass check valve 74 remains closed.
The armature 45 moves the distance of its stroke determined by the time when the electromagnet 100 deactivates (it de-energizes) and the return stroke, shown in FIG. 5, follows. The armature 45 moves in the direction of the arrow designated 144 to its rest position as shown diagrammatically in FIG. 5. This movement is accomplished when main spring 90 releases its stored energy, which moves armature 45 toward check valve 24. The check valve 24 closes prior to the return stroke, thus preventing any backflow of fluid out of the pump 10.

As this occurs, fluid between the check valve 24 and the axial end face 53 of the armature 45 becomes pressurized. This fluid makes its way through the orifice 44 and forces on check valve element 78 of the bypass check valve 74. The bypass check valve 74 opens, and fluid moves through the orifice 44, past the bypass check valve 74, and into bypass chamber 136. The arrow 146 designates the return fluid flow as shown diagrammatically in FIG. 5. Since check valve 24 is closed during the return stroke, no fluid exits the pump 10 through the inlet tube 14 during the return stroke.

The above-described cycle typically is repeated at predetermined intervals in order to deliver the prescribed amount of drugs, medicine, insulin, chemotherapy, pain management drugs, and chemicals to the patient. Also, because the pump 10 can comprise titanium, titanium alloys, and other non-corrosive materials, it is well suited for these applications.

The pump 10 can be used in combination with other implantable medical devices, and in combination with primary cell batteries, for example lithium batteries. It can also be used in combination with rechargeable power sources, for example rechargeable lithium batteries. It also can be used with capacitors rechargeable by radio frequency energy or other means. Another use for the present pump 10 is in life critical situations as a means to deliver drugs, medicines, pain killers, wherein the pump 10 is located external to the patient.

It is noted that the portion of the housing 32 that accommodates the plunger portion 49 is formed as a surrounding wall or cylinder 35 as shown in FIG. 4. The plunger portion 49 is adjacent the cylinder 35 and is guided by the cylinder 35, so that no parts have to be aligned during assembly of the plunger portion 49 and housing 32. To allow for this, the plunger portion 49 has a greater length as compared with pistons/plungers used in other low power electromagnetic pumps. This increased plunger portion 49 length tends to reduce leakage between the cylinder wall 35 of the housing 32 and the plunger portion 49. Clearance between the cylinder 35 and the piston portion 49 can therefore be increased for ease of manufacture, while retaining the accuracy of the volume delivered by the pump 10.

Further simplification of the pump 10 is achieved by incorporating a solid pole portion 50 of non-corrosive magnetic material rather than a pole button or portion in which the magnetic material is encapsulated in titanium or other material. Additional simplification of the assembly process may be achieved by the improved method used to pot and face the coil as described in U.S. Pat. No. 6,264,439 and U.S. Pat. No. 6,454,485.

The simplified assembly process, the increased plunger portion 49 length, and the better control of the plunger portion 49 and cylinder 35 diameters have made it possible to predict more accurately the structural requirements for obtaining the desired stroke volume. Stroke volume is defined as the cross sectional area of plunger 49 times the total displacement of plunger 49 during the forward armature stroke. It is designed that the stroke volume be less than about 0.4 microliters. Obtaining a desired stroke volume, in turn, advantageously allows reduction of the amount of magnetic material in the pump, reduction in the degree of saturation in the pump magnetic circuit and increase in the stroke frequency associated with a fixed fluid delivery rate. The armature pole portion 48 and plunger portion 49 are of fixed length, and the structural relationship thereof to housing 32 and/or components of the pump in the housing provides a selected stroke volume. One way of accomplishing this is by precisely machining armature plunger 49 to the exact length for a desired stroke volume.

Another way is to provide one or more shims in housing 32. This affects the structural relationship between housing 32 and armature 49 thereby affecting the stroke volume. One such shim is designated 64 and is installed between the plunger portion axial end face 53 and the main check valve 24. This reduces the manufacturing time required to arrive at the desired stroke volume, and as a result, the cost of the pump 10 is reduced. Still another way is by means of check valve 24, i.e. by way of a pump component in housing 32. The check valve assembly can be adjusted to change the axial location of the end face of check valve element 27 which contacts the plunger axial end face 53 when the armature is in the rest position. This, in turn, adjusts the extent of axial movement of plunger 49 thereby adjusting the stroke volume.

The attachment of the pole portion 48 to the plunger portion 49 has also been improved and simplified, in that the number of crimps in the flange 58 has been decreased from eight to six in one of the preferred embodiments.

The electromagnetic pump 10 also has simplified circuitry as shown in FIG. 6, which is a schematic of the circuitry 119. There is a circuit 115 that is capable of charging a capacitor 117 to the battery voltage. The capacitor 117 can then be fully or partially discharged through the coil 104 to create a magnetic field so that pulses of energy can be delivered to the electromagnet 100 at timed intervals. The circuit 115 includes a battery 116, a capacitor 117, a diode 118 in parallel with a pump coil 104, and first and second timer controlled switches 120, 121, respectively. In one of the preferred embodiments the battery 116 is a lithium battery. When the first switch 120 is closed and second switch 121 is: open, the capacitor 117 charges and stores energy in an electric field. Then the first switch 120 is opened and the second switch 121 is closed such that the charge from the capacitor 117 is rapidly delivered to the coil 104. This results in current flow through the coil 104, causing a magnetic field to be created, and the magnetic field draws the armature pole portion 48 toward it which causes fluid to be moved out of the pump 10. When the second switch 121 is opened the diode 118 provides a current path for the coil current to flow through, and this allows the stored energy of the coil 104 to be slowly dissipated. This decreases the likelihood of a voltage spike when the second switch 121 opens which protects the components of the circuit components described above.

Energy can be saved if it is possible to recharge the capacitor 117 directly from the battery 116 without a circuit to increase the voltage. However, if this is done by simply
connecting the battery 116 to an initially fully discharged capacitor, the efficiency of this process can be no greater than 50%. A large increase in the efficiency of the recharge can be achieved if the capacitor voltage at the start of the recharge is not much below the battery voltage.

[0063] If it is assumed that the capacitor voltage at the end of the pulse delivered to the solenoid is Vt, and if the capacitor is to be recharged to the battery voltage, Vb, then the energy lost by the battery during the recharge is Vb x Q where Q is the charge delivered to the capacitor. Q is equal to C x (Vb-Vt) where C is the capacitance of the capacitor. The energy gained by the capacitor during recharge is equal to \( \frac{1}{2} C (V_t^2 - V_b^2) \). The efficiency of recharging the capacitor from a constant voltage source is as follows:

\[
\text{recharge efficiency} = \frac{1}{2} \times \frac{(1+V_b/V_t)}{1+V_b/V_t}
\]

The recharge efficiency is therefore approximately 100% if Vt is very close to Vb, and the efficiency is 50% if Vt=0.

[0064] If the capacitor voltage at the end of the discharge is to be close to the battery voltage it is necessary that the capacitance be larger than the minimum value required to drive the pump. The minimum capacitance required to drive the pump, Cmin, can be expressed as

\[
C_{\text{min}} = 2 \times \frac{E_p}{V_b^2}
\]

wherein Ep is the energy required to drive the pump and Vb is the battery voltage. The energy which must be supplied by the battery to recharge the capacitor, Ereecharge, can be shown to be

\[
E_{\text{reecharge}}/E_p = 2C/(C_{\text{min}} - 1)\sqrt{1-C/C_{\text{min}}}
\]

And the reduction in the energy required to recharge the capacitor can be seen by the curve 123 in FIG. 7.

[0065] In order to take advantage of this relationship, it is necessary that the capacitor energy retained at the end of the pulse driving the solenoid is not lost between pulses. The capacitor must therefore have low leakage. It also must have capacitance significantly higher than the minimum required to drive the solenoid and, therefore, should have high energy density to avoid occupying excessive space on the circuit board. This requires a capacitor with relatively high capacitance, which must have low leakage so that the charge is not lost between pulses. A solid tantalum capacitor is suitable for this purpose.

[0066] In order to minimize the energy lost by leakage from the capacitor between pulses it is desirable for the interval between pulses be short and that the capacitor be small. In a preferred embodiment, the pump 10 is designed to deliver 0.25 microliters per pulse rather than the 0.5 microliters per pulse delivered by other low power electromagnetic pumps. For a given rate of drug delivery, the pump 10 operates at twice the pulse frequency of the other pumps and requires less than 50% of the energy per pulse. The small pulse volume both shortens the time interval between pulses and requires less energy to be delivered by the capacitor.

[0067] The pump 10 can be operated efficiently at least over the range of voltages from about 1.5 volts to about 6.0 volts by terminating the external voltage to the coil 104 at suitable time intervals. In one of the preferred embodiments the time ranges between about 1 millisecond to about 6 milliseconds. The time range can be longer or shorter in other embodiments. By winding the coil 104 with wire of different diameter, this voltage range could be shifted to higher or lower values as required.

[0068] The pump 10 is able to deliver accurate pulse volumes when operated with a wide range of catheter designs. This has been accomplished by specifying a soft accumulator to ensure that the catheter-accumulator combination does not generate a negative pressure pulse strong enough to draw additional fluid volume through the pump 10.

[0069] Several of the above-listed objectives are achieved because the stroke volume delivered by the pump 10 is reduced from the 0.5 microliters delivered by the other pumps to about 0.25 microliters. For example, with reduced stroke volume it is possible to reduce the volume of magnetic material used in the pump by approximately 50%. This reduces the magnetic resonance imaging (MRI) signature of the pump 10. Additionally, with reduced stroke volume, the coil 104 delivers fewer ampere-turns to the magnetic circuit. This makes it possible to both reduce the coil 104 volume and to reduce the degree of saturation of the magnetic circuit, thus improving the efficiency of the pump 10.

[0070] With reduced stroke volume, the size of the capacitors necessary to achieve efficient recharge of the capacitor from a constant voltage source is reduced, thus saving space on the circuit board and reducing the leakage current from the capacitor between strokes. Also, with reduced stroke volume, the stroke frequency associated with a fixed drug delivery rate is increased, further reducing the loss of capacitor energy between strokes.

[0071] The smaller stroke volume of the pump 10 compared with the earlier low power electromagnetic pumps could have been obtained by shortening the stroke length, by reducing the piston diameter, or by a combination of both. Shortening the stroke length would have increased the energy efficiency. This would, however, also have increased the difficulty of setting the stroke volume precisely, increased the effect of seat wear on the stroke volume, and increased the pump chamber dead volume, which would have consequently increased the difficulty associated with pumping bubbles. The nominal stroke length of the pump 10 can be selected to be the same as prior pumps, in which case the reduction in stroke volume is obtained almost entirely by decreasing the volume of the piston portion 49. In other embodiments, it may be feasible to reduce the stroke length by about 50%, thus reducing the stroke volume to about 0.1 microliters.

[0072] Also, the inlet check valve 24 design is improved over past check valves. In earlier low power electromagnetic pumps, the initial motion of the plunger is inhibited by the fact that the opening of the check valve 24 is limited by the motion of the piston. This effect is reduced in the pump 10 because the diameter of the check valve 24 is increased relative to diameter of the plunger portion 49. In particular, as shown in FIG. 8, the ratio of the sealing diameter of component 64 of check valve 24 to the diameter of end face 53 of the armature plunger is greater than about 0.6 to reduce inhibiting the initial motion of armature plunger 49.

[0073] The pump 10 can pump against a normal 6 (six) pounds per square inch (hereinafter p.s.i.) pressure head. This is higher than the 4 p.s.i. considered normal for other low power electromagnetic pumps. Operation against the higher pressure head increases the safety margin should a patient travel to a high altitude and the pump develop a leak.
So long as the pressure of the reservoir that supplies the pump 10 is less than the ambient pressure, a leak across the pump may disable the pump 10 but it will not cause life-threatening overdelivery of drug.

In one of the preferred embodiments the pump 10 is used in a drug delivery application in which it is implanted in a human body, and the pump 10 is used for the delivery of liquid. This assists in ensuring that under normal conditions no air will enter the pump 10. However, if some air should enter into the pump it is desirable that the pump 10 continue to operate so that it passes any air bubble and resumes delivery of the drug. Failure to do so might require that the pump 10 be explanted from the patient or some other intervention to resolve bubble problems. The ability of the pump 10 to continue to operate when air is present within the pump depends upon several factors. For one, the volume of air retained within the pump chamber 122 at rest must be small enough compared with the stroke volume so that the pressure decrease within the pump chamber during the pumping stroke is sufficient to open the inlet check valve and draw flow into the pump chamber 122. The required pressure decrease is the pressure increase against which the pump 10 is operating combined with the pressure differences required to open the two check valves. It is noted that if the pump 10 failed to meet this criterion, then even a very small bubble (comparable in volume to the pump 10 displacement) entering the pump 10 would be sufficient to cause the pump to cease operation. In addition, if the pump 10 is to operate while pumping bubbles which are much larger than the pump displacement, e.g. 50 microliters, then it is important that the liquid seal between the plunger portion 49 and cylindrical shaped surrounding wall 35 not break down during the course of passing the large bubble, or that the plunger portion 49 and cylinder 35 clearance be small enough to prevent significant air leakage through this clearance during the pumping stroke.

The ability of the pump 10 to move air has been increased beyond that of the other pumps by reducing the volume of the pump chamber 122, i.e., the volume bounded by the inlet check valve 24 (end face 64 of the check valve element), the bypass check valve 74 (orifice 44 and the included portion of the valve element end face) and the axial end face 53 of the plunger portion 49. The pump can pump continuously while passing bubble volumes up to about 300 microliters. In particular, a ratio of the volume of the pump chamber to the stroke volume is less than about 0.9 so as to enable the pump to move liquid containing gas bubbles having a volume up to about 300 microliters against a pressure increase of at least five pounds per square inch. Pumping did not fail after passage of this volume of air and it is probable that the pump 10 is capable of pumping still larger bubbles.

In estimating the capability of the pump 10 to continue operation with bubbles in the flow, two extreme situations are possible. In the first it is assumed that only liquid enters the pump 10 and only liquid leaves, but a bubble of volume Vbub remains continuously in the pump chamber 122. This situation can only exist if the volume of the bubble is smaller than the volume of the pump chamber 122. If the bubble is much larger than the volume of the pump chamber 122, which would be the case if a 50 microliter bubble is passing through the pump, then only air enters the pump 10 and only air leaves the pump chamber 122. However, some liquid remains continuously in the pump chamber 122. Thus, the bubble volume Vbub is taken to be the volume of the pump chamber 122 minus the volume of liquid remaining in the pump chamber 122. There may occur some intermediate situation in which some liquid and some air continue to pass through the pump 10, but that is not specifically considered.

At the beginning of the pump cycle with the plunger portion 49 in its rest position, the pressure in the pump chamber 122 may be equal to the outlet pressure of the pump 10 or it may be equal to the sum of the outlet pressure and the pressure required to hold the bypass check valve open. This depends upon how quickly and completely the bypass check valve seals at the end of the return stroke and whether there is a significant leak between the plunger portion 49 and cylinder 35 between pump pulses. The calculation proceeds by determining first how far the plunger portion 49 must travel before the pressure in the pump chamber 122 decreases to a low enough value to open the main check valve 24. This depends in part on the specific heat ratio, γ, of the gas. However, if there is significant heat transfer between the liquid and the gas, it is probably valid to assume that the gas expands isothermally (γ=1) rather than adiabatically. During the remainder of the pumping stroke gas or liquid is drawn into the pump chamber 122 and this amount of gas or liquid represents the amount of gas or liquid delivered during a pump cycle.

For a relatively small bubble retained in the pump chamber when the pump is delivering liquid, the resulting delivered pulse volume is:

$$\text{Volume of Liquid Delivered per Pulse} = V_b + V_{bub} \left[1 - \left(\frac{\Delta P_{out}}{\Delta P_{inlet} - \Delta P_{mcv}}\right)^{1/2}\right]$$

Where $V_b$ is the stroke volume, $V_{bub}$ is the volume of the bubble, $\Delta P_{mcv}$ is the pressure drop across the bypass check valve, $\Delta P_{inlet}$ is the pressure drop across the main check valve, and $\Delta P_{out}$ is the delivery pressure, and $\Delta P_{mcv}$ is the inlet pressure.

For a large bubble, when the pump is ingesting and delivering air, the volume delivered becomes:

$$\text{Volume of Gas Delivered Per Pulse} = \frac{V_b + V_{bub} \left[1 - \left(\frac{\Delta P_{out}}{\Delta P_{inlet} - \Delta P_{mcv}}\right)^{1/2}\right]}{\Delta P_{out}}$$

One of the major differences between these two situations results from the fact that when the outlet pressure is greater than the inlet pressure, the gas is compressed by the pump so that the volume delivered is smaller than the volume ingested by the pump 10. Note that if the bubble volume is zero, the pump 10 delivers a volume of liquid equal to the stroke volume. If the pump 10 is delivering gas, then the delivery volume is reduced by the pressure rise across the pump even with no bubble resident in the pump chamber 124.

The accuracy of other low power electromagnetic pumps depends, in part, on the presence of an orifice in the
outlet tube that limits the speed at which the plunger may pull an accumulator of relatively low compliance located at the end of the outlet tube. In that case, the pressure drop across the orifice and the back pressure which develops in the accumulator during the stroke combine to reduce the inertial overdelivery of fluid when the pressure increase across the pump is small or negative. When a bubble passes through one of these other pumps, it first reduces the fluid delivery per stroke while the bubble is located within the pump chamber. Relatively quickly the bubble passes from the pump chamber into the pump body, where it is usually trapped until it redissolves in the passing flow. However, while the bubble is located in the pump body the pump may tend to overdeliver fluid because the bubble in the pump body provides compliance upstream of the orifice negating the effect of the orifice in limiting the piston speed and the flow rate.

[0083] The pump 10 is designed to have relatively short inlet and outlet tubes, 14, 20, respectively, as compared to those of other low power electromagnetic pumps, and these result in reduced inertial flow. Also, the pump 10 can include an accumulator designed to have relatively large compliance so that the difference between the pulse volume delivered by the pump 10 with a bubble in the pump body 32 and with only fluid in the pump body 32 is relatively small.

[0084] In another embodiment, the pump 10 may be provided with a compliant element within the pump body 32 to further reduce the inaccuracy associated with inertial flow.

[0085] The pump 10 incorporates a bypass circuit 37 around the plunger portion 49. This serves several purposes. It allows passage of air through the pump 10 without breaking down the liquid seal, which inhibits leakage of air through the plunger portion 49 and cylinder 35. Efficient pumping of air by the pump 10 relies upon maintenance of this liquid seal. Another purpose of the bypass circuit 37 is to allow rapid return of the piston portion 49 to its rest position after the pumping stroke. This is of importance primarily in applications of the pump 10, which require rapid pumping rates.

[0086] From the foregoing it is clear that the performance of the pump mechanism is dependent on the piston-cylinder seal, i.e. the liquid seal between the outer surface of armature plunger portion 49 and the inner surface of cylinder 35. This seal may be comprised of if air enters the piston-cylinder interface, i.e. the space or clearance between the outer surface of armature plunger portion 49 and the inner surface of cylinder 35. The mechanism depends on this seal in both the forward pumping stroke and the return stroke.

[0087] During the forward stroke, the piston-cylinder seal sustains suction in the pump chamber 122 while at the same time resisting the pressure required to push fluid or air from the outlet chamber 17 into the outlet tube 20 which may be in fluid communication with an accumulator/catheter. Air retained in the outlet chamber 17 is at a higher pressure than the negative pressure created in the pump chamber 122 and thus tends to enter the piston-cylinder interface from the outlet chamber side. It will enter the piston-cylinder interface if the pressure exceeds the bubble point of this space. If this happens the pump mechanism will not be able to sustain suction in the pump chamber 122 or push out fluid. The stroke volume will be significantly diminished or will go to zero at low reservoir pressures.

[0088] The ability of the mechanism to pump air through the maximum pressure difference depends on three parameters: 0089. The pump chamber volume: stroke volume ratio; 0090. The bubble point of the piston-cylinder interface; 0091. The retained volume of fluid after each stroke.

Each of these parameters can be enhanced by choosing materials and surfaces which are hydrophilic and in the case of bubble point, by decreasing the diameter of the interface, by decreasing the dead volume of the pump chamber 122 thus increasing the pump chamber volume: stroke volume ratio.

[0092] The dead space in the pump chamber volume and the retention of fluid in the dead spaces can be addressed using hydrophilic materials or coatings. Hydrophilic surfaces in small cracks can draw in water and will retain water tenaciously. Less viscous hydrophilic coating materials will actually fill in cracks and other small spaces and decrease the dead volume of the pump chamber 122 thus increasing the pump chamber volume: stroke volume ratio.

[0093] The piston-cylinder interface bubble point must resist air entry from the outlet chamber 17 during the forward stroke and must resist air entry from the pump chamber 122 during the return stroke. If the bubble point is too low during the forward stroke and air enters the piston-cylinder interface, the pump may not develop enough pressure to open the main check valve 24. If air enters the piston-cylinder interface during the return stroke, the bypass check valve 74 may open late or not at all and the volume of air pumped will be small. Bubble point is strongly affected by the size of the interface and by the hydrophilicity of the interior surfaces of the interface. Bubble point is increased by decreasing the clearance between the piston and the cylinder and by making the surface of the piston and cylinder more hydrophilic using coatings, or surface treatments, or simply by using materials which are intrinsically hydrophilic.

[0094] Coating materials may be poly ethylene glycol (PEG), acrylic or other forms of hydrogels or any other hydrophilic coating. Solvent based coatings can be used to enter and fill fine cracks and crevices. Plasma treatments and abrasive treatments may be used to enhance the hydrophilic nature of surfaces. Materials such as titanium, sapphire and glass which are naturally hydrophilic are currently used, however aggressively hydrophilic coatings such as the hydrogels or PEG mentioned above could have a dramatic effect would significantly improved the low pressure pumping capability of the pump.

[0095] It is noted that the pump 10 and other low power electromagnetic pump designs allow the main check valve 24 to be held closed at rest by a strong return spring. When the pumping stroke begins, however, the force of the return spring 90 is immediately removed from the main check valve 24 and the check valve 24 is then held closed by the weak check valve spring 25. The strong return spring 90 prevents leakage back through the pump 10 between pumping strokes and is essential if the pump 10 is to deliver accurate small fluid volumes. The weak spring 25, which tends to hold the check valve 24 closed during the pumping stroke but which allows the check valve 24 to open with a minimal pressure difference in the flow direction, is important to the efficient pumping of air.

[0096] In conclusion, the simplified structure and method of assembly of the pump of this invention advantageously
reduce cost of manufacture. The various characterizing features of the pump described hereinabove contribute to its enhanced energy and operational efficiency. As previously mentioned the pump of this invention requires less than 50% of the energy per pulse required by pumps heretofore available. For example, it has been determined that the energy required by the pump described herein to pump a unit volume is 4 millijoules/mcroliter whereas the pump described in U.S. Pat. No. 5,797,733 requires energy of 11 millijoules/mcroliter to pump a unit volume. In addition, the pump of this invention has improved capability to continue operation with bubbles in the flow.

What is claimed:

1. In an electromagnetic pump for delivering an infusion medium to a patient, wherein the pump includes an inlet, an outlet, an electromagnet, and an armature positioned for magnetic attraction by said electromagnet to cause movement of said armature to force fluid from said inlet out through said outlet, the electromagnet comprising:
   a) a core of magnetic material in said electromagnet, said core having a core diameter,
   b) a coil surrounding said core,
   c) a case of magnetic material surrounding said coil and said core, said case being spaced in insulated relation to said coil, said case having a case diameter and a case length, and
   d) a ratio of said case diameter to said core diameter being in a range from about 2.5 to about 7.

2. The electromagnetic pump of claim 1, further including a ratio of said case length to said core diameter being in a range from about 1.3 to about 2.3.

3. The electromagnetic pump of claim 1 wherein said diameter of said case is less than about 0.28 inches so that said pump can be installed in an implantable drug delivery system.

4. The electromagnetic pump of claim 1 wherein said coil has a length of about 0.35 inches, said core has a diameter of about 0.08 inches, and said coil case has a thickness of about 0.013 inches.

5. The electromagnetic pump of claim 1 wherein said electromagnet is energized by partial discharge of a capacitor into said coil, and wherein said capacitor is a low leakage high energy density capacitor.

6. The electromagnetic pump of claim 5 wherein said capacitor is a solid tantalum capacitor.

7. The electromagnetic pump of claim 1 wherein a voltage supplied to said coil ranges between about 1.5 volts to about 6.0 volts.

8. The electromagnetic pump of claim 1 wherein a voltage supplied to said coil is terminated at time intervals ranging between about 1 millisecond to about 6 milliseconds.

9. The electromagnetic pump of claim 1, wherein the armature has a pole portion of chrome-molybdenum-iron alloy.

10. An electromagnetic pump for delivering an infusion medium to a patient, the electromagnetic pump comprising:
   a) a housing having an interior fluid containing region including a fluid receiving chamber and a fluid output chamber in fluid communication therewith, an inlet in fluid communication with said receiving chamber and an outlet in fluid communication with said output chamber,
   b) an electromagnet joined to said housing and located external to said fluid containing region,
   c) an armature positioned in said fluid containing region of said housing having a pole portion located for magnetic attraction by said electromagnet and having a plunger portion extending from said pole portion, said armature being movably supported in said housing for movement from a rest position through a forward pumping stroke when attracted by said electromagnet to force fluid from said output chamber through said outlet and for movement in an opposite direction through a return stroke back to said rest position, said armature having a stroke volume comprising the cross-sectional area of said armature pole portion times the total displacement of said armature plunger portion during the forward pumping stroke,
   d) a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnet to close said gap in response to electrical energization of said electromagnet, and
   e) said armature comprising said pole portion and said plunger portion being of fixed length and having a structural relationship to said housing and/or components of said pump in said housing to provide a delivered armature stroke volume less than about 0.4 microliters.

11. The electromagnetic pump of claim 10 further comprising a check valve operatively associated with said fluid containing region for allowing fluid flow in a direction from said inlet through said outlet and blocking fluid flow in a direction from said outlet through said inlet, said check valve having an element which contacts said armature plunger portion when said armature is in said rest position so as to determine the location of said rest position thereby affecting extent of armature axial movement.

12. The electromagnetic pump of claim 10 wherein said housing comprises a pair of components having at least one slim located therebetween so as to allow adjustment of the delivered armature stroke volume.

13. The electromagnetic pump of claim 10 wherein said armature pole portion is of chrome-molybdenum-iron alloy.

14. An electromagnetic pump for delivering an infusion medium to a patient, said electromagnetic pump comprising:
   a) a housing having an interior fluid containing region including a fluid receiving chamber and a fluid output chamber in fluid communication therewith, an inlet in fluid communication with said receiving chamber and an outlet in fluid communication with said output chamber,
   b) a check valve operatively associated with said fluid containing region for allowing fluid flow in a direction from said inlet through said outlet and blocking fluid flow in a direction from said outlet through said inlet,
   c) an electromagnet carried by said housing and located external to said fluid containing region,
   d) an armature positioned in said fluid containing region of said housing having a pole portion located for magnetic attraction by said electromagnet and said
armature having a plunger portion extending from said pole portion, said plunger portion having an axial end face facing said check valve, said armature being movably supported in said housing for movement from a rest position through a forward pumping stroke when attracted by said electromagnet to force fluid from said output chamber through said outlet and for movement in an opposite direction through a return stroke back to said rest position, there being a clearance between said armature plunger portion and a surface of said housing, said armature having a stroke volume comprising the cross-sectional area of said armature pole portion times the total displacement of said armature plunger portion during the forward pumping stroke,

e) a bypass check valve for allowing fluid to flow around said armature during said return stroke,

f) a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnet to close said gap in response to electrical energization of said electromagnetic,

g) a pump chamber having a volume defined by a region within said housing surface bounded by said check valve, said axial end face of said plunger, and said bypass check valve, and

h) wherein a ratio of said volume of said pump chamber to a stroke volume being less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

15. The electromagnetic pump of claim 14 wherein said ratio enables said pump to move said liquid containing said gas bubbles having a volume up to about 300 microliters against a pressure increase of at least five pounds per square inch.

16. The electromagnetic pump of claim 14 further comprising a cylinder formed in said housing and a bypass circuit including said bypass check valve formed around said plunger portion for allowing the passage of air through said pump without breaking down a liquid seal formed between said plunger portion and said cylinder.

17. The electromagnetic pump of claim 16 wherein said bypass circuit allows rapid return of said plunger portion to said rest position after a pumping stroke.

18. The electromagnetic pump of claim 14, wherein said armature pole portion is of chrome-molybdenum-iron alloy.

19. An electromagnetic pump for delivering an infusion medium to a patient, said electromagnetic pump comprising:

a) a housing having an interior fluid containing region including a fluid receiving chamber and a fluid output chamber in fluid communication therewith, an inlet in fluid communication with said receiving chamber and an outlet in fluid communication with said output chamber,

b) a check valve operatively associated with said fluid containing region for allowing fluid flow in a direction from said inlet through said outlet and blocking fluid flow in a direction from said outlet through said inlet,

c) an electromagnet carried by said housing and located external to said fluid containing region,

d) an armature positioned in said fluid containing region of said housing having a pole portion located for magnetic attraction by said electromagnet and said armature having a plunger portion extending from said pole portion, said plunger portion having an axial end face facing said check valve, said armature being movably supported in said housing for initial movement from a rest position through a forward pumping stroke when attracted by said electromagnet to force fluid from said output chamber through said outlet and for movement in an opposite direction through a return stroke back to said rest position, there being a clearance between said armature plunger portion and a surface of said housing,

e) a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnet to close said gap in response to electrical energization of said electromagnetic, and

f) a ratio of the sealing diameter of the check valve to the diameter of the armature axial end face being greater than about 0.6 to reduce inhibiting the initial movement of the armature.

20. The electromagnetic pump of claim 19, wherein said armature pole portion is of chrome-molybdenum alloy.

21. In an electromagnetic pump for delivering an infusion medium to a patient, wherein said pump includes a housing having an interior fluid containing region, an inlet and an outlet in fluid communication with said region, an electromagnet carried by said housing and located external to said fluid containing region of said housing, an armature positioned in said fluid containing region of said housing and having a pole portion, a magnetic circuit including said electromagnet, said armature pole portion and a gap in said fluid containing region of said housing between said armature pole portion and said electromagnet, said armature pole portion being located for magnetic attraction by said electromagnetic causing movement of said armature to force fluid out of said region through said outlet:

a) an electrical circuit including a battery, a capacitor, and a battery recharge component wherein the pump is driven by the partial discharge of said capacitor into said electromagnet; and

b) said capacitor having a capacitance greater than about 1.2 times the minimum value of said capacitor required to drive the pump.

22. The electromagnetic pump according to claim 21 wherein said capacitor has low leakage and wherein capacitor energy retained at the end of a pulse driving said armature is not lost between pulses.

23. The electromagnetic pump according to claim 21 wherein said capacitor is in electronic communication with said battery having a battery voltage and said capacitor has a voltage at a start of a recharge that is closely below said battery voltage in order that energy lost by a moving charge from said battery voltage to said capacitor voltage is small.

24. The electromagnetic pump according to claim 21 wherein a voltage supplied to said electromagnet ranges between about 1.5 volts to about 6.0 volts.

25. The electromagnetic pump of claim 21 further wherein a voltage supplied to said electromagnet is terminated at time intervals ranging between about 1 millisecond to about 6 milliseconds.

26. In an electromagnetic pump for delivering an infusion medium to a patient, wherein said pump includes a housing having an interior fluid containing region, an inlet and an outlet in fluid communication with said region, an electro-
magnet carried by said housing and located external to said fluid containing region of said housing, an armature positioned in said fluid containing region of said housing and having a pole portion, a magnetic circuit including said electromagnet, said armature pole portion and a gap in said fluid containing region of said housing between said armature pole portion and said electromagnet, said armature pole portion being located for magnetic attraction by said electromagnetic causing movement of said armature to force fluid out of said region through said outlet:

a) an electrical circuit including a battery, a capacitor, and a battery recharge component wherein the pump is driven by the partial discharge of the capacitor into the electromagnet; and

b) wherein the minimum value of the capacitor required to drive the pump is \( C_{\text{min}} = \frac{2 \times E_p \times V_b^2}{E_p} \) where \( E_p \) is the energy required to drive the pump and \( V_b \) is the voltage of said battery and wherein the energy required to be supplied by said battery to recharge the capacitor is \( E_{\text{recharge}} = 2C_{\text{min}}(1 - C_{\text{min}}/C)^{1/2} \).

27. The electromagnetic pump according to claim 26, wherein the capacitor is a low leakage capacitor.

28. The electromagnetic pump according to claim 26, wherein the capacitor has a value greater than the minimum value of the capacitor required to drive the pump.

29. The electromagnetic pump according to claim 26, wherein the capacitor has a high energy density.

30. The electromagnetic pump according to claim 26, wherein the capacitor is a solid tantalum capacitor.

31. An electromagnetic pump for delivering an infusion medium to a patient, said electromagnetic pump comprising:

a) a housing having an interior fluid containing region including a fluid receiving chamber and a fluid output chamber in fluid communication therewith, an inlet in fluid communication with said receiving chamber and an outlet in fluid communication with said output chamber,

b) a check valve operatively associated with said fluid containing region for allowing fluid flow in a direction from said inlet through said outlet and blocking fluid flow in a direction from said outlet through said inlet,

c) an electromagnet carried by said housing and located external to said fluid containing region,

d) an armature positioned in said fluid containing region of said housing having a pole portion located for magnetic attraction by said electromagnet and said armature having a plunger portion extending from said pole portion, said plunger portion having an outer surface and having an axial end face facing said check valve, said armature being movably supported in said housing for initial movement from a rest position through a forward pumping stroke when attracted by said electromagnet to force fluid from said output chamber through said outlet and for movement in an opposite direction through a return stroke back to said rest position, there being a clearance between said outer surface of said armature plunger portion and a surface of said housing,

e) a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnetic to close said gap in response to electrical energization of said electromagnetic, and

f) at least one of said outer surface of said armature plunger portion and said surface of said housing being hydrophilic in nature.

32. The electromagnetic pump according to claim 31, wherein at least one of said outer surface of said armature plunger portion and said surface of said housing is of hydrophilic material.

33. The electromagnetic pump according to claim 31, wherein at least one of said outer surface of said armature plunger portion and said surface of said housing is coated with hydrophilic material.

34. The electromagnetic pump according to claim 31, wherein both of said outer surface of said armature plunger portion and said surface of said housing are hydrophilic in nature.

35. The electromagnetic pump according to claim 34, wherein both of said outer surface of said armature plunger portion and said surface of said housing are of hydrophilic material.

36. The electromagnetic pump according to claim 34, wherein both of said outer surface of said armature plunger portion and said surface of said housing are coated with hydrophilic material.

37. A method for making an electromagnet for an electromagnetic pump to deliver an infusion medium to a patient, the electromagnetic pump comprising an inlet, an outlet, an electromagnet, and an armature positioned for magnetic attraction by said electromagnet to cause movement of said armature to force fluid out from said inlet through said outlet, said method comprising:

providing said electromagnet with a core of magnetic material, said core having a core diameter,

providing said electromagnet with a coil surrounding said core,

providing said electromagnet with a case of magnetic material surrounding said coil and said core, said case having a case diameter and a case length, and

establishing a ratio of said case diameter to said core diameter being in a range from about 2.5 to about 7.

38. The method of claim 37 further including establishing a ratio of said case length to said case diameter in a range from about 1.3 to about 2.3.

39. The method of claim 37 further including selecting said diameter of said case to be less than about 0.28 inches so that said pump can be installed in an implantable drug delivery system.

40. The method of claim 37 further including selecting said coil length to be about 0.35 inches, selecting said core diameter to be about 0.08 inches, and selecting said coil case thickness to be of about 0.013 inches.

41. The method of claim 37 further comprising providing a cylinder formed in said housing and forming a bypass circuit around said plunger portion for allowing the passage of air through said pump without breaking down a liquid seal formed between said plunger portion and said cylinder.

42. The method of claim 37 further comprising supplying a voltage to said coil that ranges between about 1.5 volts to about 6.0 volts.

43. The method of claim 37 further comprising supplying a voltage to said coil and terminating said voltage at time intervals ranging between about 1 millisecond to about 6 milliseconds.
The method of claim 37, wherein said armature is formed to have a pole portion of chrome-molybdenum-iron alloy.

A method of making an electromagnetic pump for delivering an infusion medium to a patient comprising:

1. The method of claim 37, wherein said armature is formed to have a pole portion of chrome-molybdenum-iron alloy.
2. The method of claim 37 wherein said armature is formed to have a pole portion of chrome-molybdenum-iron alloy.
3. The method of claim 37 wherein said armature is formed to have a pole portion of chrome-molybdenum-iron alloy.
4. The method of claim 37 wherein said armature is formed to have a pole portion of chrome-molybdenum-iron alloy.
5. A method of making an electromagnetic pump for delivering an infusion medium to a patient comprising:

   a) providing a housing having an interior fluid containing region including a fluid receiving chamber and a fluid output chamber in fluid communication therewith, an inlet in fluid communication with said receiving chamber and an outlet in fluid communication with said output chamber.

   b) providing an electromagnet joined to said housing and located external to said fluid containing region.

   c) providing an armature positioned in said fluid containing region of said housing having a pole portion located for magnetic attraction by said electromagnet and having a plunger portion extending from said pole portion, said armature being movable supported in said housing for movement from a rest position through a forward pumping stroke when attracted by said electromagnet to force fluid from said output chamber through said outlet and for movement in an opposite direction through a return stroke back to said rest position, said armature having stroke volume comprising the cross-sectional area of said armature pole portion times the total displacement of said armature plunger portion during the forward pumping stroke,

   d) defining a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnet to close said gap in response to electrical energization of said electromagnet,

   e) providing said armature comprising said pole portion and said plunger portion of fixed length and having a structural relationship to said housing and/or components of said pump in said housing to provide a delivered armature stroke volume less than about 0.4 microliters.

   f) defining a magnetic circuit including said electromagnet and said armature and a gap between said pole portion of said armature and said electromagnet for moving said armature toward said electromagnet to close said gap in response to electrical energization of said electromagnet,

   g) said pump having a pump chamber having a volume defined by a region within said housing surface bounded by said check valve, said axial end face of said plunger, and said bypass check valve, and

   h) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   i) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   j) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   k) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   l) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   m) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   n) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   o) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   p) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   q) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   r) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.

   s) selecting the stroke volume and the volume of said pump chamber so that a ratio of the volume of said pump chamber to the stroke volume is less than about 0.9 so as to enable said pump to move a liquid containing gas bubbles.
magnetic attraction by said electromagnetic causing movement of said armature to force fluid out of said region through said outlet, and an electrical circuit including a battery, a capacitor and a battery recharge component for energizing said electromagnet, the method comprising:

a) causing said capacitor to have low leakage and retaining capacitor energy at the end of a pulse driving said armature so that said capacitor energy is not lost between pulses, and

b) causing said capacitor to be in electronic communication with said battery having a battery voltage and causing said capacitor to have a voltage at a start of a recharge that is closely below said battery voltage in order that energy lost by a moving charge from said battery voltage to said capacitor voltage is small.

54. The method of operating an electromagnetic pump according to claim 53 including supplying a voltage to said electromagnet that ranges between about 1.5 volts to about 6.0 volts.

55. The method of operating an electromagnetic pump according to claim 53 wherein a voltage is supplied to said electromagnet and is terminated at time intervals ranging from between about 1 millisecond to about 6 milliseconds.

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