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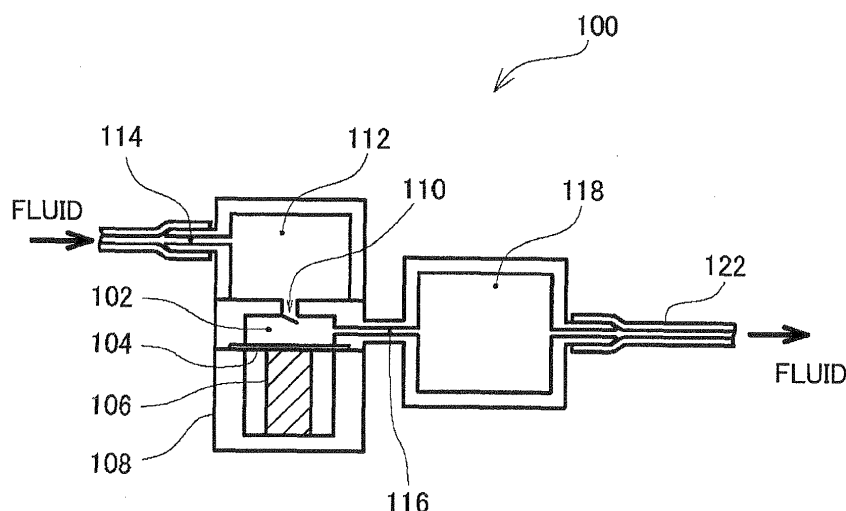
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(54) **Fluid feed pump, fluid circulation device, medical device and electronic device**

(57) A fluid feed pump is configured, such that a fluid is fed from an outlet channel of the fluid feed pump through an outlet buffer chamber to a fluid channel. The outlet buffer chamber is designed to have a higher compliance than a compliance of a pump chamber. The driving period of the fluid feed pump is set to a shorter period

than a time constant defined by the compliance of the pump chamber and a flow resistance between an inlet of the outlet channel and an outlet of the fluid channel. This enables the fluid to be fed with high efficiency by taking advantage of the pressure oscillation occurring between the pump chamber and the outlet buffer chamber.

Fig.1



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Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to Japanese Patent Applications No. 2011-199122 filed on September 13, 2011; No. 2011-199127 filed on September 13, 2011; No. 2011-252355 filed on November 18 2011; and No. 2012-55330 filed on March 13, 2012, the disclosures of which are hereby incorporated by reference in their entireties.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] The present invention relates to a fluid feed pump operated to pressure-feed a fluid, as well as a fluid circulation device, a medical device and an electronic device.

Description of Related Art

[0003] A fuel feed pump of one proposed structure repeats the operation of increasing the volume of a pump chamber to suck in a fluid and subsequently decreasing the volume of the pump chamber to pressure-feed the fluid (e.g., JP 2011-103930A). This fluid feed pump pressure-feeds the fluid in the pump chamber, every time the volume of the pump chamber is increased and subsequently decreased. The fluid feed amount per each operation is substantially equal to the differential volume given by subtracting the minimum volume from the maximum value of the pump chamber (excluded volume). The fluid feed amount of the fluid feed pump is thus approximately equal to the product of the number of cycles of increasing and subsequently decreasing the volume of the pump chamber (frequency of actuation) per unit time and the excluded volume. This means that increasing the frequency of actuation per unit time proportionally increases the fluid feed amount.

[0004] Operating the fluid feed pump in a certain operating range, the energy efficiency decline has been pointed out.

SUMMARY

[0005] The reason that a fluid feed pump of this invention can operate with high efficiency is described below with some figures. Fig. 13 illustrates the general structure of a fluid feed pump. A diaphragm forms part of a pump chamber and is deformed by expanding a piezoelectric element placed in a casing. The fluid in the pump chamber is then pressure-fed through an outlet channel. After the pressure-feed of the fluid, removal of a driving voltage applied to the piezoelectric element returns the expanded piezoelectric element to the original length and thereby increases the volume of the pump chamber. Accompanied with this volume increase, the fluid in an inlet buffer chamber flows via a check valve into the pump chamber. The inlet buffer chamber then receives supplement of the fluid through an inlet channel.

[0006] Figs. 14A and 14B illustrate changes in internal pressure of the pump chamber by application of a driving signal to the piezoelectric element. As illustrated in Fig. 14A, applying a driving voltage to the piezoelectric element expands the piezoelectric element and abruptly raises the internal pressure of the pump chamber. This results in pressure-feeding the fluid in the pump chamber through the outlet channel and thereby lowers the internal pressure of the pump chamber. Removing the driving voltage applied to the piezoelectric element contracts the piezoelectric element and increases the volume of the pump chamber to further lower the internal pressure of the pump chamber to negative pressure. The fluid is then flowed into the pump chamber from the inlet buffer chamber, so as to promptly recover the internal pressure of the pump chamber.

[0007] Under the certain driving conditions of the fluid feed pump, the time required to increase or decrease the internal pressure of the pump chamber is significantly shorter than the period of driving the fluid feed pump (i.e., time per cycle of changing the volume of the pump chamber) and the time period between application and removal of the driving voltage. It can thus be assumed that the driving voltage is removed after the fluid pressurized in the pump chamber is fully pressure-fed through the outlet channel. Similarly it can be assumed that the driving voltage is applied after the fluid is fully supplemented from the inlet buffer chamber into the pump chamber having the volume increased by removal of the driving voltage. As a result, the fluid corresponding to the excluded volume is pressure-fed, every time a driving signal pulse is applied.

[0008] When a fluid channel connected with the outlet channel has high flow resistance (as in the thin and long fluid channel) or when a fluid of high viscosity is pressure-fed, it takes a relatively long time to flow the fluid corresponding to the excluded volume out of the pump chamber having the reduced volume. This results in extending the time required for lowering the internal pressure of the pump chamber.

[0009] In the graph of Fig. 14B, the dashed-dotted-line curve shows the state that the internal pressure of the pump

chamber decreases when the fluid channel has high flow resistance or when the fluid of high viscosity is pressure-fed. Compared with the ordinary case shown by the broken-line curve (i.e., when the fluid channel has low flow resistance and the pressure-fed fluid has low viscosity), it takes a longer time to lower the internal pressure of the pump chamber. This means that a longer time is required to pressure-feed the fluid corresponding to the excluded volume. Removal of the driving voltage before a sufficient decrease of the internal pressure (i.e., before the fluid corresponding to the excluded volume is fully fed out of the pump chamber) interrupts the fluid feed and causes supplement of the fluid from the inlet buffer chamber. This lowers the efficiency of fluid feed per cycle.

[0010] Even when the fluid channel does not have the high fluid resistance and the pressure-fed fluid does not have the high viscosity, the extremely short period of driving the fluid feed pump (i.e., the time per cycle of changing the volume of the pump chamber) (i.e., high driving frequency) may cause similar problem. Even when the fluid channel does not have the high fluid resistance and the pressure-fed fluid does not have the high viscosity, it is impossible to fully flow the fluid corresponding to the excluded volume out of the pump chamber at the instance of expanding the piezoelectric element. It takes not long but still some time to fully flow out the fluid corresponding to the excluded volume. Driving the fluid feed pump in the shorter period than the time required to fully flow out the fluid corresponding to the excluded volume thus disadvantageously lowers the efficiency of fluid feed.

[0011] Driving the fluid feed pump in the shorter period than the time required to fully flow the fluid corresponding to the excluded volume out of the pump chamber (i.e., the time required to sufficiently reduce the internal pressure of the pump chamber) lowers the efficiency of fluid feed, irrespective of the flow resistance of the fluid channel and the viscosity of the pressure-fed fluid. This decrease in efficiency of fluid feed becomes non-negligibly large in the driving period of the fluid feed pump shorter than a time constant τ when the internal pressure of the pump chamber is reduced as shown in Fig. 14B. The time constant τ herein is defined by the product of the compliance of the pump chamber and the flow resistance between an inlet of the outlet channel and an outlet of the fluid channel as described later in detail.

[0012] Fig. 15 shows the relationship between the driving frequency (reciprocal of the driving period) of the fluid feed pump and the fluid feed amount. Under the ordinary driving conditions of the fluid feed pump, the driving frequency is sufficiently lower than $1/\tau$, so that the fluid feed amount increases in proportion to the driving frequency. At the higher driving frequencies, however, the fluid feed amount does not increase at a comparable rate to the increase rate of the driving frequency as shown by the solid-line curve in Fig. 15. At the driving frequency of higher than $1/\tau$, there is a significant decrease in efficiency of fluid feed by the fluid feed pump. The electrical energy applied to drive the piezoelectric element is approximately proportional to the driving frequency. Such a decrease in efficiency of fluid feed indicates an increase in potential loss of the electrical energy applied to the piezoelectric element.

[0013] The object of the invention is to provide a high-efficient fluid feed pump that feeds a fluid with high efficiency even in a shorter driving period than a time constant τ when the internal pressure of a pump chamber decreases and that significantly decreases a potential loss of electrical energy applied to a piezoelectric element, as well as a fluid circulation device, a medical device and an electronic device.

[0014] According to a first aspect, there is provided a fluid feed pump that feeds a fluid through a fluid channel. The fluid feed pump includes: a pump chamber having variable volume; an inlet channel arranged to allow inflow of the fluid from the fluid channel to the pump chamber; a check valve provided between the inlet channel and the pump chamber; an outlet channel connected with the pump chamber to feed the fluid out of the pump chamber; and an outlet buffer chamber connected with the outlet channel to feed the fluid from the outlet channel to the fluid channel. The outlet buffer chamber has a compliance higher than a compliance of the pump chamber. A time per cycle of changing the volume of the pump chamber is shorter than a time constant defined by a product of the compliance of the pump chamber and a flow resistance between an inlet of the outlet channel and an outlet of the fluid channel.

[0015] In the fluid feed pump of the first aspect, the volume of the pump chamber is increased to suck the fluid out of the inlet channel to the pump chamber via the check valve and is subsequently decreased to feed the fluid from the outlet channel to the fluid channel. The outlet buffer chamber having the higher compliance than the compliance of the pump chamber is provided between the outlet channel and the fluid channel. The time per cycle of changing the volume of the pump chamber in the fluid feed pump is shorter than the time constant τ defined by the product of the compliance of the pump chamber and the flow resistance between the inlet of the outlet channel and the outlet of the fluid channel.

[0016] When the volume of the pump chamber decreases, the fluid pressurized in the pump chamber moves through the outlet channel to the outlet buffer chamber, so that the internal pressure of the pump chamber immediately decreases (in a shorter time than the time constant τ). The inertia of the fluid going through the outlet channel causes the pump chamber to have negative internal pressure, so that the fluid is immediately supplied to the pump chamber via the check valve. This enables the fluid to be fed with high efficiency even when the fluid feed pump is driven in the period shorter than the time constant τ . The fluid flowing into the outlet buffer chamber is supposed to flow toward the fluid channel, but the flow resistance of the fluid channel interferes with the smooth fluid flow. This increases the internal pressure of the outlet buffer chamber, while the internal pressure of the pump chamber decreases. This discourages the flow from the pump chamber to the outlet buffer chamber. No check valve is provided between the pump chamber and the outlet buffer chamber, so that there is backflow from the outlet buffer chamber to the pump chamber. The check valve is, on

the other hand, provided between the pump chamber and the inlet channel. The backflow of the fluid increases the internal pressure of the pump chamber again. When the increasing internal pressure of the pump chamber reaches or exceeds the internal pressure of the outlet buffer chamber, the fluid stops the backflow but starts flowing toward the outlet buffer chamber. This causes the pump chamber to have negative pressure again and enables further supply of the fluid from the inlet buffer chamber to the pump chamber. The pressure oscillation occurring between the pump chamber and the outlet buffer chamber via the outlet channel results in increasing the amount of the fluid supplied to the pump chamber. The fluid feed amount by each cycle of decreasing and subsequently increasing the volume of the pump chamber is thus made greater than the differential volume given by subtracting the minimum volume from the maximum volume of the pump chamber (excluded volume). Using the fluid feed pump that feeds the fluid with high efficiency can significantly reduce the electrical energy applied to the piezoelectric element, thus making a significant contribution to energy saving.

[0017] According to one embodiment, there is provided the fluid feed pump of the first aspect, wherein the outlet channel may have a flow resistance lower than a flow resistance of the fluid channel.

[0018] The fluid feed pump of this embodiment immediately lowers the internal pressure of the pump chamber irrespective of the flow resistance of the fluid channel, and additionally interferes with attenuation of the pressure oscillation occurring between the pump chamber and the outlet buffer chamber. This enables the pump chamber to have the negative pressure many times and thereby supplies the fluid to the pump chamber with high efficiency. This configuration enables the fluid to be fed with high efficiency even when the fluid feed pump is driven in the period shorter than the time constant τ .

[0019] According to another embodiment, there is provided the fluid feed pump of the first aspect, wherein the compliance of the outlet buffer chamber may be at least 10 times as high as the compliance of the pump chamber.

[0020] When the compliance of the outlet buffer chamber is not sufficiently higher than the compliance of the pump chamber, the flow resistance of the fluid channel connected with the outlet buffer chamber may affect the pressure-feed of the fluid from the pump chamber to the outlet buffer chamber. In the fluid feed pump of this embodiment, however, the compliance of the outlet buffer chamber is at least 10 times as high as the compliance of the pump chamber. This causes the flow resistance of the fluid channel connected with the outlet buffer chamber to be substantially negligible during the pressure-feed of the fluid from the pump chamber. This configuration immediately lowers the internal pressure of the pump chamber, thus enabling the fluid to be fed with high efficiency.

[0021] According to another embodiment, there is provided the fluid feed pump of the first aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the fluid channel may be connected with the inlet channel, so that the fluid fed from the outlet channel to the fluid channel is returned to the inlet buffer chamber.

[0022] In the fluid feed pump of this embodiment, the fluid fed to the fluid channel is accumulated in the inlet buffer chamber and is supplied to the pump chamber via the check valve. There is accordingly no shortage of the fluid supplied via the check valve to the pump chamber, even when the fluid fed from the pump chamber is accumulated in the outlet buffer chamber and does not smoothly flow out to the fluid channel. This configuration advantageously avoids the decreased capacity of the fluid feed pump caused by insufficient supply of the fluid to the pump chamber.

[0023] According to another embodiment, there is provided the fluid feed pump of the first aspect, wherein the inlet buffer chamber may have a compliance that is at least five times as high as the compliance of the outlet buffer chamber.

[0024] It is experimentally confirmed that there is no shortage of the fluid supplied to the pump chamber when the compliance of the inlet buffer chamber is at least 5 times as high as the compliance of the outlet buffer chamber. This configuration achieves the full capacity of the fluid feed pump.

[0025] According to another embodiment, there is provided the fluid feed pump of the first aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the inlet buffer chamber may be a deformable pack.

[0026] This configuration readily achieves the inlet buffer chamber of the required level of compliance.

[0027] According to another embodiment, there is provided the fluid feed pump of the first aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the inlet buffer chamber may be a deformable pack to be attachable to and detachable from the fluid feed pump.

[0028] The fluid feed pump of this embodiment enables easy replacement of the deformed pack having the change in properties or easy replacement to a pack of the optimum compliance according to the application of the fluid feed pump.

[0029] According to another embodiment, there is provided the fluid feed pump of the first aspect, wherein the volume of the pump chamber may be changed by actuation of a piezoelectric element.

[0030] Using the piezoelectric element applies a large force to abruptly reduce the volume of the pump chamber, so that large pressure oscillation occurs between the pump chamber and the outlet buffer chamber. The fluid is fed with high efficiency by taking advantage of this pressure oscillation.

[0031] According to a second aspect, there is provided a fluid circulation device using the fluid feed pump described above.

[0032] For example, the light source of a projector generates large amount of heat and is thus required to be cooled down. An increase in light intensity leads to an increase in generated heat and an increase in required cooling capacity. The fluid feed pump of the invention is small in size but has high fluid-feed capacity (high cooling capacity). The fluid feed pump of the invention is thus preferably applicable to a liquid circulation device that circulates a fluid, such as coolant, to cool down. Applying the fluid feed pump of the invention to the fluid circulation device accordingly enables the configuration of a projector that is small in size but has high light intensity.

[0033] According to a third aspect, there is provided a medical device using the fluid feed pump described above.

[0034] The high-pressure spraying capacity is required, for example, in a fluid injection device used to prepare micro-capsules containing medicinal substances or nutritional supplements and surgical instruments like a surgical jet knife used to cut out or remove body tissues by spraying a thin jet of a pressurized fluid, such as water or normal saline solution, from a jet nozzle against the body tissues. The fluid feed pump of the invention is small in size but has high fluid-feed capacity. Using the fluid feed pump of the invention accordingly enables the configuration of a medical device that is small in size but has high spraying capacity. The heat-generating part of the medical device may be cooled down by a fluid circulation device including the fluid feed pump of the invention. This enhances the reliability of the medical device. The heat-generating part of the medical device may be, for example, a piezoelectric actuator of the surgical jet knife.

[0035] According to a fourth aspect, there is provided an electronic device using the fluid feed pump described above.

[0036] For example, circulating a fluid, e.g., coolant, efficiently cools down the heat generated in an electronic device, such as a projector. The fluid feed pump of the invention is small in size but has high fluid-feed capacity. Using the fluid feed pump of the invention accordingly enables the configuration of a compact electronic device.

[0037] According to a fifth aspect, there is provided a fluid feed pump, including: a pump chamber having volume changeable by actuation of a piezoelectric element; an outlet channel arranged to allow outflow of a fluid from the pump chamber to a fluid channel; an inlet channel arranged to supply the fluid to the pump chamber; and a check valve provided between the inlet channel and the pump chamber. The piezoelectric element is actuated in a shorter period than a time constant when internal pressure of the pump chamber increases and subsequently decreases. The fluid feed pump further includes an outlet buffer chamber provided between the outlet channel and the fluid channel and configured to have a compliance that is higher than a compliance of the pump chamber but is at most 100 times as high as the compliance of the pump chamber.

[0038] In the fluid feed pump of this aspect, the volume of the pump chamber is increased to suck the fluid out of the inlet channel to the pump chamber via the check valve and is subsequently decreased to feed the fluid from the outlet channel to the fluid channel. In the structure that the fluid channel is directly connected with the outlet channel, due to the high flow resistance of the fluid channel, the internal pressure of the pump chamber increases with a decrease in volume of the pump chamber. The subsequent direct flow of the fluid from the outlet channel to the fluid channel lowers the internal pressure of the pump chamber. The fluid feed pump is driven in the shorter period than the time constant τ when the internal pressure of the pump chamber decreases. The fluid feed pump of this aspect has the outlet buffer chamber provided between the outlet channel and the fluid channel and configured to have the compliance that is higher than the compliance of the pump chamber but is at most 100 times as high as the compliance of the pump chamber.

[0039] When the volume of the pump chamber decreases, the fluid flows from the pump chamber to the outlet buffer chamber to increase the internal pressure of the outlet buffer chamber. This results in feeding the fluid from the outlet buffer chamber to the fluid channel. The excessively high compliance of the outlet buffer chamber extends the time until the expected fluid feed amount is fulfilled after start of the operation of the fluid feed pump. As described later in detail, the capacity of the fluid feed pump increases with an increase in compliance of the outlet buffer chamber relative to the compliance of the pump chamber, but reaches the plateau when the compliance of the outlet buffer chamber becomes about 100 times as high as the compliance of the pump chamber. Setting the compliance of the outlet buffer chamber to be higher than the compliance of the pump chamber but at most 100 times as high as the compliance of the pump chamber advantageously shortens the time until the expected fluid feed amount is fulfilled after start of the operation of the fluid feed pump.

[0040] According to one embodiment, there is provided the fluid feed pump of the fifth aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the fluid channel may be connected with the inlet channel, so that the fluid fed from the outlet channel to the fluid channel is returned to the inlet buffer chamber.

[0041] In the fluid feed pump of this embodiment, the fluid fed to the fluid channel is accumulated in the inlet buffer chamber and is supplied to the pump chamber via the check valve. There is accordingly no shortage of the fluid supplied via the check valve to the pump chamber, even when the fluid fed from the pump chamber is accumulated in the outlet buffer chamber and does not smoothly flow out to the fluid channel. This configuration advantageously avoids the decreased capacity of the fluid feed pump caused by insufficient supply of the fluid to the pump chamber.

[0042] According to another embodiment, there is provided the fluid feed pump of the fifth aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the inlet buffer chamber

may have a compliance that is at least five times as high as the compliance of the outlet buffer chamber.

[0043] It is experimentally confirmed that there is no shortage of the fluid supplied to the pump chamber when the compliance of the inlet buffer chamber is at least 5 times as high as the compliance of the outlet buffer chamber. This configuration achieves the full capacity of the fluid feed pump.

[0044] According to another embodiment, there is provided the fluid feed pump of the fifth aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the inlet buffer chamber may be a deformable pack.

[0045] The fluid feed pump of this embodiment enables easy replacement of the deformed pack having the change in properties or easy replacement to a pack of the optimum compliance according to the application of the fluid feed pump.

[0046] According to another embodiment, there is provided the fluid feed pump of the fifth aspect, which may further include an inlet buffer chamber provided between the inlet channel and the check valve, wherein the inlet buffer chamber may be a deformable pack to be attachable to and detachable from the fluid feed pump.

[0047] The fluid feed pump of this embodiment enables easy replacement of the deformed pack having the change in properties or easy replacement to a pack of the optimum compliance according to the application of the fluid feed pump.

[0048] According to a sixth aspect, there is provided a fluid circulation device using the fluid feed pump described above.

[0049] For example, the light source of a projector generates large amount of heat and is thus required to be cooled down. An increase in light intensity leads to an increase in generated heat and an increase in required cooling capacity. The fluid feed pump of the invention is small in size but has high fluid-feed capacity (high cooling capacity). The fluid feed pump of the invention is thus preferably applicable to a liquid circulation device that circulates a fluid, such as coolant, to cool down. Applying the fluid feed pump of the invention to the fluid circulation device accordingly enables the configuration of a projector that is small in size but has high light intensity.

[0050] According to a seventh aspect, there is provided a medical device using the fluid feed pump described above.

[0051] The high-pressure spraying capacity is required, for example, in a fluid injection device used to prepare micro-capsules containing medicinal substances or nutritional supplements and surgical instruments like a surgical jet knife used to cut out or remove body tissues by spraying a thin jet of a pressurized fluid, such as water or normal saline solution, from a jet nozzle against the body tissues. The fluid feed pump of the invention is small in size but has high fluid-feed capacity. Using the fluid feed pump of the invention accordingly enables the configuration of a medical device that is small in size but has high spraying capacity. The heat-generating part of the medical device may be cooled down by a fluid circulation device including the fluid feed pump of the invention. This enhances the reliability of the medical device. The heat-generating part of the medical device may be, for example, a piezoelectric actuator of the surgical jet knife.

[0052] According to an eighth aspect, there is provided an electronic device using the fluid feed pump described above.

[0053] For example, circulating a fluid, e.g., coolant, efficiently cools down the heat generated in an electronic device, such as a projector. The fluid feed pump of the invention is small in size but has high fluid-feed capacity. Using the fluid feed pump of the invention accordingly enables the configuration of a compact electronic device.

BRIEF DESCRIPTION OF THE DRAWINGS

[0054]

Fig. 1 illustrates the structure of a fluid feed pump according to one embodiment of the invention;
 Figs. 2A to 2C show changes in internal pressure of a pump chamber by application of a driving signal to a piezoelectric element;
 Fig. 3 illustrates different variations in fluid feed amount in the presence and in the absence of an outlet buffer chamber;
 Fig. 4 illustrates the effect of the volume of the outlet buffer chamber on the volume of the pump chamber;
 Fig. 5 illustrates time changes before stabilization of the fluid feed amount after start of operation of the fluid feed pump;
 Fig. 6 illustrates the configuration of a circulation channel using the fluid feed pump of the embodiment;
 Fig. 7 illustrates the effect of the volume of an inlet buffer chamber on the volume of the outlet buffer chamber;
 Fig. 8 illustrates a fluid feed pump configured to increase the compliance of the inlet buffer chamber according to one modification;
 Figs. 9A to 9C illustrate circulation of a fluid through a fluid channel by the operation of the fluid feed pump of the modification;
 Figs. 10A to 10D illustrate the structure of a film pack employed in the fluid feed pump of the modification;
 Figs. 11A and 11B illustrate an application of the fluid feed pump to an electronic device;
 Fig. 12 schematically illustrates the structure of a fluid ejection system as an application of the fluid feed pump to a medical device;
 Fig. 13 illustrates the general structure of a fluid feed pump;
 Figs. 14A and 14B illustrate changes in internal pressure of a pump chamber by application of a driving signal to a

piezoelectric element; and

Fig. 15 shows the relationship between the driving frequency of the fluid feed pump and the fluid feed amount.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0055] Fig. 1 illustrates the structure of a fluid feed pump 100 according to one embodiment. As illustrated, the fluid feed pump 100 of this embodiment differs from the fluid feed pump shown in Fig. 13 by providing an outlet buffer chamber 118. More specifically, in the fluid feed pump 100 of the embodiment, part of a pump chamber 102 is formed from a diaphragm 104. A piezoelectric element 106 is placed in a casing 108. An inlet buffer chamber 112 is provided via a check valve 110 above the pump chamber 102. A fluid is supplied through an inlet channel 114 into the inlet buffer chamber 112. The pump chamber 102 is connected with the outlet buffer chamber 118 via an outlet channel 116, and a fluid channel 122 is further connected with the outlet buffer chamber 118.

[0056] When a driving signal is applied to the piezoelectric element 106 to extend the piezoelectric element 106, the diaphragm 104 is deformed to reduce the volume of the pump chamber 102. This causes the fluid in the pump chamber 102 to flow through the outlet channel 116 into the outlet buffer chamber 118 and then feeds the fluid from the outlet buffer chamber 118 into the fluid channel 122.

[0057] Figs. 2A to 2C show changes in internal pressure of the pump chamber 102 by application of a driving signal to the piezoelectric element 106 in the fluid feed pump 100 of the embodiment. Fig. 2A shows a driving signal applied to the piezoelectric element 106. Figs. 2B and 2C show time changes in internal pressure with respect to the outlet buffer chamber 118 of different volumes. As illustrated in Fig. 2A, with an increase in voltage of the driving signal (driving voltage), the piezoelectric element 106 is extended to reduce the volume of the pump chamber 102, which abruptly increases the internal pressure of the pump chamber 102. The outlet buffer chamber 118 is provided between the outlet channel 116 and the fluid channel 122, so that the fluid pressurized in the pump chamber 102 moves to the outlet buffer chamber 118, so as to immediately lower the internal pressure of the pump chamber 102. This phenomenon is seen from the pump chamber 102. The fluid channel 122 located beyond the outlet buffer chamber 118 hardly affects the pump chamber 102, because of the presence of the outlet buffer chamber 118. This configuration of connecting the fluid channel 122 with the pump chamber 102 across the outlet channel 116 and the outlet buffer chamber 118 is thus substantially equivalent to the configuration of simply connecting the outlet channel 116 with the pump chamber 102.

[0058] This phenomenon is explained more in detail below. When the fluid flows at a flow rate Q through a circular channel, such as the fluid channel 122 or the outlet channel 116, an internal pressure difference ΔP between two arbitrary points in the circular channel is expressed by Equation (1) given below:

[0059]

$$\Delta P = Q \times R \quad (1)$$

where R represents a flow resistance between the two arbitrary points in the circular channel. When the fluid flow in the channel is steady and laminar flow (Hagen-Poiseuille flow), the flow resistance R is expressed by Equation (2) given below, wherein the fluid of absolute viscosity μ flows through the circular channel having the radius r and the length L between the two arbitrary points:

[0060]

$$R = 8 \times \mu \times L / (\pi r^4) \quad (2)$$

In the structure without the outlet buffer chamber 118 between the outlet channel 116 and the fluid channel 122 like the fluid feed pump shown in Fig. 13, there is a variation in volume of the pump chamber 102. The fluid flowing through the outlet channel 116 and the fluid channel 122 accordingly makes a non-stationary flow, so that the flow resistance in the outlet channel 116 and in the fluid channel 122 is increased to the level of about four times as high as the flow resistance given by Equation (2).

[0061] When pressure is applied to inside the fluid chamber filled with the fluid, such as the pump chamber 102 or the outlet buffer chamber 118, there is volume expansion or fluid compression by deformation of the fluid chamber. For example, in a simplest application, a fluid chamber having the volume V and the bulk modulus of elasticity K is filled with a fluid of compressibility κ_F (e.g., liquid), and a pressure P is applied to the fluid in the fluid chamber. A variation ΔV_1 in volume by deformation of the fluid chamber is expressed as the following Equation (3).

[0062]

$$\Delta V_1 = V/K \times P \quad (3)$$

A variation ΔV_2 in volume by compression of the fluid is expressed as the following Equation (4).
[0063]

$$\Delta V_2 = V \times \kappa_F \times P \quad (4)$$

An apparent variation ΔV in volume of the fluid chamber by the pressure P is accordingly given as the following Equation (5).
[0064]

$$\Delta V = V \times (1/K + \kappa_F) \times P \quad (5)$$

This product $V \times (1/K + \kappa_F)$ is a value called "compliance". Under the conditions that the fluid chamber is made of a material of the same modulus of elasticity, that the fluid has the same compressibility and that the same pressure P is applied, Equation (5) indicates that the apparent variation ΔV in volume of the fluid chamber is proportional to the volume V of the fluid chamber.

[0065] As described above, in the fluid feed pump without the outlet buffer chamber 118 as shown in Fig. 13, the internal pressure of the pump chamber 102 slowly decreases by a time constant τ that is defined as the product of the flow resistance in the outlet channel 116 and the fluid channel 122 (i.e., about four times as high as the flow resistance R given by Equation (2) according to the experimental result) and the compliance of the pump chamber 102. In the fluid feed pump 100 of the invention with the outlet buffer chamber 118 having the higher compliance than that of the pump chamber 102, however, the pump chamber 102 is hardly affected by the flow resistance in the fluid channel 122. The outflow of the fluid corresponding to volume reduction of the pump chamber 102 is affected by only the flow resistance and the inertance of the outlet channel 116. This shortens the time required to complete the outflow of the fluid corresponding to the volume reduction.

[0066] The fluid moving through the outlet channel 116 receives the inertial force by the inertance of the outlet channel 116, so that the internal pressure of the pump chamber 102 becomes negative. The fluid can thus be supplied from the inlet buffer chamber 112 to the pump chamber 102. The inertance of the outlet channel 116 is larger than the inertance of a communicating path between the inlet buffer chamber 112 and the pump chamber 102. The fluid moving through the outlet channel 116 thus hardly goes back to the pump chamber 102, and the fluid is supplied from the inlet buffer chamber 112 to the pump chamber 102. This is attributed to the extremely small inertance of the channel on the inlet side (i.e., passage with the check valve 110) compared with the inertance of the channel on the outlet side (i.e., outlet channel 116).

[0067] The inertance is a characteristic value of the channel and indicates the flowability of the fluid flowing through the channel under application of a pressure on one end of the channel. In a simple example, it is assumed that a channel having the cross sectional area S and the length L is filled with a fluid (e.g., liquid) having the density ρ and that a pressure P is applied on one end of the channel (more specifically, pressure difference P between both ends). The force of pressure $P \times$ cross sectional area S then acts on the fluid in the channel, so that the fluid in the channel flows out. When the fluid flowing out has the acceleration " a ", since the mass of the fluid in the channel is given by the density $\rho \times$ cross sectional area $S \times$ length L , the equation of motion is transformed as the following Equation (6).

[0068]

$$P = \rho \times L \times a \quad (6)$$

When the fluid flowing through the channel has the volumetric flow rate Q and the flow velocity v , the following equation is given:

[0069]

$$Q = v \times S, \text{ so that} \\ \frac{dQ}{dt} = a \times S \quad (7)$$

5 **[0070]** Substituting Equation (7) into Equation (6) gives the following equation:

$$P = (\rho \times L/S) \times (dQ/dt) \quad (8)$$

10 This equation transforms the motion of equation with respect to the fluid in the channel using the pressure P applied on one end of the channel (more specifically, pressure difference between both ends) and dQ/dt. Equation (8) indicates an increase in dQ/dt (i.e., a greater change in flow velocity) with a decrease in value ($\rho \times L/S$) under application of the same pressure P. This value ($\rho \times L/S$) is called inertance.

15 **[0071]** In the fluid feed pump 100 of Fig. 1 according to the embodiment, the outlet channel 116 has the large inertance, because of its small inner diameter and long channel length. The channel on the inlet side of the pump chamber 102, on the other hand, has the small inertance, because of the short channel length of the passage with the check valve 110. When the pump chamber 102 has negative pressure, the fluid on the outlet side having the large resultant inertance is hardly sucked into the pump chamber 102, while the fluid on the inlet side having the small resultant inertance is
20 sucked into the pump chamber 102. Because of the reasons described above, reducing the volume of the pump chamber 102 causes the fluid pressurized in the pump chamber 102 to move through the outlet channel 116 to the outlet buffer chamber 118, so that the internal pressure of the pump chamber 102 immediately decreases (within a shorter time than the time constant τ). The internal pressure of the pump chamber 102 becomes negative by the inertia of the fluid flowing through the outlet channel 116, and the fluid is immediately supplied to the pump chamber 102 via the check valve 110.
25 The fluid can thus be fed into the pump chamber 102 with high efficiency, even when the fluid feed pump 100 is driven in shorter periods than the time constant τ .

[0072] The fluid flowing into the outlet buffer chamber 118 hardly flows out, due to the high flow resistance in the fluid channel 122. This results in increasing the internal pressure of the outlet buffer chamber 118. The internal pressure of the pump chamber 102 decreases in this state, so that the inertial force of the fluid in the outlet channel 116 gradually
30 decreases. Since no check valve 110 is provided between the pump chamber 102 and the outlet buffer chamber 118, there is a reverse flow from the outlet buffer chamber 118 into the pump chamber 102. Even when the fluid flows back to the pump chamber 102, the check valve 110 prevents the fluid from flowing into the inlet buffer chamber 112. This increases the internal pressure of the pump chamber 102 again and causes the back-flow fluid to flow toward the outlet buffer chamber 118. This again causes the negative pressure in the pump chamber 102, so that the fluid can further be
35 supplied from the inlet buffer chamber 112 to the pump chamber 102. Repeating such oscillating motions opens the check valve 110 a plurality of times (twice in the illustrated example of Figs. 2A to 2C) during one operation and enables the fluid to be supplied to the pump chamber 102.

[0073] This phenomenon is typically regarded as propagation by the pressure wave in the fluid propagating between the pump chamber 102 and the outlet buffer chamber 118. The fluid feed pump 100 of the embodiment has the short
40 distance between the pump chamber 102 and the outlet buffer chamber 118 (about 10 cm at the longest, irrespective of the size of the outlet buffer chamber). The oscillation period by propagation of the pressure wave is expected to be 0.2 msec at the longest when the sonic speed in the fluid is about 1000 m/sec. The natural oscillation period of the oscillation shown in Fig. 2B or Fig. 2C is, however, about 0.35 msec for the outlet buffer chamber 118 of the smaller volume and about 0.4 msec for the outlet buffer chamber 118 of the larger volume. These values are not explainable
45 by propagation of the pressure wave.

[0074] This phenomenon is explainable by taking into account the compressibility of the fluid (in other words, by treating the fluid as compressive fluid). When this phenomenon is regarded as natural oscillation (resonance) defined by the compliance of the pump chamber 102, the inertance of the outlet channel 116 and the compliance of the outlet buffer chamber 118, the natural oscillation period T is expressed by Equation (9) given below:

50 **[0075]**

$$T = 2\pi(MC)^{1/2} \quad (9)$$

55 where M represents the inertance of the outlet channel 116 and C represents the resultant compliance of the pump chamber 102 and the outlet buffer chamber 118. When C_1 represents the compliance of the pump chamber 102 and C_2 represents the compliance of the outlet buffer chamber 118, the resultant compliance C is given by Equation (10) below:

[0076]

$$C = 1/(1/C_1 + 1/C_2) \quad (10)$$

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Using the natural oscillation defined by Equation (9) can reproduce the oscillations shown in Figs. 2B and 2C and can explain why the natural oscillation period T is increased with an increase in volume of the outlet buffer chamber 118 (which results in increasing the compliance of the outlet buffer chamber 118). From Equations (9) and (10) given above, it is understood that the volume of the pump chamber 102 affects the natural oscillation period T.

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[0077] Fig. 3 illustrates different variations in fluid feed amount in the presence and in the absence of the outlet buffer chamber 118. More specifically, Fig. 3 shows the measurement results of the fluid feed amount in the fluid feed pump without the outlet buffer chamber 118 and in the fluid feed pump 100 of the embodiment with the outlet buffer chamber 118. As shown in Fig. 3, providing the outlet buffer chamber 118 significantly increases the fluid feed amount. Additionally, the fluid feed amount increases with an increase in volume of the outlet buffer chamber 118. This is due to the reasons given below.

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[0078] The fluid in the inlet buffer chamber 112 flows into the pump chamber 102 during the time period when the pump chamber 102 has negative pressure (negative pressure time period). The longer negative pressure time period increases the flow rate of the fluid flowing from the inlet buffer chamber 112 into the pump chamber 102 (this flow rate corresponds to the fluid feed amount). As shown in Figs. 2B and 2C, the oscillation of the internal pressure of the pump chamber 102 is attenuated by the flow resistance in the outlet channel 116, so that there is a limited number of times when the internal pressure of the pump chamber 102 becomes negative. The longer negative pressure time period each time increases the flow rate into the pump chamber 102. The longer natural oscillation period T is accordingly preferable. As clearly understood from Equation (9), the higher resultant compliance C results in increasing the natural oscillation period T. Increasing the volume (compliance) of the pump chamber 102, however, decreases the ratio of the volume reduction caused by decreasing the volume of the pump chamber 102 to the volume of the pump chamber 102 and thereby lowers the pressure of the pump chamber 102. The volume (compliance) of the outlet buffer chamber 118 is accordingly increased to increase the fluid feed amount.

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[0079] Fig. 4 illustrates the effect of the volume of the outlet buffer chamber 118 on the volume of the pump chamber 102. More specifically, Fig. 4 shows a variation in fluid feed amount with a variation in volume (compliance) of the outlet buffer chamber 118 relative to the volume (compliance) of the pump chamber 102. As illustrated, setting the volume (compliance) of the outlet buffer chamber 118 to 10 times or more the volume (compliance) of the pump chamber 102 at least doubles the fluid feed amount. The fluid feed amount reaches the plateau when the volume (compliance) of the outlet buffer chamber 118 is 100 times or more the volume of the pump chamber 102. During this time period of natural oscillation, the internal pressure of the pump chamber 102 varies. The variation in internal pressure of the pump chamber 102 decreases with an increase in volume (compliance) of the outlet buffer chamber 118 relative to the volume (compliance) of the pump chamber 102. Increasing the volume (compliance) of the outlet buffer chamber 118 relative to the volume (compliance) of the pump chamber 102 accordingly has the effect of reducing pulsation.

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[0080] Fig. 5 illustrates measurement examples of time change before stabilization of the fluid feed amount after start of operation of the fluid feed pump 100 of the embodiment. The solid-line curve of Fig. 5 shows a time change with respect to the outlet buffer chamber 118 of the large volume (the volume of the outlet buffer chamber 118 is 100 times as large as the volume of the pump chamber 102). The broken-line curve of Fig. 5 shows a time change with respect to the outlet buffer chamber 118 of the larger volume (the volume of the outlet buffer chamber 118 is 200 times as large as the volume of the pump chamber 102). Immediately after start of operation of the fluid feed pump 100, the fluid feed amount increases, accompanied with a gradual increase in internal pressure of the outlet buffer chamber 118. An excessively large volume (high compliance) of the outlet buffer chamber 118 slows the increase in internal pressure of the outlet buffer chamber 118 and extends the time before stabilization of the fluid feed amount. The excessively large volume (high compliance) of the outlet buffer chamber 118 is thus non-preferable. In the presence of a circulation channel where the fluid flowing through the fluid channel 122 is circulated to the inlet channel 114 as illustrated in Fig. 6, an increase in amount of the fluid accumulated in the outlet buffer chamber 118 causes deficiency of the fluid circulating through the fluid channel 122 and causes the inlet buffer chamber 112 to have negative pressure, which may result in decreasing the fluid feed amount. Due to these reasons, the volume (compliance) of the outlet buffer chamber 118 is preferably at least about 100 times as large as (as high as) the volume (compliance) of the pump chamber 102.

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Fig. 6 illustrates the configuration of a circulation channel using the fluid feed pump 100 of the embodiment. Connecting the circulation channel with the fluid feed pump 100 is referred to as fluid circulation device 100X.

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[0081] Fig. 7 illustrates the effect of the volume of the inlet buffer chamber 112 on the volume of the outlet buffer chamber 118. More specifically, Fig. 7 shows a variation in fluid feed amount with a variation in volume (compliance) of the inlet buffer chamber 112 relative to the volume (compliance) of the outlet buffer chamber 118. Setting the volume

(compliance) of the inlet buffer chamber 112 to 5 times or more the volume (compliance) of the outlet buffer chamber 118 stabilizes the fluid feed amount. This may be because the inlet buffer chamber 112 having the sufficient volume (compliance) does not have extreme negative pressure even when the fluid fed from the pump chamber 102 is accumulated in the outlet buffer chamber 118. The volume (compliance) of the inlet buffer chamber 112 is thus preferably 5

times or more the volume (compliance) of the outlet buffer chamber 118.
[0082] Fig. 8 illustrates a fluid feed pump 200 configured to increase the compliance of the inlet buffer chamber 112 according to one modification. In the illustrated example of Fig. 8, a circulation channel is configured using the fluid feed pump 200 of the modification.

[0083] As illustrated, the fluid feed pump 200 of the modification is generally structured by integrating a piezoelectric element casing 210 with a channel casing 240. The piezoelectric element casing 210 has a through hole 210h of circular cross section, which is formed in the approximate center of a joint surface with the channel casing 240 to pass through the piezoelectric element casing 210. The bottom of the through hole 210h is securely closed by a bottom plate 212. A laminated-type piezoelectric element 214 is placed in the through hole 210h of this piezoelectric element casing 210, and the bottom of the piezoelectric element 214 is fastened to the bottom plate 212. A circular reinforcement plate 216 is attached to the upper end of the piezoelectric element 214, and a circular diaphragm 218 made of e.g., metal thin plate, is fixed to the upper surface of the reinforcement plate 216. The outer diameter of the diaphragm 218 is larger than the inner diameter of the through hole 210h. The thickness of the reinforcement plate 216 is set, such that the diaphragm 218 fixed to the reinforcement plate 216 comes into contact with the upper surface of the piezoelectric element casing 210 (i.e., joint surface with the channel casing 240).

[0084] The channel casing 240 has a circular recess 240c formed on the joint surface with the piezoelectric element casing 210, and a ring-shaped annular member 220 is set in this recess 240c. The inner diameter of the annular member 220 is smaller than the outer diameter of the diaphragm 218. When the channel casing 240 and the piezoelectric element casing 210 are fixed to each other, e.g., by screwing, the diaphragm 218 is located between the annular member 220 and the piezoelectric element casing 210. A pump chamber 230 is accordingly defined by the recess 240c of the channel casing 240, the inner circumferential face of the annular member 220 and the diaphragm 218. Deformation of the diaphragm 218 by expanding or contracting the piezoelectric element 214 changes the volume of the pump chamber 230 as described later in detail.

[0085] The channel casing 240 also has a fluid chamber 246 arranged to lead the fluid to the pump chamber 230, an outlet channel 242 arranged to lead the fluid in the pump chamber 230 to one end of a fluid channel 300 connected with the side face of the channel casing 240, and an inlet channel 244 arranged to lead the fluid supplied from the other end of the fluid channel 300 connected with the side face of the channel casing 240 to the fluid chamber 246. Although being omitted from the illustration to avoid complexity, as in the fluid feed pump 100 of the embodiment, in the fluid feed pump 200 of the modification, the pump chamber 230 is connected with an outlet buffer chamber via the outlet channel 242, and the fluid channel 300 is connected with the outlet buffer chamber.

[0086] The fluid chamber 246 has one end open to the upper surface of the channel casing 240 (i.e., opposite surface opposed to the joint surface with the piezoelectric element casing 210) and the other end open to the pump chamber 230 and is tapered (to have the smaller cross sectional area) toward the pump chamber 230. The inlet channel 244 is connected with the middle of the fluid chamber 246. A check valve 248 is provided on one end of the fluid chamber 246 on the side of the pump chamber 230 to allow the inflow of the fluid from the fluid chamber 246 to the pump chamber 230 but to prohibit the backflow of the fluid from the pump chamber 230 to the fluid chamber 246. A connection member 262 of a film pack 260 made of a flexible film having gas barrier property and heat resistance is air-tightly fit in an end of the fluid chamber 246 open to the upper surface of the channel casing 240. The film pack 260 of the embodiment is attachable to and detachable from the channel casing 240. The structure of the film pack 260 will be described later in detail with reference to another drawing.

[0087] The fluid channel 300 may be made of a pressure-resistant silicone tube or resin tube. In the circulation channel of this structure, the fluid is circulated through the fluid channel 300 by actuation of the piezoelectric element 214 of the fluid feed pump 200 as described below.

[0088] Figs. 9A to 9C illustrate circulation of the fluid through the fluid channel 300 by the operation of the fluid feed pump 200. Fig. 9A shows the state that the fluid feed pump 200 does not work (i.e., the state before application of the driving voltage to the piezoelectric element 214). In this state, the pump chamber 230 is filled with the fluid.

[0089] When the driving voltage is applied to the piezoelectric element 214 in the state that the pump chamber 230 is filled with the fluid as shown in Fig. 9A, the increasing driving voltage expands the piezoelectric element 214 as shown in Fig. 9B. This results in pressing the diaphragm 218 toward the pump chamber 230 via the reinforcement plate 216, so that the volume of the pump chamber 230 is reduced and the fluid in the pump chamber 230 is pressurized. In this state, the check valve 248 is in the closed position to prevent the backflow of the fluid from the pump chamber 230 to the fluid chamber 246. The fluid corresponding to the volume reduction of the pump chamber 230 is accordingly pressure-fed through the outlet channel 242 and the outlet buffer chamber (not shown) toward the fluid channel 300.

[0090] While the fluid is fed into the fluid channel 300, the fluid in the fluid channel 300 is gradually pressed downstream.

As described above, in the circulation channel of the modification, the fluid channel 300 and the fluid feed pump 200 form the closed system. The fluid pressed out of the fluid channel 300 and returned to the fluid feed pump 200 flows through the inlet channel 244 into the film pack 260. The film pack 260 is made of a flexible film and is attached not in the fully-tense state filled with the fluid but in the state having some room for further expansion. The fluid going back from the fluid channel 300 flows into the film pack 260 to expand the film pack 260. This structure prevents the pressure increase in the film pack 260 or in the fluid chamber 246 connecting with the film pack 260.

[0091] When the piezoelectric element 214 is subsequently contracted to its original length by the decreasing driving voltage as shown in Fig. 9C, the volume of the pump chamber 230 is increased and returned to the original volume. In this state, the pump chamber 230 has the negative pressure, so that the check valve 248 is opened to suck the fluid from the fluid chamber 246 into the pump chamber 230. The negative pressure in the pump chamber 230 also acts on the outlet channel 242. The flow resistance of the outlet channel 242 is set to be lower than the flow resistances of the fluid chamber 246 and the check valve 248. The fluid is thus likely to flow from the fluid chamber 246 into the pump chamber 230, rather than from the outlet channel 242. The fluid chamber 246 is connected with the film pack 260, and a sufficient amount of fluid is kept in the film pack 260. The fluid can thus be continuously supplied to the pump chamber 230. The film pack 260 is contracted, accompanied with supply of the fluid in the film pack 260 to the pump chamber 230. This effectively prevents the fluid chamber 246 and the film pack 260 from having negative pressure.

[0092] When the piezoelectric element 214 is expanded again by the increasing driving voltage after filling the fluid into the pump chamber 230 returned to the original volume, the fluid pressurized in the pump chamber 230 is press-fed toward the fluid channel 300 as shown in Fig. 9B. The fluid feed pump 200 repeats this series of operations to circulate the fluid through the fluid channel 300.

[0093] Figs. 10A to 10D illustrate the structure of the film pack 260. Fig. 10A is an exploded perspective view of the film pack 260. The film pack 260 includes a pair of flexible films 264 having gas barrier property and heat resistance, a connection member 262 provided to have a connection hole 262a and used to detachably attach the film pack 260 to the fluid chamber 246, and an opening member 266 provided to have an openable and closeable opening. The pair of films 264 are formed in a substantially rectangular shape. The film pack 260 is assembled by air-tightly bonding the peripheries of the pair of films 264 by, e.g., thermal compressing bonding, in the state that the connection member 262 is placed between the pair of films 264 on one end in the longitudinal direction and the opening member 266 is placed between the pair of films 264 on the other end.

[0094] Fig. 10B illustrates the film pack 260 formed by bonding the pair of films 264. The hatched areas in Fig. 10B show the sealed portions bonded by, e.g., thermal compression bonding. As illustrated in Fig. 10B, the pair of films 264 are in contact with each other, when the film pack 260 contains no fluid.

[0095] When the fluid flows through the connection hole 262a of the connection member 262 into the film pack 260, the film pack 260 is expanded to increase the volume and allow accumulation of the fluid between the pair of films 264 as shown in Fig. 10C. When the fluid in the film pack 260 flows out through the connection hole 262a of the connection member 262, on the other hand, the film pack 260 is contracted to decrease the volume. In this manner, the film pack 260 is deformable according to the amount of fluid contained in the film pack 260.

[0096] Fig. 10D illustrates the structure of the film 264 used for the film pack 260. The illustrated film 264 has multilayer structure and includes a middle layer of aluminum foil between an outer layer of polyethylene terephthalate (PET) having excellent impact resistance and an inner layer of polypropylene (PP) having excellent fluid resistance. The respective layers are bonded to one another. Providing the middle layer of aluminum foil enhances the strength and the gas barrier property of the film 264. The film pack 260 of this structure has excellent heat resistance to allow treatment at high temperature (e.g., up to 150°C) and has flexibility to be readily deformable. This film pack 260 is light in weight and is readily formable by thermal compression bonding.

[0097] The structure of the film 264 used for the film pack 260 is, however, not limited to the structure shown in Fig. 10D. For example, the middle layer of aluminum foil may be replaced with ethylene-vinyl alcohol copolymer (EVOH) or polyvinylidene chloride (PVDC). According to another embodiment, the film 264 may be a transparent film prepared by directly bonding an outer layer of polyamide (nylon) to an inner layer of polypropylene (PP). This application enables the user to visually check the inside of the film pack 260 (e.g., fluid level and fluid flow).

[0098] The fluid feed pump 200 of the modification structured as described above has the film pack 260 for the inlet buffer chamber 112 in the fluid feed pump 100 of the embodiment described above. Using the material having the small modulus of elasticity (film 264) for the inlet buffer chamber 112 sufficiently increases the compliance of the inlet buffer chamber 112. As explained previously, the sufficiently high compliance of the inlet buffer chamber 112 relative to the compliance of the outlet buffer chamber 118 enables the fluid to be fed stably at a high flow rate (Fig. 7). Using the film pack 260 for the inlet buffer chamber 112 achieves the full capacity of the fluid feed pump 200.

[0099] The foregoing describes the fluid feed pump 100 of the embodiment and the fluid feed pump 200 of the modification. The invention is, however, not limited to the above embodiment or modification, but a multiplicity of variations and modifications may be made to the embodiment without departing from the scope of the invention. The invention is applicable to various electronic devices, for example, a fluid circulation device configured to circulate a fluid, such as

coolant, and thereby cool down the heat generated in an electronic device, such as a projector. The invention is also applicable to a fluid injection device used to prepare microcapsules containing, for example, medicinal substances or nutritional supplements, surgical instruments like a surgical jet knife used to cut off a target with a high-pressure jet of fluid (e.g., water, normal saline solution, or medicinal solution) ejected from the small-diameter tapered end of the fluid channel, and other medical devices, such as chemical injection device. In the fluid feed pump 100 of the embodiment, the outlet buffer chamber 118 or the inlet buffer chamber 112 may not be necessarily made of a very hard material, such as stainless steel but may be made of any material having small modulus of elasticity. Using the material having small modulus of elasticity provides the sufficiently high compliance even in small volume and thereby gives an extremely-compact fluid feed pump. The following describes applications of the fluid feed pump of the embodiment (or the fluid feed pump of the modification) to an electronic device and a medical device.

[0100] Figs. 11A and 11B illustrate an application of the fluid feed pump of the embodiment (or the fluid feed pump of the modification) to an electronic device. More specifically, in the illustrated example of Figs. 11A and 11B, the fluid feed pump 100 of the embodiment is applied to a projector 301 as an electronic device. As illustrated in Fig. 11A, the projector 301 has an optical system including a plurality of optical components, cooling devices 330 serving to cool down the optical components, a power unit (not shown), and a control unit (not shown), which are placed inside an outer casing 320. The optical system includes light sources 322 arranged to emit light fluxes, liquid crystal light valves 324 arranged to perform light modulation according to image information, a dichroic prism 326 and a projection lens 328.

[0101] The light sources 322 include three light sources 322R to 322B, i.e., R light source 322R emitting R (red) color light, G light source 322G emitting G (green) color light and B light source 322B emitting B (blue) color light. Various solid-state light-emitting elements, such as LED elements, laser diodes, organic EL elements and silicon light-emitting elements, may be used for the respective color light sources 322R to 322B. The light flux is emitted from each of the color light sources 322R to 322B to the corresponding liquid crystal light valve 324.

[0102] The liquid crystal light valve 324 is a transparent liquid crystal panel and changes the array of liquid crystal molecules in the liquid crystal cell to allow or prohibit transmission of light, in response to a driving signal from the controller (not shown), so as to form an optical image according to image information. The operation of allowing or prohibiting transmission of light in the liquid crystal cell herein is called "light modulation". As the results of light modulation by the liquid crystal light valves 324, an R optical image is formed by a liquid crystal light valve 324R receiving the light flux from the light source 322R; a G optical image is formed by a liquid crystal light valve 324G receiving the light flux from the light source 322G; and a B optical image is formed by a liquid crystal light valve 324B receiving the light flux from the light source 322B. The optical images of the respective colors thus obtained are transmitted to the dichroic prism 326.

[0103] The dichroic prism 326 is an optical element of substantially cubic shape provided by bonding four rectangular prisms. A dielectric multilayer film is formed on each interface between adjacent rectangular prisms. The dielectric multilayer film having the controlled film thickness reflects the light flux of only a specific wavelength, while transmitting the light fluxes of the other wavelengths. By taking advantage of this characteristic, the dichroic prism 326 reflects the color light fluxes emitted from the liquid crystal light valves 324 toward the projection lens 328. As the results of reflecting the color light fluxes from the respective liquid crystal light valves 324R to 324B toward the projection lens 328, optical images of the respective color light fluxes are combined and are transmitted to the projection lens 328 as a composite color image. The projection lens 328 projects the composite color image to be enlarged on a screen (not shown).

[0104] The light sources 322 generate heat simultaneously with emitting light. Fluid circulation devices 331 of the closed system are accordingly employed as the cooling devices 330 to cool down the respective color light sources 322R to 322B. Although the cooling devices 330 are used to cool down the light sources 322 according to this embodiment, the cooling devices 330 may be employed to cool down other components (e.g., the liquid crystal light valves 324 or the power unit).

[0105] Fig. 11B illustrates the structure of the cooling device 330. As described previously with reference to Fig. 11A, a plurality of (i.e., three) cooling devices 330 are provided for the respective color light sources 322R to 322B. All the cooling devices 330 have the same structure. The following thus describes one cooling device 330 used to cool down one light source 322.

[0106] As illustrated, the cooling device 330 includes the fluid feed pump 100 and a fluid tube 332 as the components of the fluid circulation device 331. A heat receiver 334 to cause the fluid to absorb the heat from the light source 322 and a radiator 336 to release the heat of the fluid are provided in the middle of the fluid tube 332. On activation of the fluid feed pump 100, a fluid as coolant (for example, water, aqueous ethylene glycol, aqueous propylene glycol or silicone oil) is circulated through the fluid tube 332, the heat receiver 334 and the radiator 336. The flow direction of the coolant is shown by the broken-line arrows in Fig. 11B.

[0107] In the heat receiver 334, the fluid flows in contact with a heat transfer member (not shown) made of a material having high thermal conductivity, such as metal, and the heat transfer member is located in contact with the heat-generating part of the light source 322. The heat of the light source 322 is accordingly transferred to the fluid via the heat transfer member, so that the light source 322 is cooled down. The radiator 336 releases the heat of the fluid flowing

inside to the surrounding air by a plurality of radiator fins provided on the surface. The fluid going through the radiator 336 is accordingly cooled down and returned to the fluid feed pump 100.

[0108] The cooling device 330 is also equipped with a cooling acceleration unit to accelerate the heat release by the radiator 336. This cooling acceleration unit includes a cooling fan 340, a fan motor 342 operated to rotate the cooling fan 340, a motor controller 344 provided to control the operations of the fan motor 342, and a temperature sensor 346. The temperature sensor 346 is located in the vicinity of the light source 322 to detect the temperature of the light source 322 and output the detected temperature to the motor controller 344. The motor controller 344 controls the operations of the fan motor 342, based on the detected temperature. For example, in response to the high temperature detected by the temperature sensor 346, the motor controller 344 increases the rotation speed of the fan motor 342 to accelerate the heat release by the radiator 336. This lowers the temperature of the fluid flowing out of the radiator 336 and supplies the fluid of the lowered temperature to the heat receiver 334, thus lowering the temperature of the light source 322.

[0109] Fig. 12 schematically illustrates the structure of a fluid ejection system 400 as an application of the fluid feed pump of the embodiment (or the fluid feed pump of the modification) to a medical device. The fluid ejection system 400 includes a fluid ejection device 420 and a fluid circulation device 450 used to cool down the fluid ejection device 420. The fluid ejection device 420 is a surgical water jet cutter to spray the water jet stream against the body tissues, such as skin, and separate or cut the body tissues by its impact energy. More specifically, the fluid ejection device 420 of the embodiment is a surgical pulsative water jet cutter to intermittently spray the water jet stream.

[0110] The fluid ejection device 420 includes a pulsation generator 430 operated to spray the water jet stream, a fluid vessel 440 provided to hold water, a feed pump 442 provided to suck water out of the fluid vessel 440 and feed the water to the pulsation generator 430, a connection tube 444 arranged to connect the fluid vessel 440 with the feed pump 442, and a connection tube 446 arranged to connect the feed pump 442 with the pulsation generator 430.

[0111] The pulsation generator 430 includes a fluid chamber 432 provided to temporarily hold water supplied through the connection tube 446, a piezoelectric actuator 434 provided to pulsate the water held in the fluid chamber 432, a fluid spray pipe 436 arranged to allow passage of the water pulsated by the piezoelectric actuator 434, a lower casing 438 provided to place the piezoelectric actuator 434 therein, and an upper casing 439 coupled with the lower casing 438 to define the fluid chamber 432.

[0112] The piezoelectric actuator 434 is a laminated-type piezoelectric element and deforms the diaphragm by taking advantage of the piezoelectric effect of the piezoelectric element to change the volume of the fluid chamber 432. Reducing the volume of the fluid chamber 432 causes the water held in the fluid chamber 432 to go through the fluid spray pipe 436 and to be sprayed out in the form of water jet stream.

[0113] The fluid circulation device 450 is used to cool down the piezoelectric actuator 434 of the fluid ejection device 420 and includes a fluid channel 490 formed as a circulation channel having both ends connected with the fluid feed pump 100 and a controller 496 provided to control the fluid feed pump 100. According to this embodiment, the fluid feed pump 100 and the fluid channel 490 form the circulation channel of the closed system. The fluid in the fluid circulation device 450 is accordingly circulated in the state isolated from the outside air.

[0114] The fluid channel 490 is made from a pressure-resistant, flexible tube. Available examples of the pressure-resistant, flexible tube include medical tubes and general industrial tubes made of, for example, fluororesins such as PTFE, polyimide resins, thermoplastic resins such as PVC, and silicone rubber, although these are only illustrative. According to this embodiment, a silicone tube is employed for the fluid channel 490. The fluid channel 490 is wound on the piezoelectric actuator 434. The heat generated in the piezoelectric actuator 434 is accordingly transferred to the fluid circulating in the fluid channel 490 (circulating fluid), so as to cool down the piezoelectric actuator 434. The hot circulating fluid is cooled down by the air during circulation through the fluid channel 490. A radiator may additionally be provided to accelerate cooling down the circulating fluid. From the standpoint of heat exchange efficiency, the circulating fluid according to this embodiment is a liquid. Water is employed as the liquid in the fluid circulation device 450.

[0115] As described above, the fluid feed pump of the embodiment (or the fluid feed pump of the modification) is applicable to various equipment including fluid circulation devices, electronic devices and medical devices.

[0116] In the embodiments of Figs. 1 and 6, the check valve 110 is employed to prevent the backflow of the fluid from the pump chamber 102 to the inlet buffer chamber 112. Alternatively, any other suitable fluid resistance element may be employed, instead of the check valve 110, to prevent the flow of the fluid from the pump chamber 102 to the inlet buffer chamber 112. The fluid resistance element may be, for example, an orifice. In another example, a channel having the diameter tapered from the inlet buffer chamber 112 toward the pump chamber 102 may be provided as the fluid resistance element. A serpentine channel may also be provided between the inlet buffer chamber 112 and the pump chamber 102 as the fluid resistance element. The serpentine channel is preferable made by a row of short flow paths having the diameter gradually tapered from the inlet buffer chamber 112 toward the pump chamber 102. Similarly, in the embodiment of Fig. 8, any of such other fluid resistance elements may be employed, instead of the check valve 248.

Claims

1. A fluid feed pump that feeds a fluid through a fluid channel, comprising:

a pump chamber having variable volume;
an inlet channel arranged to allow inflow of the fluid from the fluid channel to the pump chamber;
a check valve provided between the inlet channel and the pump chamber;
an outlet channel connected with the pump chamber to feed the fluid out of the pump chamber; and
an outlet buffer chamber connected with the outlet channel to feed the fluid from the outlet channel to the fluid channel, wherein
the outlet buffer chamber has a compliance higher than a compliance of the pump chamber, and
a time per cycle of changing the volume of the pump chamber is shorter than a time constant defined by a product of the compliance of the pump chamber and a flow resistance between an inlet of the outlet channel and an outlet of the fluid channel.

2. The fluid feed pump according to claim 1, wherein
the outlet channel has a flow resistance lower than a flow resistance of the fluid channel.

3. The fluid feed pump according to either one of claims 1 and 2, wherein the compliance of the outlet buffer chamber is at least 10 times as high as the compliance of the pump chamber.

4. The fluid feed pump according to any one of claims 1 to 3, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the fluid channel is connected with the inlet channel, so that the fluid fed from the outlet channel to the fluid channel is returned to the inlet buffer chamber.

5. The fluid feed pump according to claim 4, wherein
the inlet buffer chamber has a compliance that is at least five times as high as the compliance of the outlet buffer chamber.

6. The fluid feed pump according to any one of the preceding claims, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the inlet buffer chamber is a deformable pack.

7. The fluid feed pump according to any one of the preceding claims, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the inlet buffer chamber is a deformable pack to be attachable to and detachable from the fluid feed pump.

8. The fluid feed pump according to any one of claims 1 to 7, wherein
the volume of the pump chamber is changed by actuation of a piezoelectric element.

9. A fluid feed pump, comprising:

a pump chamber having volume changeable by actuation of a piezoelectric element;
an outlet channel arranged to allow outflow of a fluid from the pump chamber to a fluid channel;
an inlet channel arranged to supply the fluid to the pump chamber; and
a check valve provided between the inlet channel and the pump chamber, wherein
the piezoelectric element is actuated in a shorter period than a time constant when internal pressure of the pump chamber increases and subsequently decreases,
the fluid feed pump further comprising:

an outlet buffer chamber provided between the outlet channel and the fluid channel and configured to have a compliance that is higher than a compliance of the pump chamber but is at most 100 times as high as the compliance of the pump chamber.

10. The fluid feed pump according to claim 9, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the fluid channel is connected with the inlet channel, so that the fluid fed from the outlet channel to the fluid
channel is returned to the inlet buffer chamber.

11. The fluid feed pump according to either one of claims 9 and 10, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the inlet buffer chamber has a compliance that is at least five times as high as the compliance of the outlet
buffer chamber.

12. The fluid feed pump according to any one of claims 9 to 11, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the inlet buffer chamber is a deformable pack.

13. The fluid feed pump according to any one of claims 9 to 12, further comprising:

an inlet buffer chamber provided between the inlet channel and the check valve, wherein
the inlet buffer chamber is a deformable pack to be attachable to and detachable from the fluid feed pump.

14. A fluid circulation device, comprising the fluid feed pump according to any one of claims 1 to 13.

15. A medical device, comprising the fluid feed pump according to any one of claims 1 to 13.

16. An electronic device, comprising the fluid feed pump according to any one of claims 1 to 13.

Fig.1

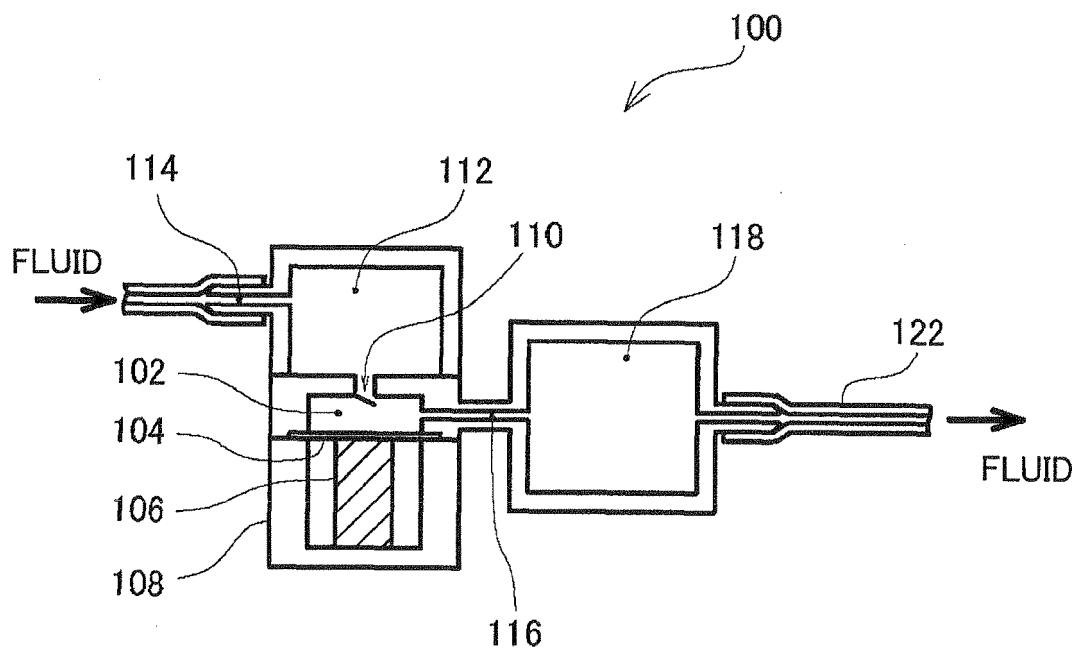


Fig.2A

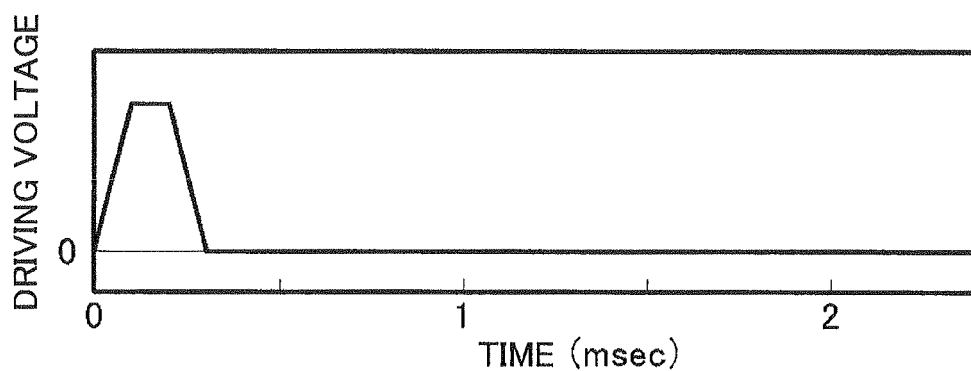


Fig.2B

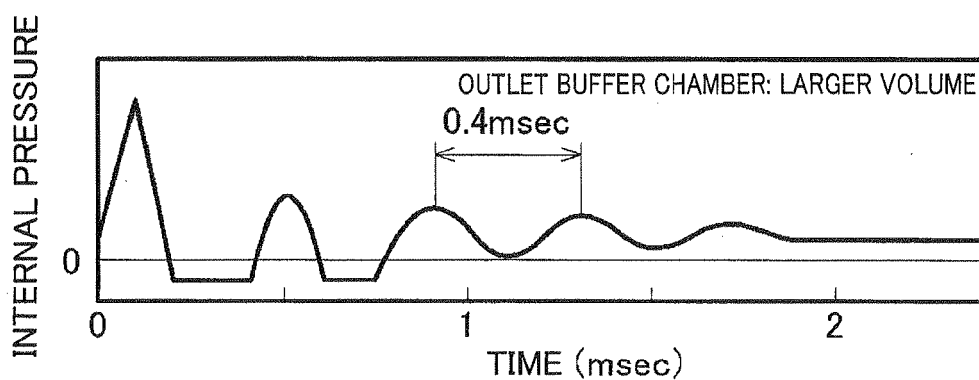


Fig.2C

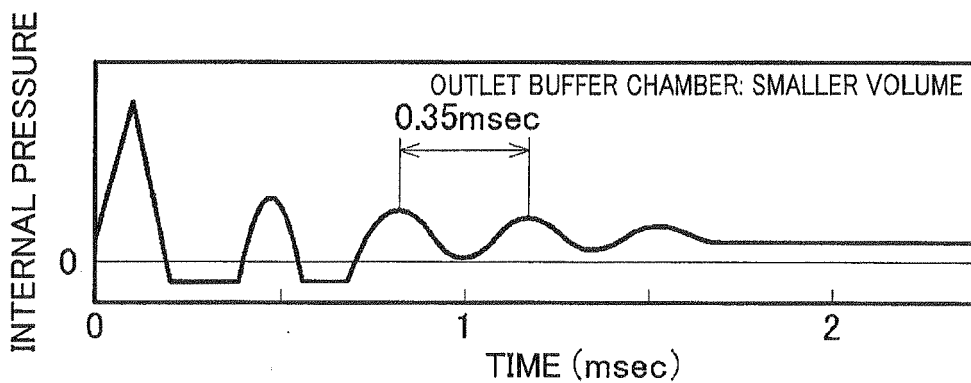


Fig.3

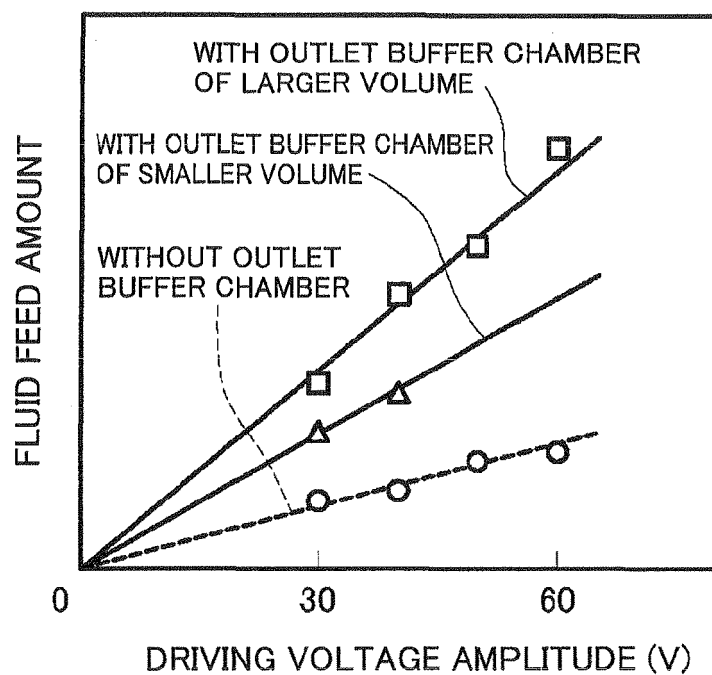


Fig.4

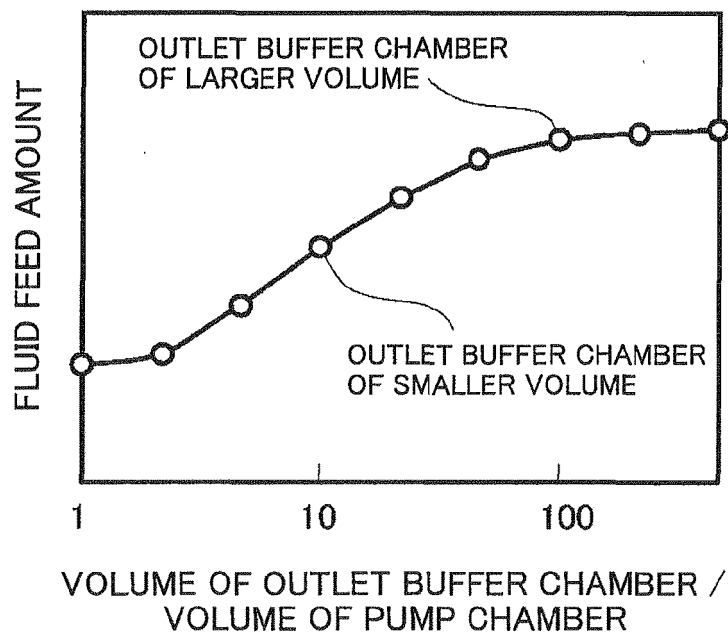


Fig.5

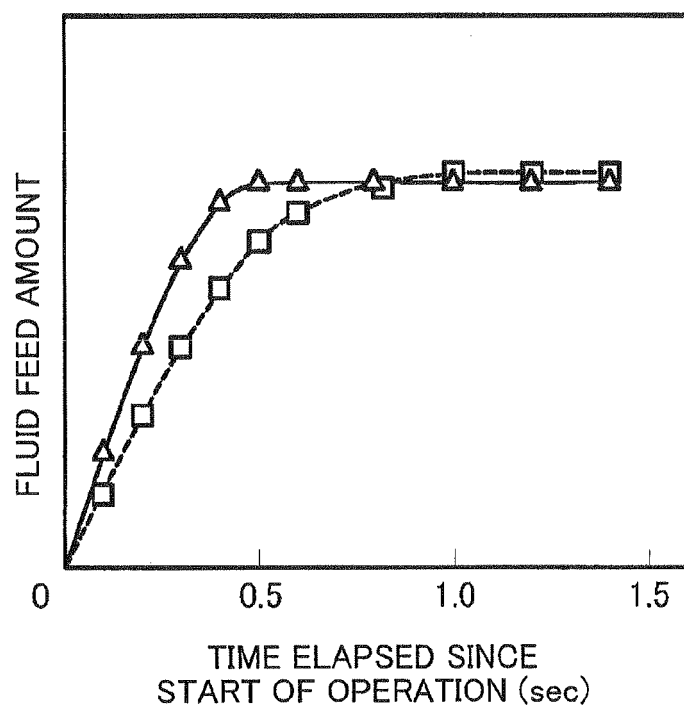


Fig.6

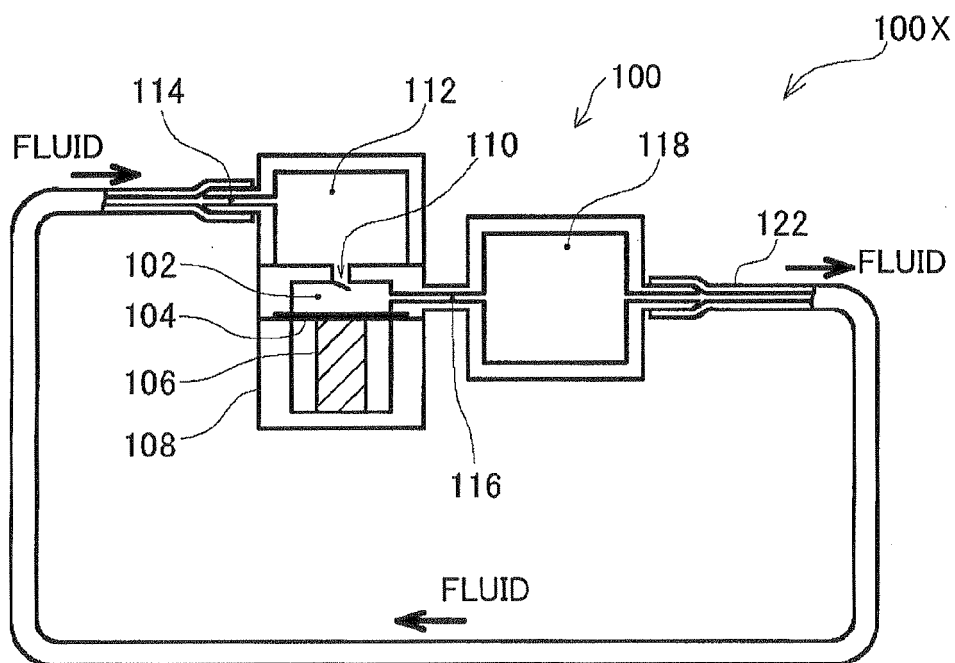


Fig.7

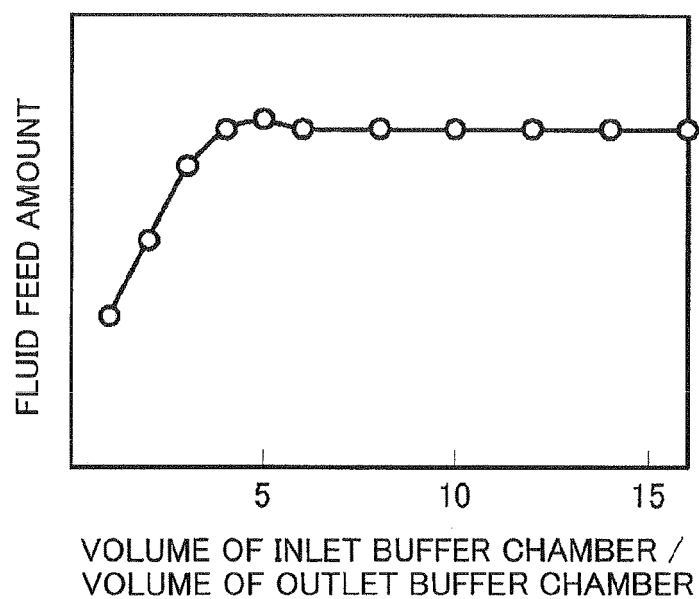


Fig.8

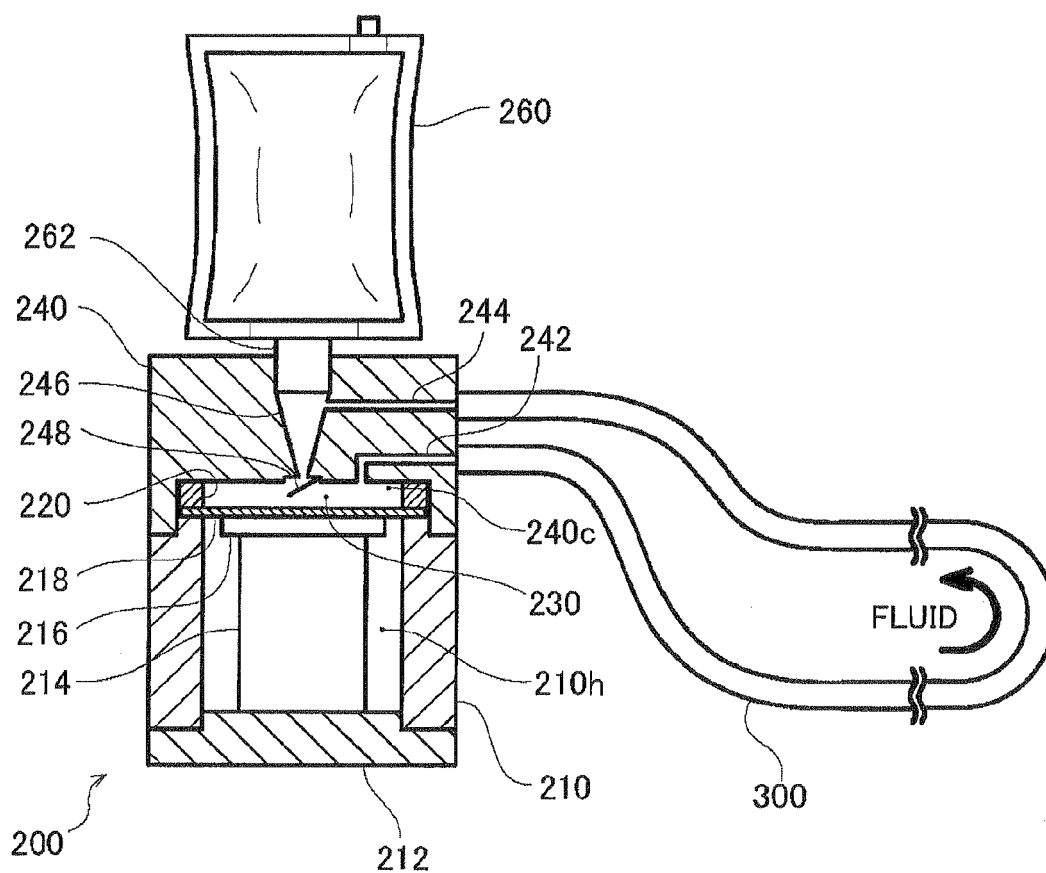


Fig.9A

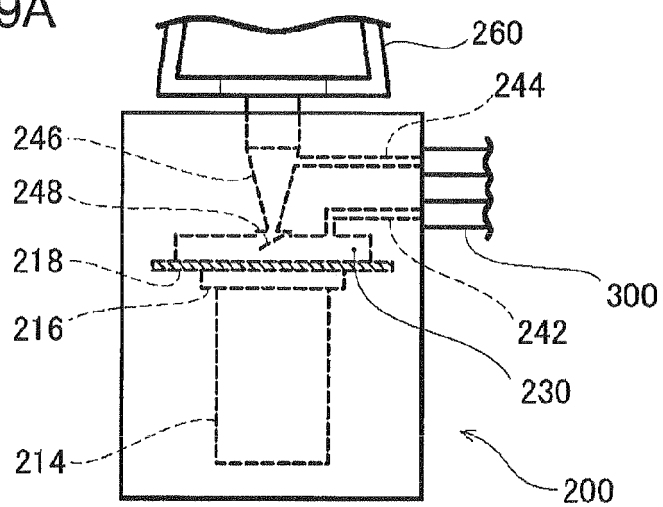


Fig.9B

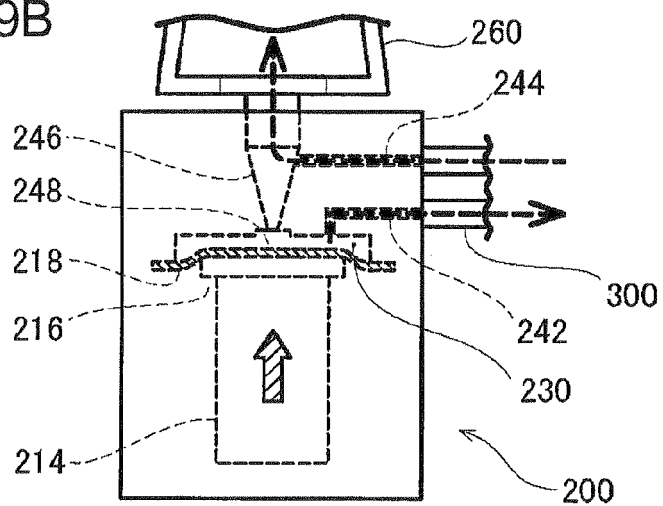


Fig.9C

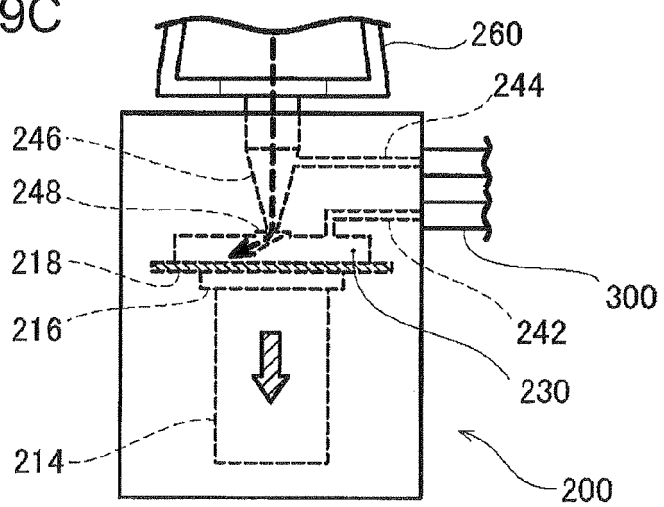


Fig.10A

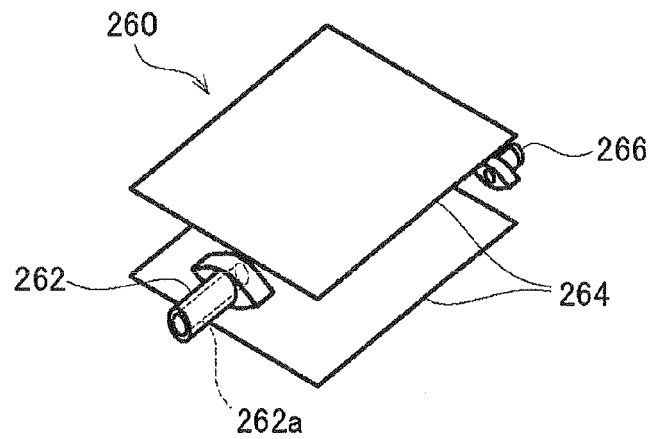


Fig.10B

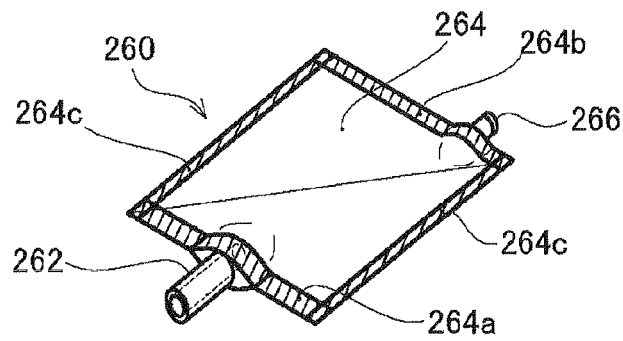


Fig.10C

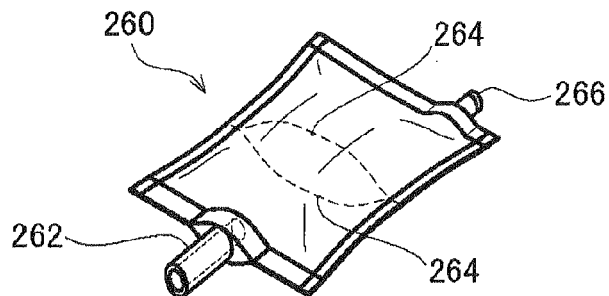


Fig.10D

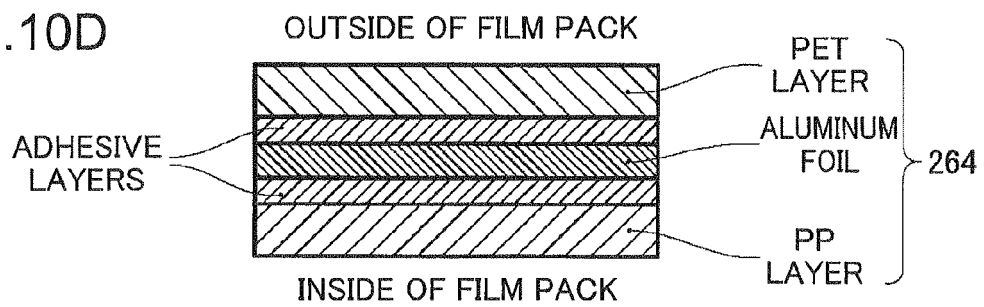


Fig.11A

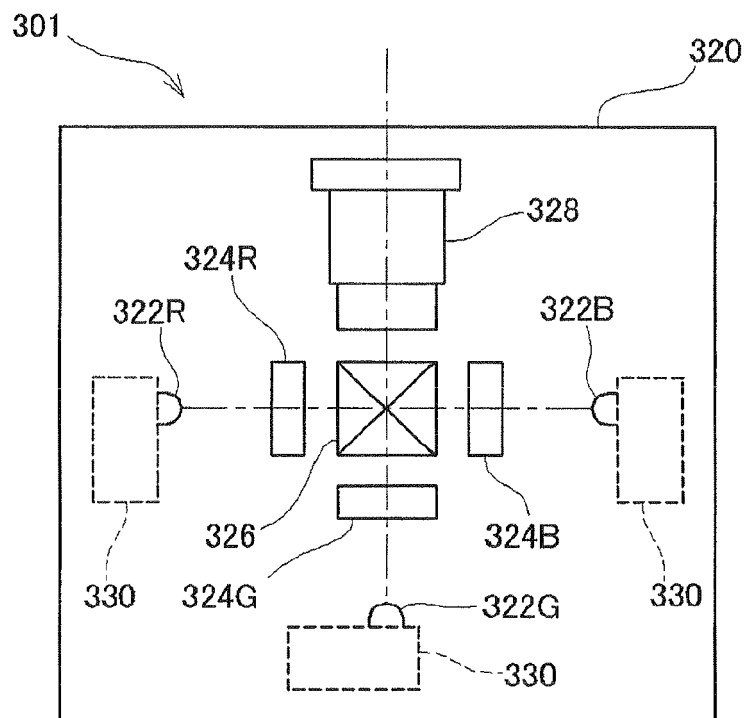


Fig.11B

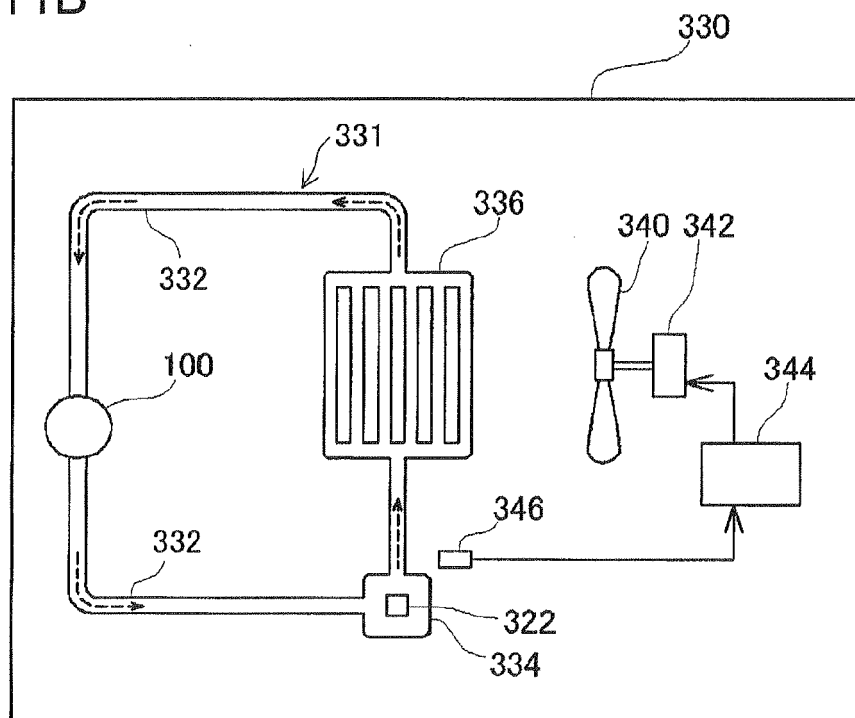


Fig.12

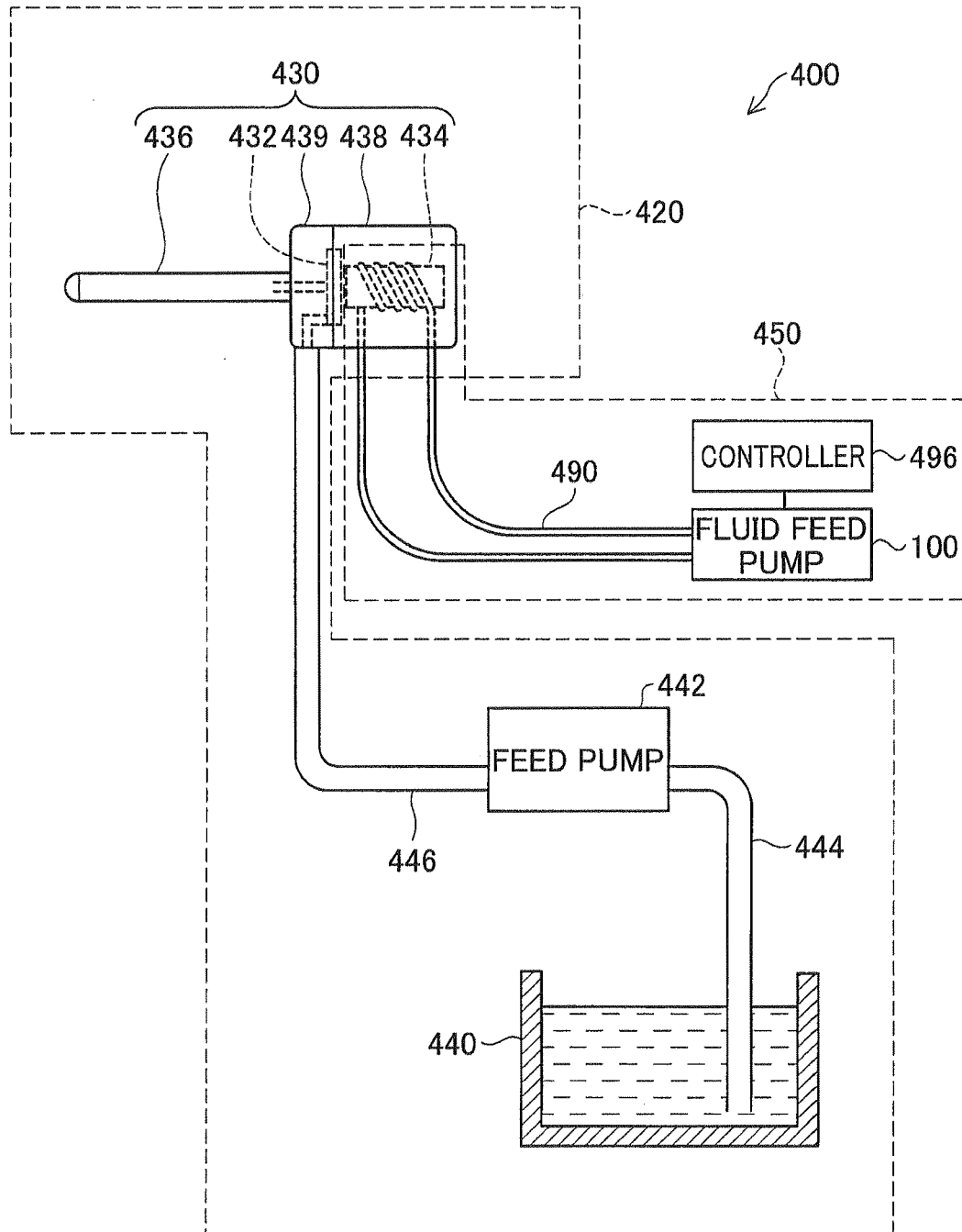


Fig.13

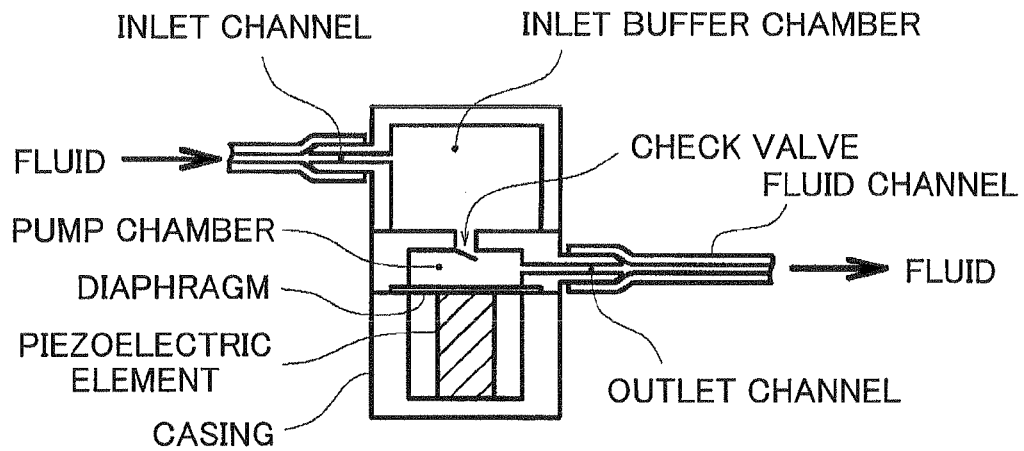


Fig.14A

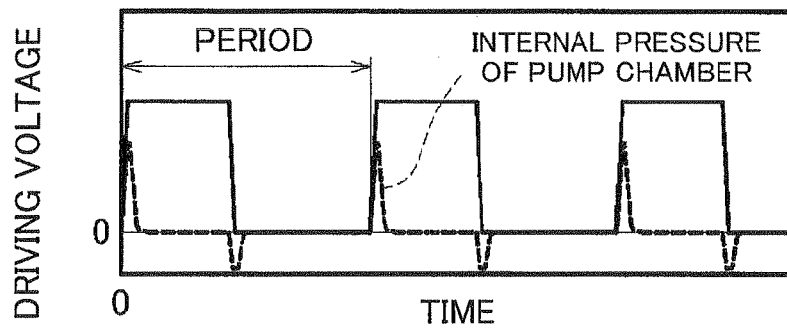


Fig.14B

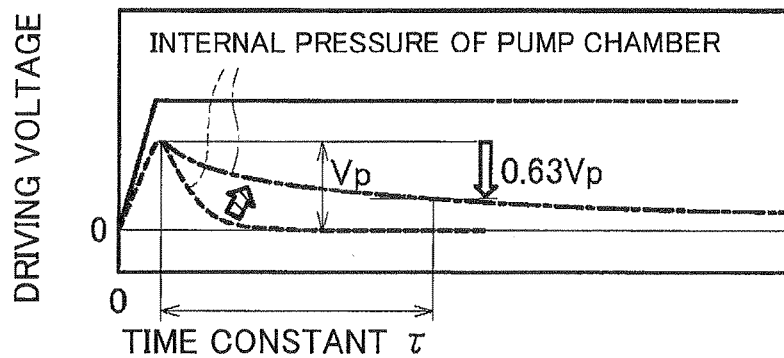
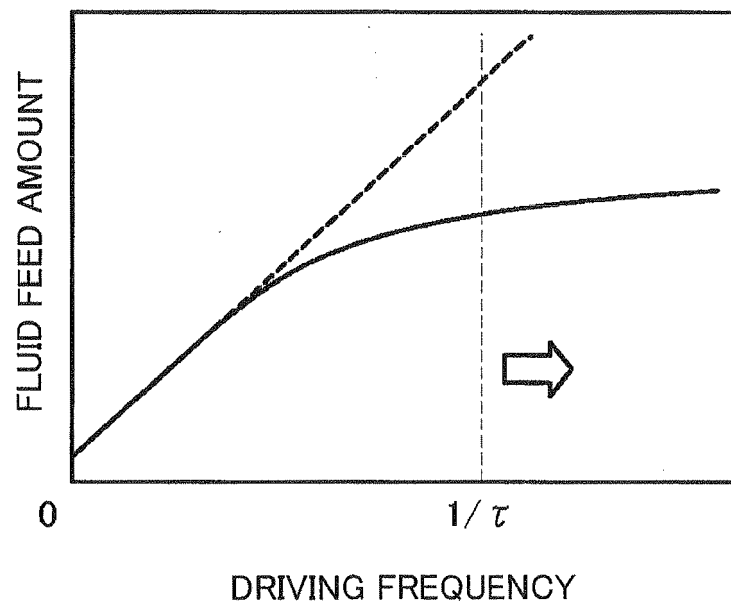


Fig.15





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Application Number
EP 12 18 3683

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Y	* paragraphs [0038] - [0046]; figure 4 * -----	4,10	
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Place of search Munich		Date of completion of the search 30 January 2013	Examiner Ziegler, Hans-Jürgen
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