Micro Robotics

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Lecture-36

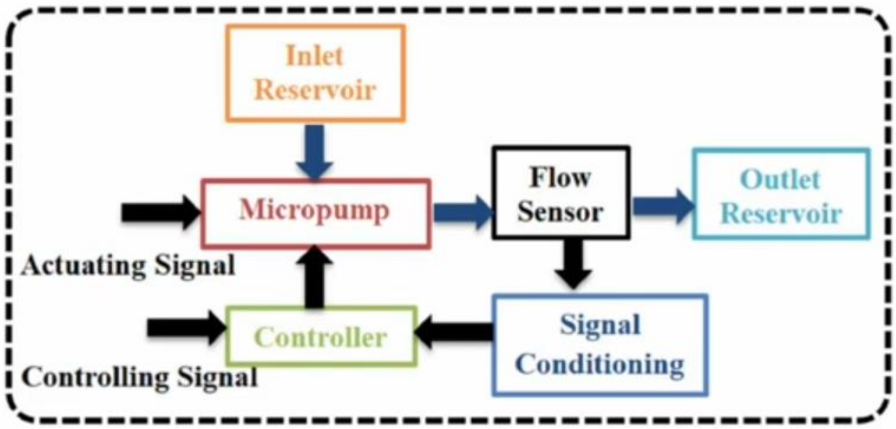
Microsystems for Microrobots (Actuators) - Module 01

Here we will discuss microsystems for Microrobotics. In microsystems, multiple subsystems are available. These subsystems are integrated for the required functional applications; for example, if we want to develop a small micro robotic system for endoscopy-related applications. So, we need to integrate certain sub-elements, like micro pumps and micro actuators. We can integrate these systems and appropriately deploy them for functionally related applications. So, in this particular module, we will discuss the different microsystems that are available for Microrobotics-related applications; we will also discuss some of the key case studies that are being deployed for these applications.

For better understanding, the microsystem for Microrobotics applications is divided into three different categories. One category is for actuation, the other category is for manipulation, and the third category is for integration. With reference to the actuation point of view, we will focus on the microsystem related to actuation. From an actuation point of view, we have discussed different configurations of micropumps and micro engines, different actuation systems that are being deployed for micropumps and micro engines, and different case studies and applications relevant to micropumps and micro engines.

Here we will also discuss a specific aspect, known as magnetic helical micro missions, which will be discussed in detail with reference to the relevant case studies. First, we will discuss micropumps. Micropumps are a key element in microsystems for micro-robotic applications. These micro pumps are used efficiently for discharging a certain amount of targeted drug for delivery or to reach a particular point to control the flow rate. So, these are some of the applications. We will go into detail about different applications relevant to micropumps. The overall configuration of a micro pump is as follows: an inlet reservoir, a flow sensor, and an outlet reservoir. Therefore, the micro pump needs to be appropriately actuated. So, it is fed by an appropriate actuated signal. Then the reservoir that is available in targeted drug delivery will act as a reservoir for the concerned drug.

From the reservoir, the drugs are being pumped and fed into the system where a controller is present. The main function of the controller is to control the micro pump for appropriate actuation. Besides, there is a flow sensor through which we are directing it to the outlet reservoir. To control the flow, a flow sensor is used in the signal conditioning system, and the controller will efficiently participate in it, allowing us to optimally use these micro pumps for the relevant application or functionality. In this particular case, the inlet reservoir and the outlet reservoir play a vital role.



Schematic of miniaturized pumping system

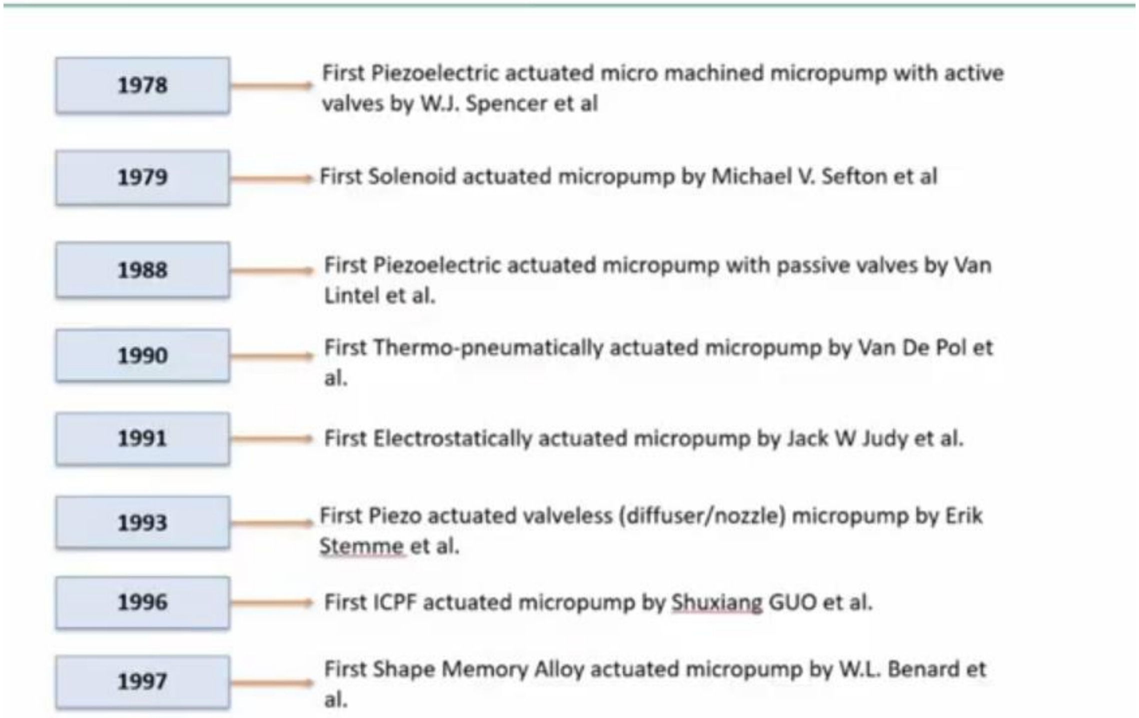
The overall configuration of this inlet reservoir and the outlet reservoir highly depend on the type of fluid we are using, the overall functionality of the fluid, and the system we are going to work with. Now I am discussing the overall history of these micropumps, which are being developed. These micro pumps were initially developed in 1978; the first piezoelectric actuated micromachined micro pump came into existence by W.J. Spencer, where the first active valve-based micropumps were integrated.

Then in 1979, the first solenoid-actuated micro pumps were developed, along with the invention of piezoelectric technology, referencing an appropriate modification in piezoelectric structures. The first piezoelectric-actuated microprome with passive valves was established by Vann. Then later in 1990, the first thermo pneumatically actuated micro pump came into existence. Then slowly, with the increase in technology related to electrostatic actuations, the first electrostatically actuated micro pump was realized in 1991, and in 1993, the first valveless piezoelectric-based micro pump was investigated. So, with reference to valveless-based micropumps, it has good efficiency.

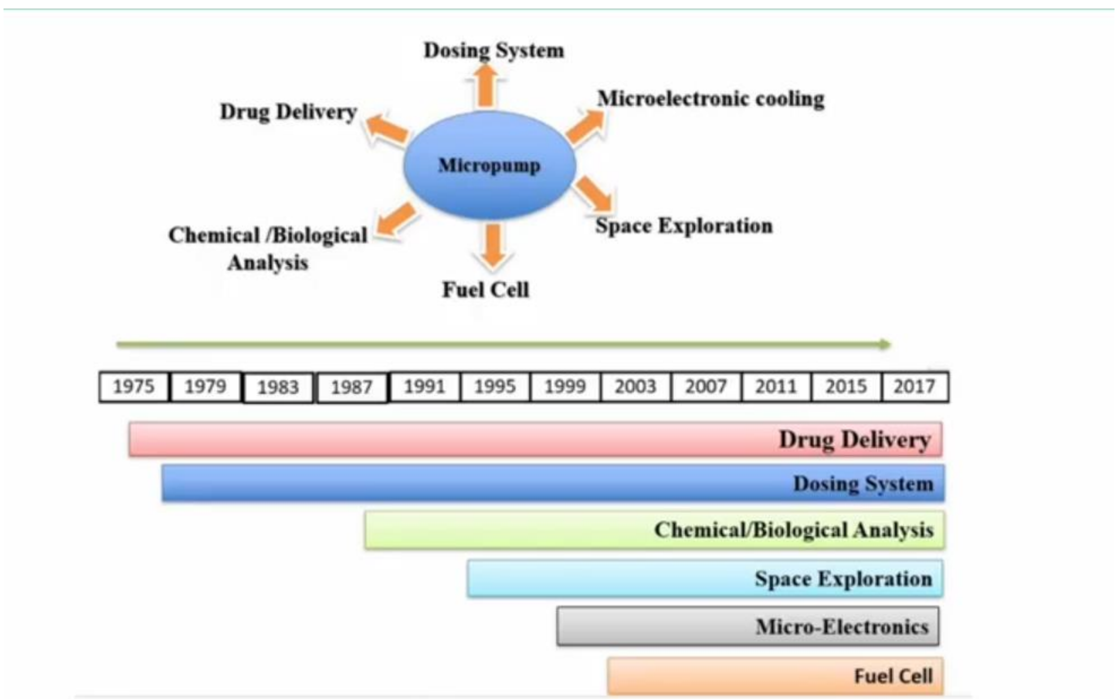
We discuss in detail valveless micro pumps. Based on this, we can understand that actuation behavior plays a vital role in categorizing the micro pump for different requirements or for different characteristics. Let's discuss the first ICPF actuated micro pump that came into existence. In 1997, shape memory alloy-based micro pumps also started getting realized with the overall architecture for different applications and structures. So ideally, with reference to the biomedical perspective, piezo and shape memory alloy-based micro pumps are effectively used.

In most cases, either shape memory alloy polymers are used, or shape memory alloy-based thin films are used. Where it is highly biocompatible and appropriate, it is being efficiently used for some of the targeted drug delivery applications, such as insulin injections, which are some of the key applications of this micro pump. The overall application of the micro pump with reference to different technological advancements is significant. These micro pumps are efficiently used for dosing systems, microelectronic cooling, space exploration, fuel cell-related applications, biological analysis, and targeted drug delivery. In targeted drug delivery, these microsystems micro pumps have been efficiently used since 1975.

Similarly, for precise dosing, it includes insulin dosing, which also entails targeted drug delivery dosing. So, for these applications, such kinds of micro pumps are efficiently used. Then, with reference to chemical and biological analysis, space exploration, and microelectronics-related applications, especially for microelectronics cooling and fuel cell-related applications, are predominant applications of micro pumps. Now, these micro pumps are classified into two categories: one is a mechanical type micro pump, and the other is a non-mechanical type micro pump. Again, we can classify the mechanical type micro pump into two categories: one is a reciprocating type micro pump and the other is a rotary type of micro pump.



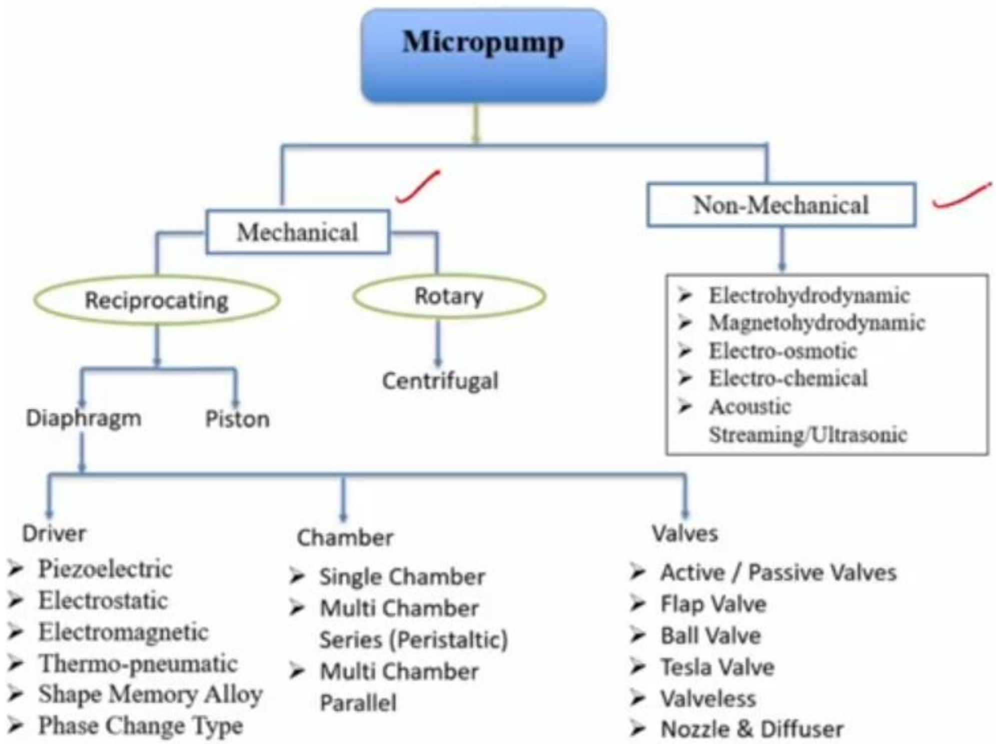
History of micropump development



Timeline of establishment of micropump applications in different domains.

In rotary type micro pumps, centrifugal-based pumps are being deployed for different applications based on a reciprocating pump point of view. A diaphragm and piston arrangement that is being efficiently deployed for different applications. In diaphragm-based micropumps, based on the actuation medium, we can classify the diaphragm-based micropump. In a diaphragm-based micro pump, it has the driver base, the chamber base, and the valve base. In the case of a driver base, we have a piezoelectric structure-based system, an electrostatic structure-based system, an electromagnetic-based system, a thermo-pneumatic system, a shape memory alloy-based system, and phase change material-based systems, which are some of the key drivers that are being deployed for developing diaphragm-based micropumps.

As far as chambers are concerned, they have a multi-chamber micro pump and a single-chamber micro pump, which have been established. The multi-chamber micro pump is classified into two types: one is a peristaltic-based micro pump and the other is a parallel-based micro pump. Now, to classify this kind of actuators or micro pumps with reference to walls' point of view, it has active and passive walls that have an efficient control system. Accordingly, there are active-based walls, passive-based walls, and flap-based walls, which are available under the micro pump category. Besides, there are ball wall-based micro pumps, Tesla valve-based micro pumps, valve-less micro pumps, and nozzle and diffuser micro pumps.



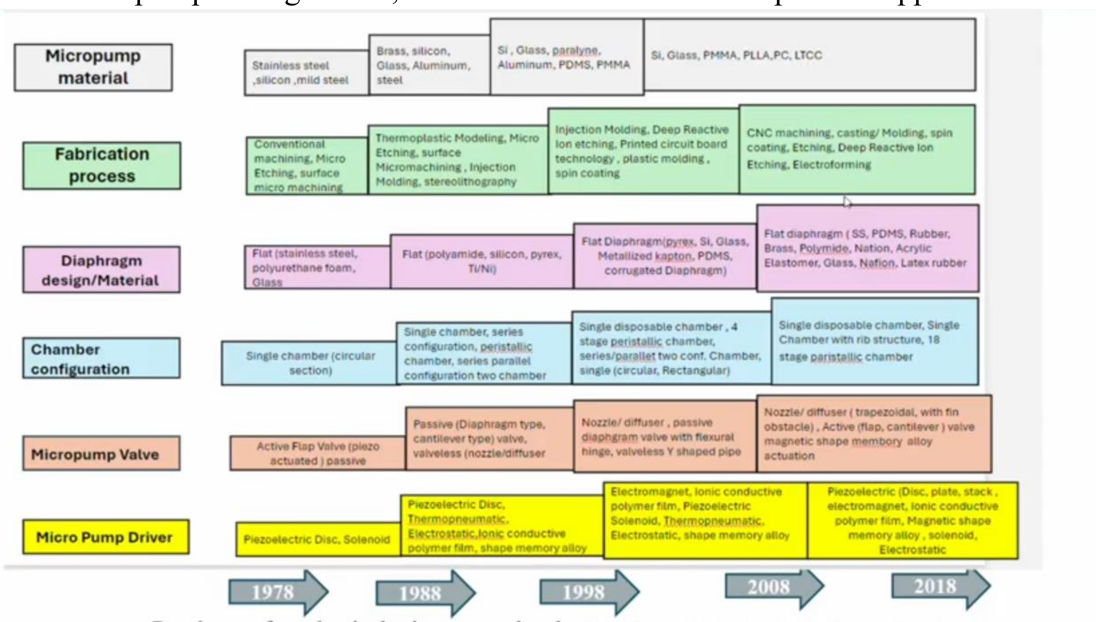
Classification of Micropump

Now, in the classification of non-mechanical-based micropumps, there are electro-hydrodynamic-based micropumps, magneto-hydrodynamic-based micropumps, electro-osmotic-based micropumps, electrochemical-based micropumps, and acoustic streaming or ultrasonic-based micropumps that have also been deployed for different functional applications. Among these classifications, the selection of micro pumps is determined by the appropriate actuation mechanism as well as by the appropriate applications. We can select the micro pumps based on our requirements. Now, let us discuss some of the key fundamentals and the sub-elements that are available for the development of this micro-pump. One of the key aspects includes micropump material, different fabrication processes or fabrication methodologies that have been deployed for micropump development, and different diaphragm designs and materials.

There are different chamber configurations exhibited on this micro pump. Here, we have micro pump-based walls and micro pump-based drivers. For micro pump materials, stainless steel, silicon, and mild steel play a vital role. There are brass, silicon, glass, and aluminum steel available. Besides, SI glass, parylene, aluminum, PDMS, and PMMA structures are also used efficiently for these micro pump-related materials.

With reference to the overall aspects of these micro pump-related materials, they can be categorized into two types. One is static-based material, which is used for appropriate insulation or protection, and the other is dynamic-based material, which is used for appropriate actuation in relevant applications. So, the material mostly works on static-based systems, whereas on dynamic-based systems, the diaphragm design and the diaphragm material are considered. So, these materials are appropriately maintaining the overall geometric configuration and providing appropriate insulation to protect against their different interferences. Let us discuss the different fabrication processes that are being used for these microprobes.

For the micropump configuration, we can consider both the top-down approach and the



Roadmap of mechanical micropump development

bottom-up approach. Hence, conventional machining can be deployed, micro-hitching can be utilized, and surface micro machining can be deployed. In addition to this, micro etching, micro machining, injection-based micro molding, and stereolithography are some of the key fabrication processes. In addition to this, with reference to a highly sophisticated material that has direct relevance to microsystem-related applications, we need to use specialized techniques like deep reactive ion etching, printed circuit board technology, plastic molding, or spin coating technology. However, for appropriate operation, we need to go for CNC machining, casting, and molding; a spin coating technique for taking care of the thin film coating; etching; deep reactive ion etching; and the electroforming process are being efficiently deployed.

Now let us discuss the diaphragm-based material, which is being used for micropump-related applications. For diaphragm-based materials, we need a flat stainless steel polyurethane foam with glass and a corrugated diaphragm or a PDMS-based diaphragm. In certain cases, we can also have a metallized Kapton-based diaphragm that can be deployed. In addition to this, there are certain elements that have a direct relevance to the diaphragm, like PDMS, rubber, elastomers, latex levers, etc., which can be efficiently deployed for diaphragm-related applications.

From a chamber configuration point of view, we have a single chamber that has a circular section, a single chamber with series configurations, which includes a peristaltic chamber and series-parallel chamber configurations. Besides, we can also design a chamber like a single disposable chamber, four four-stage peristaltic chambers, and a single chamber with circular and rectangular sections. Some chambers with rib-like structures are also being deployed for peristaltic chamber-related applications. Let us discuss the different configurations or the different orientations and configurations of the micro pump. If we classify this micro pump with reference to the valve's perspective point of view, it is an active flap valve, which is a piezo-actuated passive structure being deployed.

So there are a kind of passive diaphragm-type cantilever valves and valveless systems that are being deployed. In certain cases, there is a nozzle, a diffuser, or a passive diaphragm valve with a fluctuating hinge, and valveless Y-shaped pipes are being deployed. In addition to this, there are some nozzle diffusers, active flap cantilevers, a magnetic valve, and shape memory alloy valve-based actuation systems that are being efficiently used for such a valve or valve-less micro pump. Now, to discuss micro pump drivers, there are different types of micro pump drivers that are efficiently contributing to the configuration of micro pumps. One such driver includes a piezoelectric disc or a solenoid and also has thermopneumatic structures, electrostatic structures, ionic conductive systems, polymer films, and shape memory alloys.

Highly sophisticated systems like electromagnetic base structures, piezoelectric base structures, solenoid base structures, and shape memory alloy base structures efficiently contribute to the development of such micro-pumps. When there is an improvement in microfabrication, we can develop these drivers, or we can customize them based on our requirements. One such system includes a piezoelectric disc plate stack, an electromagnet, an ionic conductive polymer film, a magnetic shape memory alloy, and a solenoid-based electrostatic structure, which can also be deployed appropriately. Now, discuss the overall configuration of a micropump. In micropumps, we have discussed that these devices are designed to transport fluid in a controlled manner at the microscale. In the overall configuration, there is a piezoelectric sheet and a diaphragm arrangement. Besides, there are two valves: one is an inlet valve and the other is an outlet valve. So here, an inlet reservoir is present. Voir and an outlet reservoir are present. So, the liquid from the inlet reservoir is pumped and made to pass through the wall.

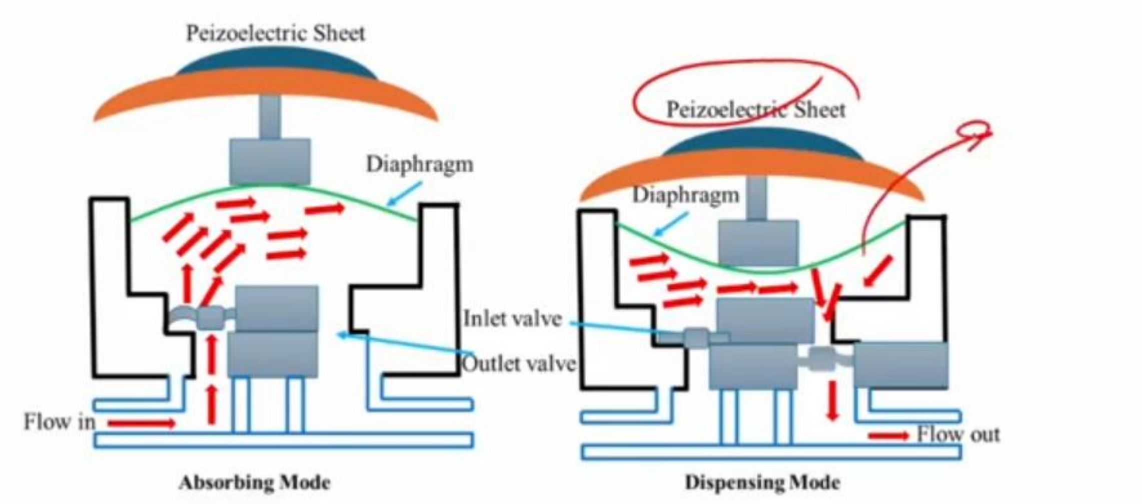
The suction occurs through the diaphragm, and the actuation of the diaphragm is managed by the piezoelectric sheet. The main application of this piezoelectric sheet is to create a suction mechanism. So, the diaphragm will move along with the piezoelectric actuator, creating a suction in this domain. Finally, pumping the liquid from the reservoir flows to the outlet. Here, we can classify it into two modes of operation. The first mode of operation is called the absorbing mode. So, in the case of an absorbing mode, the absorption happens because of the movement of the diaphragm and the suction of the liquid. The liquid is flowing appropriately through the outlet wall. Next in dispensing mode, the diaphragm pushes in the downward stroke. Therefore, when the diaphragm moves appropriately, the liquid pushes towards the walls and then tries to flow out of the wall.

So, in the case of an absorbing mode, the piezoelectric structures will be in a particular actuation state, initiating a kind of suction mechanism. In the case of dispensing mode, the piezoelectric sheet is pushed towards the forward stroke so that pressure is created, the suction mode is stopped, and the fluid is made to flow through the surface. Now, from the overall functionality perspective or the parameters perspective, we may need to look into the frequency of this pump as well as the overall actuation displacement of this pump. In that aspect, the operating dimension will range from a few micrometers to several millimeters, enabling precise fluid handling for various applications. This precise handling can disperse in a few microliters at a particular frequency based on the application.

This is in the case of a passive type. In an active-based micro pump, if we want to take feedback, as we have seen in the basic configuration where a sensor gets the overall output from the output reservoir and from that, it gives an appropriate signal to the actuation condition. So the pumping happens, and the pumping is appropriately used for dispensing the fluid, like in the case of insulin. So, after a particular time interval, automatic dispersion happens; hence, automatic suction occurs. The automatic absorbing and dispensing mode happens because of a timer or sometimes in reference to the requirement of the output. Appropriately, the absorbing mode or the dispersing modes gets activated.

The use of such a motion in a solid, such as a gear, diaphragm, or fluid, generates the pressure difference that is needed to move the liquid. Ideally, these gears and/or diaphragm act as the main key actuating medium for the movement of the fluid. The most common mechanical displacement micropumps are the diaphragm pumps. Diaphragm pumps have a wide variety of structures, such as shape memory alloy-based or piezoelectric-based ones.

In the case of a mechanical micropump, it utilizes a diaphragm actuated by a physical



Piezoelectric based Micropump

actuator for pumping the fluid that leads to a pressure drop.

This pressure drop causes the fluid to flow from the high-pressure reservoir to the pumping chamber, which corresponds to the supplied mode. As discussed earlier, the working principle involves the volume change in the pump chamber by the diaphragm as well as by the mechanical element. These are some of the basic configurations where two modes exist: one is an absorbing mode, and the other is a dispensing mode. Now, discuss the key configurations of micro pumps, such as wall-less micro pumps and wall micro pumps. In the walls micro pump, during the expansion phase, the chamber volume increases and creates a negative pressure that draws the fluid in through the liquid.

During the compression phase, the chamber volume decreases and creates a positive pressure that forces the liquid to flow through it. The overall illustration shows the valve and the valveless pump. In the case of a valve pump, there will be a valve that restricts the overall flow, and it will also be helpful in holding the pressure and appropriately pushing for the dispensing mode. The valve will take care of both the absorption mode and the dispensing mode appropriately for the correct fluid output. Now there are two modes; one is called supply mode, which is the absorption mode through which the fluid is pushed.

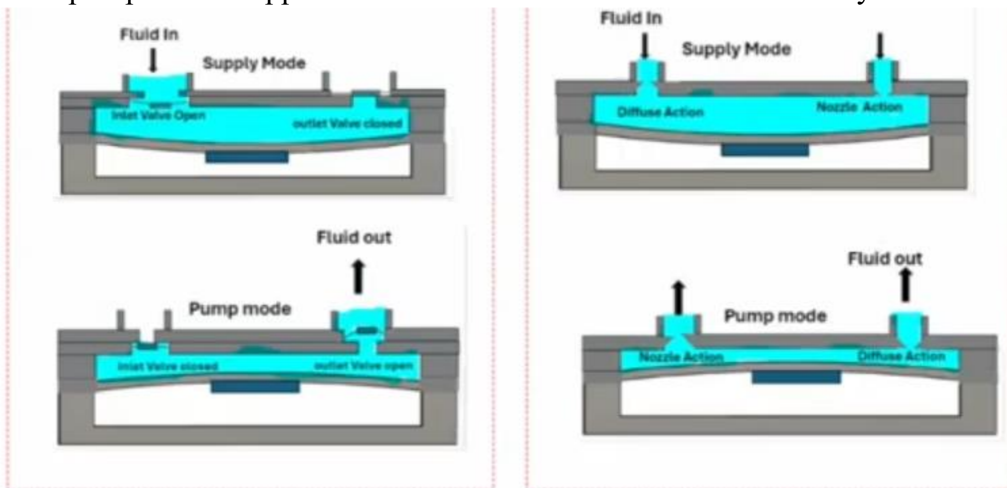
The valve also participates in the fluid flow, allowing the liquid to fill through this structure, and then a pump mode is available. During this pump mode, the diaphragm tries to push an outlet that is coming out of it due to certain other actuation principles. This is a pump mode through which the fluid is made to pressurize towards the outlet unit. In the case of a valveless perspective, it is like a process in which there is an efficient flow. These valveless micro pumps are efficiently used in a certain amount of passive-based systems.

In passive-based systems, the passive base will react based on the output or based on the overall environment. Then the active base will react and will try to disperse. In the case of a valve-based system, we can use it for both active and passive. In the case of valve-less systems, we can also use it for both active and passive. Furthermore, the valve-less system is efficiently used for certain active-based systems, such as changes in the environment where we can disperse the liquid appropriately. Now let us discuss some of the key applications of these pumps. One is with reference to the absorbing mode and the dispensing mode; the other is with reference to the valve and with reference to the valve bus. With reference to the application perspective, the first application is targeted drug delivery for biomedical-related applications. When it reaches a particular point, we can disperse a drug for immediate relief. Another is thermal management for electronic cooling, where an electronic system is needed.

In thermal management, such systems can be deployed. In a gas chromatography system, a mixing of gases occurs, so that we can have control over the convection behavior of this system. Then in a fuel cell, when the delivery of fuel in combustion is made, the relief of the fuel is taken care of by this system. For example, in an application where a kind of pump can be deployed to dispense the lubrication in a controlled environment. For example, for a roller bearing or a bearing that is being employed for certain applications, it is very difficult to pump the lubricant onto those particular rollers or bearings in a controlled environment. In these conditions, there is a requirement for micro pumps that will be deployed appropriately, and these micro pumps will attempt to dispense the fluid onto these rollers.

Based on the variation in the pressure difference, they will try to dispense the liquid onto the roller bearing. Hence, these are an active-based system. It might either be a valve or valve-less based on the configuration. However, when we try to look at the output perspective point of view, it might be due to the overall suction behavior, or it might be because of thermal management. In bearings, when heat is generated, it is sensed, and accordingly, liquid is dispensed or the liquid can be lubricated appropriately to reduce the temperature.

This can be efficiently used for a lubrication system. So this micro pump acts as an efficient lubrication system. Next, we will discuss the different configurations of micro pumps. Furthermore, we will also discuss different actuation media that are being deployed for micro pump-related applications. We will also discuss a case study in which micro



Schematic illustration of micropump with (a) valves (b) valveless

pumps have been used for an endoscopic-related application. We will also go through the key configurations where a kind of micro motors is being integrated into it and how it is being used for an endoscopic application for targeted drug delivery.