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Review Article

Advances and Applications of Piezoelectric Micropumps: A Comprehensive Review

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ABSTRACT

In recent years, micro pump technology has garnered significant attention and established itself as a pivotal area of research, particularly within the domain of microfluidic applications. The growing interest in developing micro pump systems stems from the critical need to integrate efficient and precise pumping mechanisms into microfluidic devices, enabling accurate and controlled fluid delivery at micro- and nanoscale levels. This review explores the latest advancements and research in micro pump technology, with a primary focus on piezoelectric micro pumps due to their versatility and high performance. The study offers a comprehensive analysis of how operational parameters, diaphragm material selection, variations in piezoelectric layer geometries, and microvalve designs influence the efficiency and reliability of micro pumps. Furthermore, the review examines the diverse functional requirements of micro pumps and highlights their applications in a broad range of fields, including biomedicine, targeted drug delivery, thermal management systems, fuel cell technology, and other emerging areas of technological innovation. By analyzing the interplay of these factors, this paper underscores the critical role of micro pumps in advancing microfluidic systems and their transformative impact across various industries.

1. Introduction

The rapid growth of sub-millimeter and microscale engineering technologies in recent years has led to the development of miniaturized devices and systems. This miniaturization primarily focuses on reducing the size of systems with the aim of lowering costs and improving performance. Miniaturized devices offer numerous advantages, including higher speed, lower cost, portability, the use of disposable materials, reduced sample volume requirements, and decreased energy consumption. These advancements have paved the way for new applications, particularly in fields such as medicine, electronics industries, and microfluidic laboratories [1]. The potential advantages of miniaturization have motivated many researchers to develop systems capable of handling fluids and liquids at micro- to nanoscale levels. This drive has led to advancements in microfluidics through an integrated approach that combines microscale engineering and fluid mechanics. Microfluidics is primarily concerned with the manipulation and analysis of small volumes of fluids or liquids. Microfluidic devices are a type of miniaturized pumping system that can pump, mix, monitor, and control extremely small volumes of fluids [2]. Many researchers have made significant contributions to the field of microfluidics, leading to the development of various types of microfluidic devices, such as micropumps, micromixers, microvalves, microfilters,

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microreactors, and microseparators [3]. For distinct applications and given the need for microfluidic systems to move fluids at micro- to nanoscale levels, researchers and scientists have recognized the necessity for a pumping system capable of delivering small amounts of fluid with sufficient pressure to enable flow through the microfluidic system. This requirement has led to the development of various micropumps with different actuation principles and fabrication technologies.

A micropump is a device that can transfer or deliver the working fluid (liquid or gas) in precise volumes from a reservoir to the target. The potential advantages of micropumps include precise fluid delivery in the range of microliters to milliliters per second or per minute, as well as the flexibility for integration with various electromechanical systems while effectively reducing spatial requirements [4]. Micropumps can be classified based on various characteristics Fig. 1 shows a broad classification of micropumps. In this study, the classification is based on the types of actuators used in micropumps. Micropumps are divided into two types based on their physical mechanisms: mechanical and non-mechanical micropumps.

In the structure of mechanical micropumps, there are moving mechanical components such as pumping diaphragms and check valves. In contrast, the structure of non-mechanical micropumps lacks any mechanical components for fluid movement. Instead, these micropumps utilize hydrodynamic effects, electroosmosis, or electrowetting to achieve fluid flow rates [5].

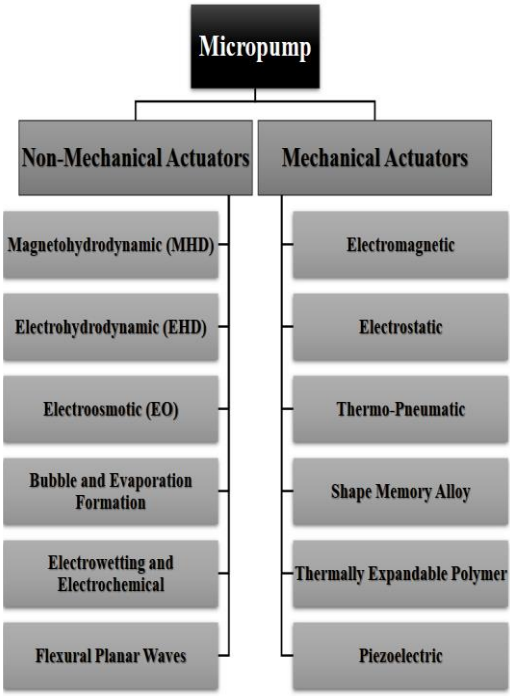

Fig. 1. Classification of micropumps based on types of actuators.

2. Application of micropumps

The initial stage of micropump development focused on therapeutic drug delivery/injection. Micropumps developed between 1978 and 1988 were primarily designed for insulin delivery to maintain blood glucose levels in diabetic patients [6]. Moreover, the first design of a piezoelectric micropump was intended for drug delivery. The micropump designed for controlled insulin delivery systems was utilized for diabetic patients, reducing the need for continuous needle injections in these individuals [7]. Busmann et al. [8] developed a small silicon-based piezoelectric micropump for continuous subcutaneous insulin delivery applications. The micropump measured 5×5 mm in size and was capable of generating backpressure of 12.5 kPa and a maximum water flow rate of 74 μL/min. This study was conducted on ten silicon piezoelectric micropumps for insulin delivery. The design and fabrication process of the micropump adhered to silicon standards. These micropumps hold promise for effective insulin delivery; however, further modifications are required to enhance dosing precision. In addition to insulin delivery, medical conditions such as bone infections, cancer, and tumors have utilized micropumps for drug delivery to cancer cells and the bloodstream. Accurate measurement and distribution of drugs at the required rate are fundamental aspects of the application of micropumps in drug delivery and dosing [9]. Ma et al [10] developed an innovative detachable piezoelectric micropump for medical applications, designed to deliver fluids at a low cost. The actuator of the proposed micropump can be reused repeatedly to reduce costs, whereas the pump chamber is disposable to prevent contamination and infection, making it unsuitable for repeated use. The micropump was fabricated using a highly precise CNC machine. Accurate measurement and distribution of drugs at the required rate are essential aspects of micropumps designed for drug delivery and dosing applications [11].

Micropumps capable of delivering fluids at micro and nanoscale, primarily through microchannels, have gained significant importance in chemical/biological analysis systems. These devices are designed in the form of μTAS (Micro Total Analysis Systems), aimed at reducing the amount of samples and reagents used in analyses within a limited time and with minimal manual intervention. Liu et al. [12] provided a comprehensive description of the working process and analysis of a micropump composed of a circular single-mode piezoelectric actuator, a control valve, and a pump body. Their laboratory prototypes were fabricated and tested, demonstrating good output performance. Specifically, at 170 V and 120 Hz, the maximum flow rate of a two-chamber series pump reached 65.5 mL/min. The proposed piezoelectric micropump offers advantages such as a simple structure, low cost, small size, and high output performance, making it highly applicable in biomedical fields, cooling systems, fuel supply, and chemical applications.

Micropumps also find applications in space exploration, aiding the propulsion of mini/micro satellites or spacecraft. The small size and lightweight nature of micropump technology allow seamless integration with satellites. As the working environment for propulsion is gaseous, a larger stroke volume is required to pump gases with sufficient pressure to lift satellite or spacecraft payloads [13]. Micropumps have also been utilized for the continuous dissipation of heat in electronic equipment with space constraints through single-phase or two-phase cooling systems. With their ability to transfer liquids or air through microchannels, these pumps are effectively employed in cooling applications, resulting in improved performance of electronic devices. As fluid flow within heat sinks is conducted through channels, a higher-pressure fluid is required to reduce temperature differences, enabling the dissipation of significant amounts of heat. Fuel cells, which convert chemical energy into electrical energy, whether in the form of Proton Exchange Membrane Fuel Cells (PEMFC) or Direct Methanol Fuel Cells (DMFC), heavily rely on miniaturized micropumps. The application of micropumps in fuel cells is primarily focused on the precise delivery of liquid fuel (methanol) [14]. Zhang and Wang [15] conducted an experimental study to evaluate the performance of a small methanol fuel cell using a valveless piezoelectric micropump for fuel delivery. The core of this micropump consists of a ring-shaped piezoelectric bending actuator and a nozzle/diffuser system for directing fuel flow. Three factors methanol filling, reduction of diffusion resistance, and carbon dioxide removal can contribute to improved performance. McDonald and Hamdan [16] designed commercial micropumps for use in direct methanol fuel cells. The main objective of this study was to investigate the use of two types of piezoelectric micropumps for controlling the methanol-to-water ratio in a fuel cell in order to reduce methanol crossover and maintain an optimal methanol concentration at the anode. The micropumps operate over a wide temperature range, are easily reprogrammable, and can function in any direction. Furthermore, the use of these micropumps leads to an increase in the operational time and specific power of the fuel cell. Fig. 2 shows the most common applications and the timeline of micropump deployment in different fields.

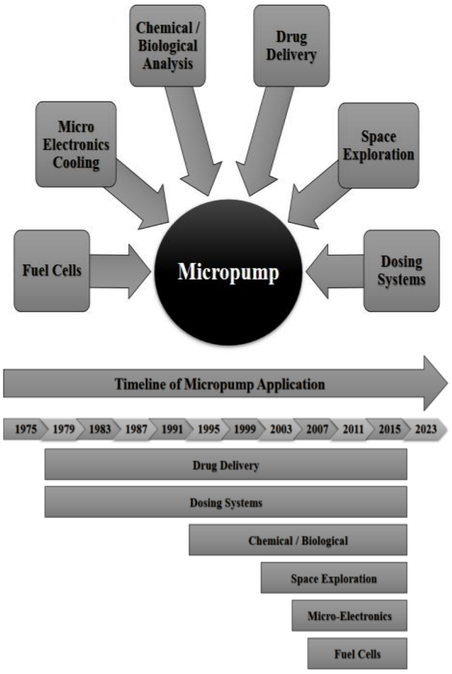

Fig. 2. Applications and deployment timeline of micropumps.

3. Piezoelectric micropump components

A piezoelectric micropump consists of a piezoelectric disc mounted on a diaphragm, a valve, and a pressure chamber. "Fig 3 shows a schematic of the piezoelectric micropump". These micropumps are activated by the deformation of piezoelectric materials caused by the application of voltage. Piezoelectric micropumps offer many advantages, such as high actuation force, short response time, and a simple structure. However, they also have disadvantages, such as high operating voltage and low displacement. It is important to note that due to the presence of mechanical components in the micropumps, the response time or operating frequency is limited, and in this regard, the performance of the valves plays a crucial role. To increase the operational frequency, nozzle-diffuser valves, as mentioned earlier, can be used. Most of these micropumps are fabricated on silicon substrates. In the past, the piezoelectric layer was manually bonded to a diaphragm, which was also made of silicon or glass. However, with advances in technology, this process is now fully automated, and this increase in precision leads to improved efficiency. Fig. 3 shows the schematic of a piezoelectric micropump [17].

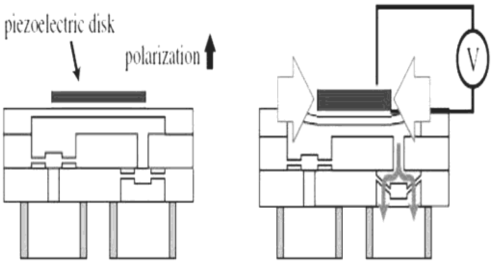

Fig. 3. Schematic of piezoelectric micropump [17].

3.1. Micropump chamber configuration

In all micropumps, fluids are transferred from the reservoir to the chamber by activating the actuators and passing through microvalves. Eventually, the microfluidic mass in the chamber is transferred to the output channel. Accordingly, the dimensions and geometric shapes of the chamber affect the diffuser-nozzle loss coefficients, volumetric stroke, and pressure characteristics [18]. Most of the proposed micropumps have a single chamber [19]. However, to increase the flow rate, several micropumps with two chambers [20] and three chambers [21] have also been introduced. In general, micropump chambers are made using traditional microfabrication technologies such as polymethyl methacrylate (PMMA) [22], polydimethylsiloxane (PDMS) [22], and borosilicate glass [23]. The design of the chambers plays a significant role, and much research has been done on circular, rectangular, and nozzle-diffuser conical chamber shapes. For example, Singh et al. [24] designed, fabricated, theoretically modeled, and numerically simulated a piezoelectric micropump without valves. The research included theoretical modeling and numerical simulations for the electrohydrodynamic structural interactions. In the initial design of this micropump, the chamber was considered circular. The results show that modified chamber designs can improve the flow rate, particularly a conical chamber with a 120-degree angle that reduces the return area and increases the flow rate by over 20% at high frequencies of 100 Hz. The fabricated micropump was able to achieve a maximum flow rate of 20 microliters per minute and a return pressure of 220 Pascals with a voltage of 30 volts. Furthermore, the results show that the flow rate increases linearly with voltage, and the natural frequency of the micropump is confirmed to be around 200 Hz. B. Fan et al. [25] numerically studied the performance of an active valve-less micropump with piezoelectric actuation, considering the three-way electro-mechanical fluid couplings, where the pump chamber is rectangular. The simulation results show that the pumping efficiency depends not only on the actuator frequencies and the maximum deflection of the diaphragm but also on the shape of the diaphragm's deflection. At low actuator frequencies, the deflection shapes are nearly identical for different types. The frequencies and pumping rate are proportional to the activation frequency. Therefore, activation frequencies above 50 kHz reduce the pump efficiency. Fig. 4 shows a view of all 3 types of circular and conical enclosures with diffuser and rectangular nozzles.

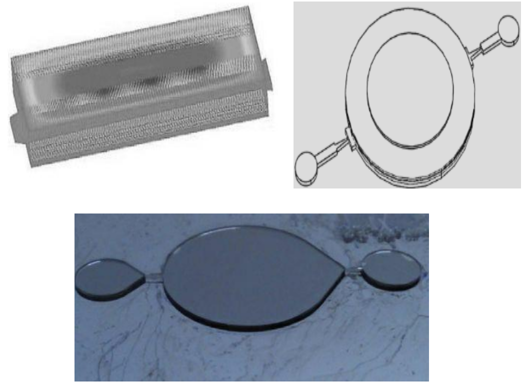

Fig. 4. Three types of chambers designed for piezoelectric micropumps [24, 25].

Recently, the study of multi-chamber piezoelectric micropumps has received special attention. Due to the intermittent flow, the use of single-chamber micropumps is limited. Based on conducted studies, multi-chamber micropumps have higher stability and flow rates compared to single-chamber micropumps. Many studies have been carried out in this regard. For example, Lintel et al. [26] proposed a two-chamber piezoelectric micropump. They constructed this micropump based on silicon micro-machining technology. They also used passive silicon check valves to regulate the flow speed. Cao et al [27] simulated a three-chamber piezoelectric micropump, where the chambers were connected in series by channels. Fig. 5a shows the schematic of the proposed micropump. The micro-inlet valve of this micropump was connected to the left chamber, and the outlet valve was connected to the right chamber. Each chamber had a separate diaphragm and piezoelectric actuator. In this micropump, they improved the flow rate by generating peristaltic motion. Kan et al. [28] designed and fabricated a multi-chamber micropump, the schematic of which is shown in Fig. 5b. This design aimed to achieve a high flow rate while consuming low voltage. The structure of this micropump was made of PMMA material, with chambers having a diameter of 10 mm and a height of 0.2 mm. Additionally, console valves were used to control the inlet and outlet flow, with dimensions of 4 mm by 1.35 mm. This study examined three key aspects: the impact of increasing the number of chambers on the flow rate, the role of actuator frequency on the output flow, and the measurement of the maximum flow rate, which was ultimately 7.6 mL per minute. This value was achieved when four micropumps were connected in series, and a 40V voltage with a frequency of 300 Hz was applied to the piezoelectric actuators. This design demonstrated the high efficiency of piezoelectric systems in specific applications and showed how different configurations could optimize performance. Ma et al. [29] designed a valve-less piezoelectric micropump that was actuated from one side and featured a secondary chamber. This micropump consisted of two chambers, with the secondary chamber located between the primary chamber and the outlet channel, as shown in Fig. 5-c. In this design, the top of both chambers was sealed with PDMS, and a rectangular piezoelectric plate was attached to the diaphragm of the primary chamber. The diaphragm of the secondary chamber vibrated simultaneously with the primary diaphragm. This design achieved a maximum net flow rate of 1.183 milliliters per second at a frequency of 150 Hz. The presence of the secondary chamber increased the net flow rate to 0.989 milliliters per second, indicating the positive impact of the secondary chamber on improving the micropump's performance. These results suggest the success of the design in enhancing efficiency.

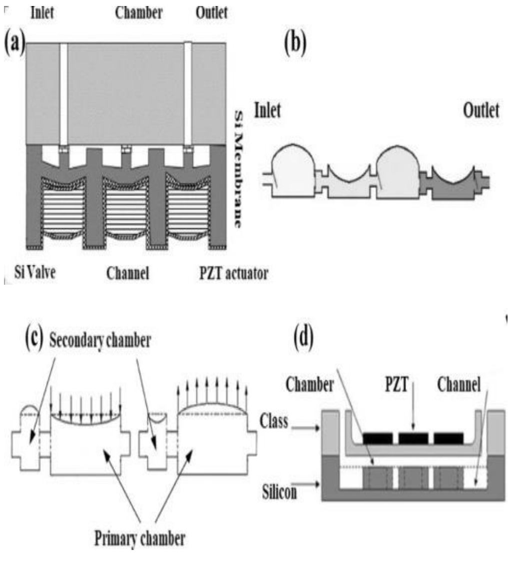

Fig 5. Schematic of developed multi-chamber micropumps Micro valves [27- 30].

Jang et al. [30] designed a three-chamber micropump, with all chamber diameters measuring 12 millimeters, as shown in Fig. 5d. In this micropump, glass was used as the diaphragm, and square piezoelectric actuators measuring 12 mm × 12 mm were mounted on the diaphragms. To create peristaltic motion (wave-like motion), they used three-phase and six-phase excitation sequences. The best performance of this micropump was achieved when the six-phase sequence was used. In this case, the maximum net flow rate was 36.8 microliters per minute at a voltage of 100 VP-P and a frequency of 700 Hz. This design demonstrates high performance and precision in controlling the flow rate.

Micro-valves in micropumps are generally classified into two main categories: active valves and passive valves. Active valves play an important role in controlling fluid flow in micropumps. These valves act as key components in micro-pumping systems. They are opened or closed by an external control system, in coordination with the rest of the components [31]. These valves function similarly to electrical diodes, preventing the flow of fluid in one direction. Active valves use various components, such as plates [32], flaps [33], and balls [34], to regulate resistance. Although these valves prevent backflow, they have a complex structure and may suffer from wear or clogging in the presence of particles or bubbles [35]. Passive valves, on the other hand, open and close due to the pressure and movement of the fluid itself and do not require an external controller. Therefore, they are easier to manufacture and cost less compared to active valves [17]. The advantages of passive valves include a simple structure, low cost, and no need for external control. Examples of these valves include Tesla valves and nozzle/diffuser elements. Tesla valves are devoid of moving parts and create diode-like flow by the angles at which the channels meet [36]. Nozzle/diffuser elements are differentiated by their structural features: a diffuser is a channel with an expanded cross-section, and a nozzle is a channel with a reduced cross-section. Fluid flow in the nozzle experiences a greater pressure drop than in the diffuser, and this difference helps guide the flow [17]. In this case of miniaturization, the maintenance and care of the micropump will encounter fewer issues. The recent study conducted in this project focuses on valve-free micropumps. Kan et al .[37] constructed two micropumps with piezoelectric cantilever valves. The difference between these micropumps lies in the size of their cantilever valves, which were 2.5 mm and 3 mm, respectively. The micropump with the larger cantilever. Fig. 6a shows the schematic design of the cantilever valve. Ma et al .[38] designed and produced a piezoelectric micropump with unidirectional actuation for use in a cooling system. The housing of this micropump was made of aluminum and shaped using CNC machining. In this study, a unidirectional cantilever valve was embedded inside the pump chamber. The materials used for the cantilever valve and diaphragm in this micropump were chosen to be PDMS. Fig. 6b shows the operation of the valve. This micropump was able to achieve a maximum flow rate of 72 milliliters per minute under the conditions of applying ±50V (AC) voltage and a 100 Hz frequency to the piezoelectric actuator. Cheng and Tseng [39] used one-way valves in their proposed micropump to control backflow. "The exploded view of this piezoelectric micropump is shown in Fig. 6c. The one-way valves connected to the chamber were designed in a bridge-like configuration. The operation of these valves was regulated by the vibratory position of the diaphragm, which allowed the process of opening and closing the channels to occur synchronously. In the supply mode, the inlet channel was open while the outlet channel was closed, and in the pump mode, the outlet channel was open while the inlet channel was closed. This micropump was able to achieve a maximum flow rate of 1.82 milliliters per minute under the application of 120 V peak-to-peak voltage and a frequency of 160 Hz. Ren et al. [40] proposed the use of a string-type one-way valve for managing the liquid inlet and outlet in the micropump chamber. The structure of this type of valve is depicted in Fig. 6d. The valve consists of a seat and flexible rubber strands. The seat had rectangular-shaped holes, which, when the diaphragm was not vibrating and the pressure inside the chamber was zero, were completely covered by the rubber strands. Pressure changes inside the chamber caused the rubber strands to open and close. Thus, in the supply mode, the rubber strands opened the inlet channel, while in the pump mode, the rubber strands opened the outlet channel. Water was used as the liquid in the pumping process, and the micropump achieved a maximum flow rate of 67.1 milliliters per minute when a sinusoidal voltage of 170 V peak-to-peak and a frequency of 1 kHz were applied to the piezoelectric actuator. The initial idea of using valve-free pumps was proposed by Estme and Estme in 1993. They designed and manufactured a piezoelectric micropump that used nozzle/diffuser elements to achieve unidirectional flow These researchers collected valuable experimental data on the performance of this micropump, which was later used by other researchers in subsequent studies. Experimental results showed a linear relationship between flow rate and head pressure in this micropump. Valve-less micropumps have attracted significant attention from researchers and have been extensively studied. One of the most prominent studies was conducted by Foster and colleagues in 1995, who analyzed viscosity loss and dynamic reduction in nozzle/diffuser elements and Tesla valves for the first time. Forster et al. [41] introduced the Tesser valve with a parametric design. This valve was made by combining the geometry of the Tesla valve and nozzle/diffuser elements. As a result, the Tesser valve was more complex than the nozzle/diffuser elements and Tesla valve, containing a large number of independent geometric parameters. A 2D image of this valve is shown in Fig. 6e. In this study, the performance of the Tesser valve was compared with the performance of nozzle/diffuser elements and the Tesla valve. The simulation results indicated that nozzle/diffuser elements and the Tesla valve performed better than the Tesser valve. Cui et al. [42] proposed a valve-free piezoelectric micropump and investigated its performance using the finite element method (FEM). A 2D design of the nozzle/diffuser element is shown in Fig. 6f. Their simulation results indicated that at constant frequencies, an increase in voltage led to an increase in the pump flow rate and pressure. Additionally, increasing the length of the nozzle/diffuser element increased the flow rate, and reducing the diffuser angle also enhanced the micropump's net flow rate. The key features of this micropump included high reliability, low sensitivity to pharmaceutical particles, and good biocompatibility. Guan et al. [43] fabricated silicon-based serrated microchannels using deep reactive ion etching (DRIE) techniques. In this study, the performance of the serrated microchannel was compared to nozzle/diffuser elements at various voltages, frequencies, and driving signals. The maximum flow rate of the micropump with the serrated microchannel was 1.85 times higher than that of the micropump with traditional nozzle/diffuser elements. The serrated microchannel is shown in Fig. 6g. Ji et al. [44] simulated three piezoelectric micropumps using COMSOL Multiphysics software and subsequently built them. In these micropumps, the piezoelectric actuator was connected to the upper wall, and the nozzle/diffuser elements were attached to the lower wall of the chamber. The study investigated the effect of the valve hole spacing on the performance of the micropump. Three different hole spacings (15 mm, 3 mm, and 25 mm) were tested. The maximum flow rate for the micropump with a 3 mm hole spacing was 8.43 mL/min, which was 13.6% and 47.1% higher than the flow rates of the micropumps with 15 mm and 25 mm hole spacings, respectively. The simulation and numerical analysis results were almost identical. The design of the nozzle/diffuser elements and the valve holes is shown in Fig. 6h.

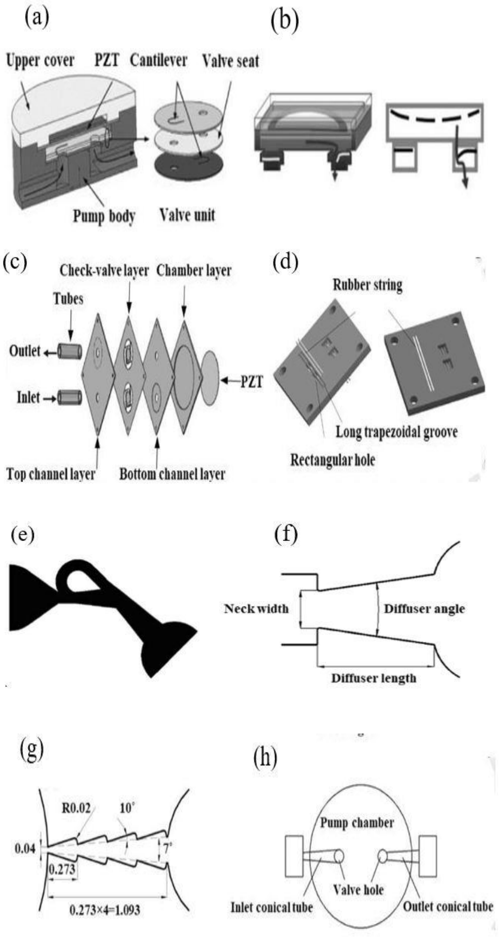

Fig. 6. Valves used in micropumps [37-44].

3.2. Diaphragm

The diaphragm separates the liquid inside the micropump chamber from the actuator. In fact, the diaphragm is the flexible wall of the chamber that comes into contact with the liquid inside it. The side walls of the diaphragm are attached to the micropump body, so the diaphragm diameter is equal to the chamber diameter. The actuator is located on the other side of the diaphragm, where it causes the diaphragm to vibrate in the vertical direction. The diaphragm's vibration creates a pressure difference inside the chamber, which helps transfer the liquid from the reservoir to the chamber and from the chamber to the outlet. One of the key factors to consider in the manufacturing of micropumps is selecting the appropriate material for the diaphragm. The diaphragm material must be chosen based on the specific application of the micropump. Particularly from the perspective of flow rate and biocompatibility, selecting the physical and mechanical properties of the diaphragm is crucial. Additionally, cost and wear resistance should also be carefully considered [45]. Table 1 shows the diaphragm materials commonly used in various studies.

Table 1. The type of diaphragms used in micropumps

Diaphragm material	reference
Silicon	Yazdi et al [46]
Beryllium bronze	Wang et al. [47]
Polyethylene Terephthalate (PET)	Pabst et al. [48]
Soft Magnetorheological Elastomer (SMRE)	Ehsani and Nejat [49]
Polydimethylsiloxane (PDMS)	Zhou and Amirouche [50]Kawun et al [51]
Thermoplastic Polyurethane (TPU)	Shaegh et al [52]
Elastomeric	Robertson et al [53].
Polyimide	Hamid et al[54]
Brass	Dong et al. [55]

3.3. Piezoelectric

The ability of certain materials to convert mechanical energy into electrical energy and vice versa is known as the piezoelectric effect. This phenomenon was discovered by the Curie brothers, Pierre and Jacques Curie, in the 1880s. Materials exhibiting this phenomenon are called piezoelectric materials. The piezoelectric effect can be observed in various materials, including single crystals, ceramics, polymers, and composites [56] .Materials that exhibit the piezoelectric effect typically lack a center of symmetry in their structure. When stress is applied to such materials, it alters the separation between positive and negative charges, resulting in a net polarization on the surface. This polarization induces an electric field, which generates a voltage [11]. Essentially, piezoelectric materials generate an electric charge on specific surfaces when compressed or subjected to stress. This phenomenon is known as the direct piezoelectric effect and is a reversible process. In other words, when a material with this property is placed in an electric field, its dimensions change (inverse piezoelectric effect). When the direction of the applied stress or pressure changes, the polarization of electric charges reverses. Similarly, changing the direction of the electric field alters the material’s dimensions. Both types of effects have a wide range of applications [57]. Many modern micropumps use piezoelectric materials as actuators. These micropumps are highly efficient and well-suited in terms of both performance and size. The inverse piezoelectric effect drives the suction and discharge mechanisms in these micropumps. Alternating voltage (AC) generates horizontal vibrations in piezoelectric materials. These actuators are tangentially attached to the diaphragm (or pumping membrane), with their edges fixed to the diaphragm. As a result, the horizontal vibrations of the piezoelectric material are transformed into vertical vibrations. The resonance frequencies and vibration patterns of these actuators depend on several factors, including the physical and mechanical properties of the materials, the amplitude and frequency of the AC voltage, the fluid load, and the boundary conditions [58]. Various designs for piezoelectric actuators have been proposed and studied. Revathi and Padmanabhan [59] introduced a composite-based piezoelectric micropump. The components of this micropump included a pair of identical nozzle/diffuser elements, a diaphragm made of PDMS, a chamber, and a piezoelectric actuator. The diameter of the diaphragm and the actuator was precisely equal to the diameter of the chamber. Fig. 7a shows the schematic design of this micropump, which uses a disk-shaped piezoelectric actuator. The objective of this study was to achieve a flow rate at low voltages and frequencies. To this end, the effect of voltage and frequency on the flow rate was investigated. The results indicated that within the frequency range of 1 to 20 Hz, the flow rate increased linearly, reaching its maximum value of 11.34 μL/min at 20 Hz. However, at frequencies higher than 20 Hz, the flow rate decreased. At higher frequencies, the piezoelectric actuator generated more force, but due to the increased pressure applied to the diaphragm, the diaphragm's displacement decreased. This reduction in displacement caused the flow rate to decline at frequencies above 20 Hz. Furthermore, with an increase in voltage, the flow rate of the micropump increased linearly because the diaphragm's displacement amplitude increased with higher voltage. Wang et al. [60] developed an analytical solution to study the deflection of a ring-shaped actuator made of lead zirconate titanate (PZT) for droplet ejection applications. In the formulation of this analytical solution, it was assumed that the strain distribution varies linearly along the thickness. The results from the analytical analysis showed good agreement with those obtained from finite element analysis. Additionally, the fabrication process of a droplet ejection device actuated by PZT was described. In this process, PZT was produced using powder metallurgy and patterned with polarized electrodes. The ejector was fabricated using the nickel electroforming method. Experimental results for the static deflection of the fabricated device confirmed the effectiveness of the proposed analytical solution. Finally, the performance of the ejector in droplet ejection was demonstrated. Fig. 7b shows the schematic design of this micropump. Haldkar et al [61] presented a novel design of a piezoelectric actuator and compared it with the conventional circular actuator design. In this study, fluid flow analysis was also investigated. The finite element method was utilized for this analysis using the ANSYS 12.1 software. Fig. 7c shows the piezoelectric design in this micropump. The simulation results demonstrated that the deflection in the new design, Strip Piezo Bimorph Disc (SPBD), was improved, leading to enhanced performance of the micropump. Jang and Chiang Yu [62] designed and fabricated a three-chamber micropump, where the chambers were connected to each other in series via channels. Fig. 7d shows the mechanical structure of this peristaltic piezoelectric micropump. The main components of the device included silicon, pyrex glass, and a piezoelectric actuator. The chambers and channels were made of silicon, while the diaphragm was produced from pyrex glass. Each diaphragm was equipped with a square piezoelectric actuator with a thickness of 191 micrometers. For all piezoelectric actuators, similar voltages and frequencies were applied. However, to generate peristaltic motion, alternating current (AC) voltage with different phases was applied to the actuators. The maximum displacement and flow rate of this micropump, under conditions of a 100-volt peak-to-peak (VP-P) voltage and a 100 Hz frequency, were recorded as 2.91 micrometers and 17.58 microliters per minute, respectively.

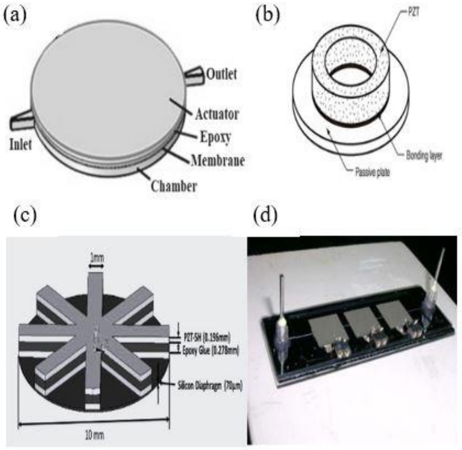

Fig. 7. Piezoelectrics designed for piezoelectric micropumps [59- 62].

Smits et al. [7] presented the first design of a piezoelectric micropump for drug delivery. This micropump was used in insulin infusion control systems for diabetic patients. This design reduced the need for continuous syringe injections in these patients. In such applications, transferring a large volume of fluid into the body is not of primary importance. Moreover, the pressure generated by the pump is not the only essential indicator of its performance. Other parameters, such as high reliability, low energy consumption by the actuator, low manufacturing cost, and compatibility with biological conditions, are also critically important. Wang et al. [63] investigated the effect of diaphragm thickness and diameter, piezoelectric material thickness and diameter, and chamber diameter on diaphragm deformation through simulations. The results of this study showed that as the diaphragm thickness increases, the amount of deformation decreases. However, very thin diaphragms may not have sufficient strength. The study also determined that the thickness of the piezoelectric material should be greater than that of the diaphragm. Furthermore, it was demonstrated that piezoelectric actuators are relatively weak in terms of mechanical strength. Therefore, significantly increasing the thickness of the piezoelectric material leads to a reduction in diaphragm deformation. The ratio of diaphragm dimensions to piezoelectric material dimensions should be considered based on the micro-pump design. The study also showed that the chamber diameter has a direct correlation with diaphragm deformation. Wang et al [64] introduced a piezoelectric micropump with a folded vibrator for fuel transfer. The main components of this micropump include a folded piezoelectric vibrator, a silicon diaphragm, a chamber, two one-way valves made of PDMS, and two flexible compressible spaces. The innovation of this study lies in the design of the folded vibrators and the compressible spaces located near the one-way valves. The designed vibrator consists of three folded layers, each equipped with a piezoelectric actuator. This innovative vibrator increases the displacement of the diaphragm. Additionally, the designed compressible spaces, along with the one-way valves, enable contraction and expansion. The presence of these flexible spaces in the channels reduces the fluid load. Consequently, with the reduction in fluid load, the flow rate in the channels increases. According to the results of this study, the maximum diaphragm displacement was recorded at 425 µm under a voltage of 80 VP-P. Furthermore, the highest flow rate of 118 mL/min was achieved at a voltage of 120 VP-P and a frequency of 361 Hz. Singh et al. [24] investigated the effects of various components of micropumps using simulation and experimental methods. In this study, factors influencing the flow rate, including the nozzle/diffuser angle, chamber diameter and height, as well as the diaphragm diameter and thickness, were evaluated. The results showed that the maximum flow rate of this micropump was 20 microliters per minute, achieved at a voltage of 30 volts. Eladi et al. [65] designed and fabricated a valveless micropump using a PZT actuator. The design of this micropump consisted of three distinct layers, two made of silicon and one made of glass. These layers were stacked together to form an integrated and composite structure. For pumping operations, water and methanol were selected as the test fluids. They investigated the effects of factors such as the nozzle/diffuser design, the height of the micropump chamber, and the diaphragm's vibration voltage and frequency on the net flow rate. The results indicated that the optimal voltage and frequency for the micropump's operation were 80 volts and 250 Hz, respectively. Under optimal conditions, the back pressure was measured to be zero for water and 360 Pa for methanol. Cazorla et al. [66] investigated the effect of diaphragm vibration frequency on the flow rate. In this study, the actuation voltage applied to the piezoelectric actuator was set to 24 volts at different frequencies. The maximum diaphragm displacement at its center was observed to be 5.6 micrometers. In this micropump, the flow rate increased linearly up to a frequency of 0.8 Hz and then changed sublinearly in the range of 0.8 to 1 Hz. The maximum flow rate of 3.5 microliters per minute was achieved at a frequency of 1 Hz. The main advantage of this study was the micropump's ability to operate at low voltages with low energy consumption. Revathi and Padmanaban [59] presented the design of a composite-based piezoelectric micropump. This micropump consisted of components such as a pair of identical nozzle/diffuser elements, a PDMS diaphragm, a chamber, and a piezoelectric actuator. The diameters of the diaphragm and the actuator matched the diameter of the chamber. The primary objective of this study was to evaluate the performance of the micropump at low voltages and frequencies, and the effects of these parameters on the flow rate were investigated. The results showed that the flow rate increased linearly in the frequency range of 1 to 20 Hz, with a maximum flow rate of 11.34 microliters per minute recorded at a frequency of 20 Hz. However, at frequencies higher than 20 Hz, the flow rate decreased. Although an increase in frequency generated more force by the piezoelectric actuator, this increase in pressure at higher frequencies resulted in reduced diaphragm displacement. Additionally, an increase in voltage caused a linear increase in the flow rate. This phenomenon occurred due to the greater displacement amplitude of the diaphragm at higher voltages.

4. Conclusions

Microfluidics has various applications, such as micromixers, separation devices [67-73], and micropumps. Piezoelectric micropumps, as one of the key technologies in the fields of medicine, chemistry, aerospace, and cooling systems, have revolutionized the design and performance of microscale systems. In this review article, advancements in the design and fabrication of various components of micropumps, including the chamber, diaphragm, valves, and piezoelectric layer, were explored. Additionally, the applications of micropumps in various fields were thoroughly examined. These micropumps, utilizing piezoelectric properties, have successfully met the demands for precision, efficiency, compact size, and the ability to operate in diverse environments. From medical applications such as insulin delivery and targeted drug administration to their use in fuel cell systems and the cooling of electronic devices, this technology has played a vital role in enhancing the performance of modern systems. However, challenges such as improving dosing precision, reducing production costs, and increasing durability and reliability still require further research. In the future, the development of advanced materials, optimization of micromechanical designs, and the adoption of innovative manufacturing techniques could elevate piezoelectric micropumps to new levels of performance and applicability in various industries. Consequently, this technology has the potential to serve as a key enabler in the realization of advanced microscale systems and in improving the quality of human life.

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