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REVIEW

Advances in Valveless Piezoelectric Pump with Cone-shaped Tubes

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Abstract This paper reviews the development of valveless piezoelectric pump with cone-shaped tube chronologically, which have widely potential application in biomedicine and micro-electro-mechanical systems because of its novel principles and deduces the research direction in the future. Firstly, the history of valveless piezoelectric pumps with cone-shaped tubes is reviewed and these pumps are classified into the following types: single pump with solid structure or plane structure, and combined pump with parallel structure or series structure. Furthermore, the function of each type of cone-shaped tubes and pump structures are analyzed, and new directions of potential expansion of valveless piezoelectric pumps with cone-shaped tubes are summarized and deduced. The historical argument, which is provided by the literatures, that for a valveless piezoelectric pump with cone-shaped tubes, cone angle determines the flow resistance and the flow resistance determines the flow direction. The argument is discussed in the reviewed pumps one by one, and proved to be convincing. Finally, it is deduced that bionics is pivotal in the development of valveless piezoelectric pump with cone-shaped tubes from the perspective of evolution of biological structure. This paper summarizes the current valveless piezoelectric pumps with cone-shaped tubes and points out the future development, which may provide guidance for the research of piezoelectric actuators.

Keywords Piezoelectric pump · Valveless · Cone-shaped tube · Bionics

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1 Introduction

In 1993, Swedish scientists Stemme et al [1], published the paper entitled “A valveless diffuse/nozzle-based fluid pump”. It marked the birth of the first non-rotary pump without any movable valve body driven by piezovibrators, which is invented based on the dynamic passive valve presented by Smith [2]. The proposed pump consists of a diffuser, a nozzle and a piezoelectric vibrator, where the diffuser and the nozzle are mounted below the pump chamber as inlet and outlet of pump, and the piezoelectric vibrators are used as driving source to generate reciprocating change of volume in pump chamber. Along flow direction, the tube whose cross-section broadens is defined as the diffuser tube, while the one whose cross-section tapers off is defined as the nozzle tube. The two aforementioned flow tubes are collectively named cone-shaped tubes by their shape. Hence, the valveless piezoelectric pump encompassing these tubes is known as valveless piezoelectric pump with cone-shaped tubes.

The appearance of the valveless piezoelectric pump with cone-shaped tubes influences directly the classification of pumps. The conventional volume-type reciprocating pump is divided into the pumps using valve, but the cone-shaped tube pump does not have any valve from a common sense perspective. And in the definition of non-rotary pump, the valveless concept was thus generated. The emergence of the valveless piezoelectric pump with cone-shaped tubes also manifests the discovery of a novel driving source, piezoelectric vibrator, which can convert electric energy into mechanical strain energy of piezoelectric ceramic, and then transfer the mechanical strain into kinetic or potential energy of fluid through pump chamber and cone-shaped tube. This pump breaks through the banal definition of conventional pump and driving source, and eliminates the maladjustment between conventional pump and new driving source, as well as between new function and old principle [3]. It is like a spring breeze blowing into the traditional industry of pump. Unlike the situation in a conventional pump with valve(s) and vibrator(s), no compromise should be made in the valveless piezoelectric pump with cone-shaped tubes because the cone-shaped tube with dynamic unidirectional character matches the driving source, piezoelectric vibrator, surprisingly well. Thanks to the facts that the driving source matches channel and the pump structure adapts its function, the valveless piezoelectric pump with cone-shaped tubes becomes competitive in the fields of bio-engineering, micro/nano manufacturing and micro/nano driving [4–9], thus attracting much attention of researchers. According to our retrieve data using “piezoelectric pump” as a key word, there are nearly 1400 papers available, of which the papers about the valveless pump with cone-shaped tubes accounts for nearly one-third of the total.

Hence, this paper will review the structural evolvement of the valveless piezoelectric pump with cone-shaped tubes over the past 25 years and pinpoint those milestones in its developing history. After the classification of various valveless piezoelectric pumps with cone-shaped tubes and the functional analysis of each type, researchers will also endeavor to shape the future development and implications.

2 Single Valveless Piezoelectric Pump with Cone-shaped tubes

2.1 Three-dimensional structure

Drawing on the research results of predecessors, such as piezoelectric fluid actuator, valve piezoelectric pump[10–18], and applying the concept that the cone-shaped tube can be regarded as dynamic passive valve[2], Stemme proposed the valveless piezoelectric pump with cone-shaped tubes in 1993, and subsequently patented their design. The diffuser (a) and nozzle (b) of this pump are sketched in Fig. 1, and the piezoelectric pump structure is shown in Fig. 2, containing the diffuser/nozzle. Stemme built two prototype pumps, in which the angles of cone-shaped tube are 5.3° and 10.7°, respectively. Test results showed that, the maximum volume flow rate was 18 mL/min and the maximum pump pressure was 2 m hydraulic pressure at driving frequency of 100 Hz. Referred to the structure shown in Fig. 2, the fluid in the pump flowed clockwise.

Furthermore, after an in-depth investigation, the two researchers pointed out:

(1) The resonant frequency of pump depended on the structure of pump, fluid density and piezoelectric parameter of vibrator, etc.
(2) The amplitude of vibrator was linear with driving voltage.
(3) The pressure output of the valveless piezoelectric pump with tapered angle of 5.3° (Type A) was higher than that with tapered angle of 10.7° (Type B), but the volume flow rate of Type A was smaller than that of Type B. The pressure loss coefficient of the nozzle tube was always larger than that of the diffuser tube.

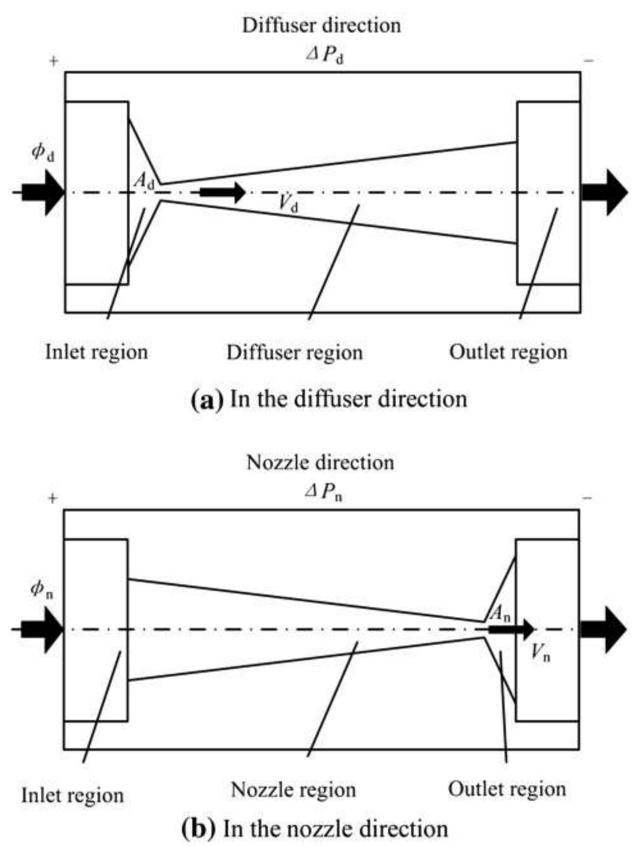

Fig. 1 Design principle of the diffuser/nozzle element with three flow regions

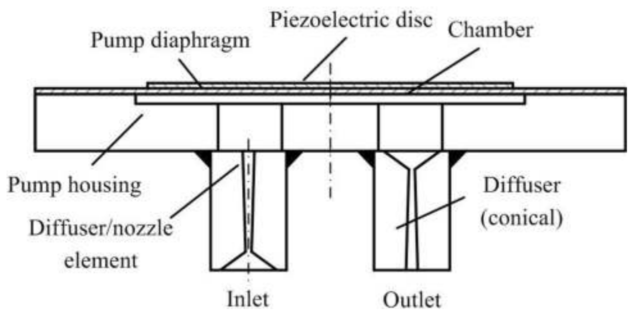

Fig. 2 Valveless piezoelectric pump developed by Stemme, et al

(4) The performance of the diffuse was related to the element geometry of flow channel, while that of the nozzle was independent of the element geometry.
(5) The flow channel of the diffuser/nozzle element can be divided into three regions, i.e., the inlet region, the outlet region, and the diffuser/nozzle region in the middle (Fig. 2).

Although their results seem to be a little out-dated and some are even not quite right, Stemme E. and Stemme G. are still two pioneers in the field. They created a new era of piezoelectric pump with their unique piece of work. With the presentation of valveless pump, the match between the old valve body and novel driving source, like an intermarriage of traditional European aristocrats and American newly rich, is no longer worrisome. Eventually, the cone-shaped tube perfectly adapts to the piezoelectric vibrator dynamically.

Since then, piezoelectric pumps have entered a new period of development and stepped onto a broader arena. The research and development of valveless piezoelectric pumps, led by the investigation on the valveless pump with cone-shaped tubes have drawn increasing attention and achieved fruitful results. Therefore, we subsequently survey the progresses in the development of valveless piezoelectric pump with cone-shaped tubes.

In addition to the suggestion that the fluid in the valveless pump flows clockwise, it is worth noting that there are four more implicit assumptions in Fig. 2.

(1) Suppose that the piezoelectric oscillator is bounded on the pump chamber.
(2) Suppose that pump chamber is connected to transfer flow through at least one cone-shaped tube.
(3) Suppose that using macroscopic flow direction define the different types of cone-shaped tubes, with the macroscopic flow direction becoming wider gradually defined diffuser and on the contrary, defined nozzle.
(4) The definition is that no matter how figure shows in papers, flow channel sectional area flowing into pump chamber from the left of center line of piezoelectric pump is larger than that from the right of center line.

To facilitate below discussion, in this paper, the four pieces of hypothesis are defined premise hypothesis. Certainly they do not influence intrinsic quality of pump, they are just convenient to illustration. For the planar structure, the hypotheses still valid, as shown in Fig. 3.

In 1995, Gerlach, et al [19], developed a valveless piezoelectric micro-pump with tapered flow tubes by using MEMS technology on a silicon plate. The micro- tapered flow tube using MEMS technology on a silicon substrate is shown in Fig. 3, and the valveless piezoelectric micro-

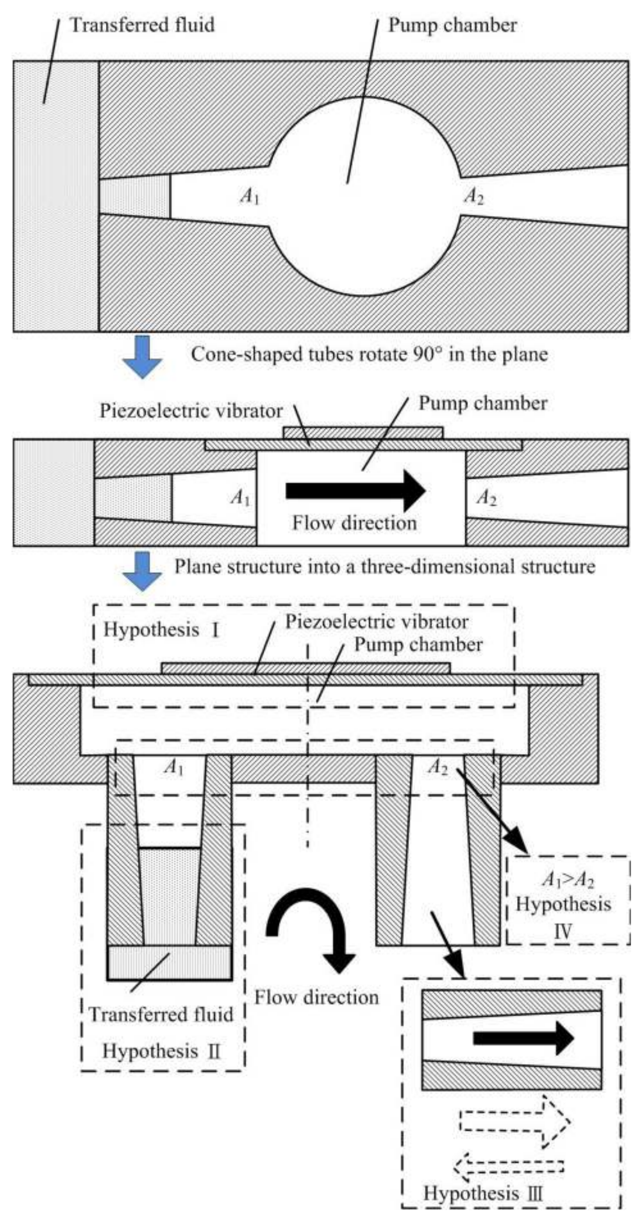

Fig. 3 Schematic of the hypotheses determining flow direction of micropump

pump with tapered flow tubes is shown in Fig. 4. The channel of diffuser/nozzle tube proposed by Stemme was complex and difficult to realize micromation, and some regions even played a role of preventing the pump from working effectively. Contrarily, the silicon-based valveless piezoelectric micro-pump with tapered flow tubes directly removed the redundant factors that prevent the pump from working effectively, and thus pioneered the use of MEMS technology to microminiaturize the piezoelectric pump.

On the wafer of the single-crystal silicon, trapezoidal cone flow channel was etched, whose shape could be imagined as a hollow topless pyramid. Etching was processed along lattice angle formed naturally. The angle between the bottom surface and any side face is 54.74°, and the angle between either opposite couple of side faces is 70.52°, that is, the angle of square cone is 70.52°, as shown in Fig. 4. By using the equivalent circuit method, it can be concluded that the pump mechanism cannot be in effect until the Reynolds number of the micro-conical flow tube is larger than 100.

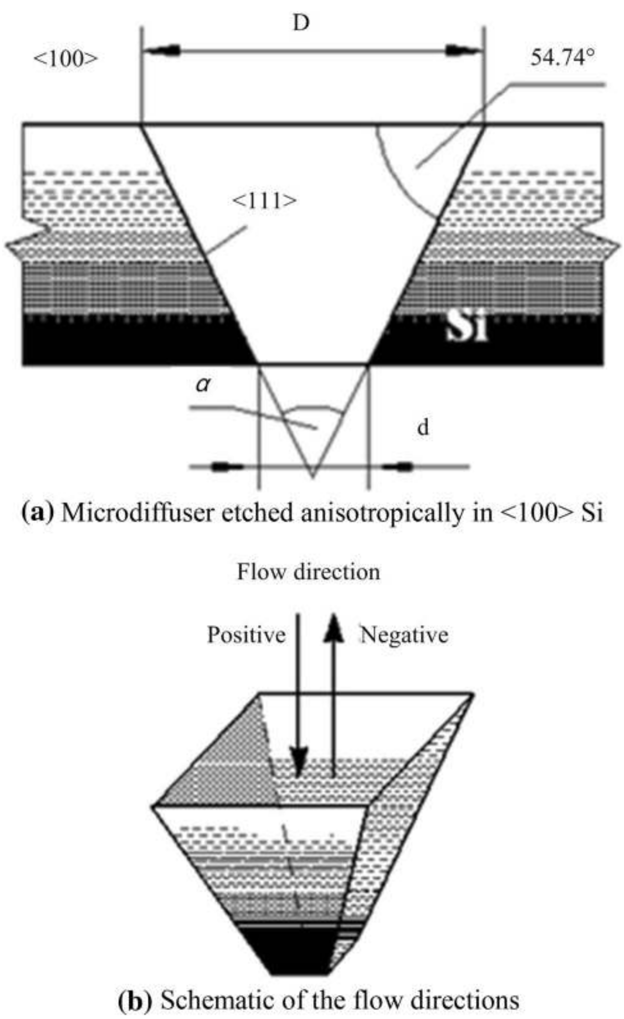

Fig. 4 Trapezoidal cone flow channel

The minimum side length of the cross-section of the square channel on the top/bottom of the wafer is defined as a design variable, varying from 80 μm to 300 μm. The piezo-bimorph in thickness of 200 μm was pasted on a heat-resistant glass film in thickness of 120 μm with its equal side length of 11 mm, 7 mm, and 5 mm respectively to form a piezoelectric vibrator. An isotope was used to etch two kinds of silicon wafers, one to be the pump chamber in shape of a large hollow square cone, the other to be diffuser and nozzle which are a pair of small hollow trapezoidal cones inversely arranged with each other and their square cone angle was calculated as 70.52°. Then, the piezoelectric vibrator, pump chamber, and diffuser and nozzle were packaged together in turn to form a valveless piezoelectric micro-pump with cone-shaped tubes. Among them, when driving frequency of 3000 Hz, the pump with a minimum side length of 143 μm and pump side length of 7 mm had the maximum flow rate of nearly 400 mL/min. According to the premise assumptions, the direction of flow in the pump should be counterclockwise in Fig. 5.

Cheng, et al[20], developed a valveless piezoelectric pump with cone-shaped tubes in 1998. This pump had a large cone angle of 70°. According to the premise assumptions, the direction of flow in the pump should be counterclockwise in Fig. 6.

Nguyen and Huang proposed a valveless piezoelectric micro-pump with cone-shaped tubes in 2001 [21] (see Fig. 7). Taking the premise assumptions and the sizes shown in Fig. 7, the cone angle was calculated as 2.15°, and the direction of flow in the pump should be clockwise.

One year later, Schabmueller, et al[22], developed a valveless piezoelectric pump with cone-shaped tubes (See Fig. 8). This pump had its cone-shaped tubes with a moderate cone angle of 35.3°. Based on the premise assumptions, the direction of flow in the pump should be counterclockwise.

In 2006, Zhang and Wang [23] developed a valveless piezoelectric pump with cone-shaped tubes. This pump

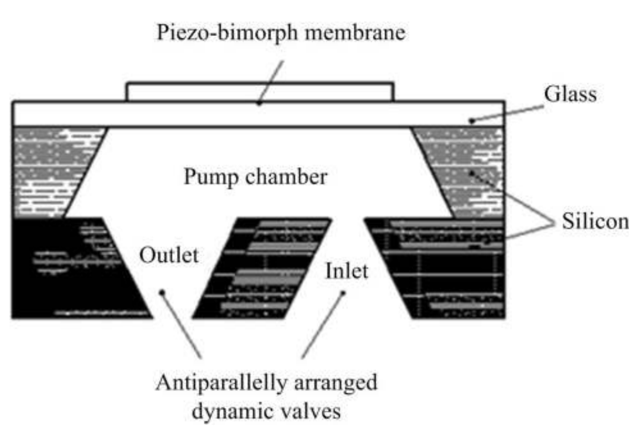

Fig. 5 Cross-sectional view of the tested micropumps

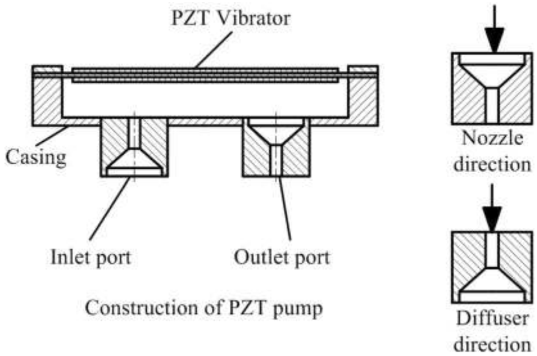

Fig. 6 Valveless piezoelectric pump of large cone angle

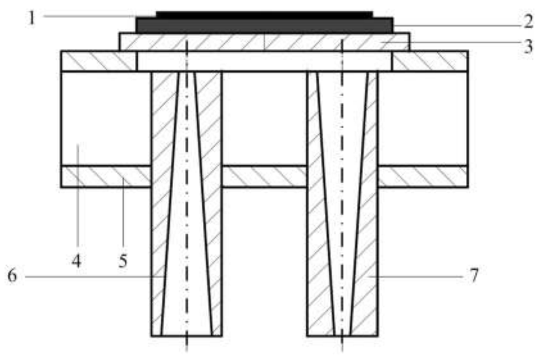

Fig. 7 Pump structure. 1. Conductive layer; 2. Piezoelectric disc; 3. Brass plate; 4. PCB-substrate; 5. Copper layer; 6. Outlet tube; 7. Inlet tube

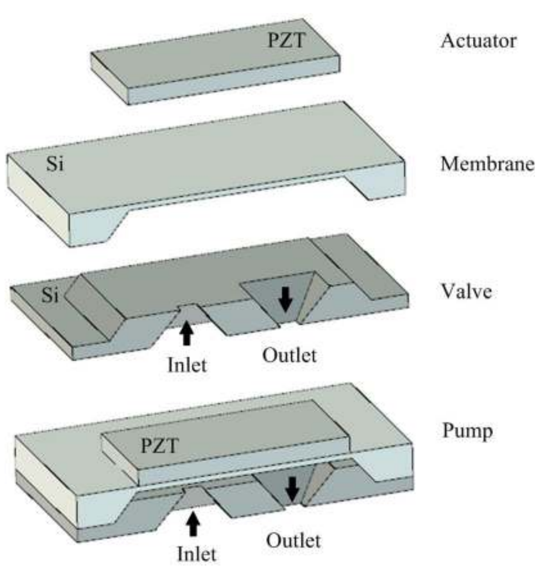

Fig. 8 Schematic of the different units creating the micropump

used a piezoelectric ceramic ring as an actuator, and arranged a pair of tapered flow tubes in the pump chamber (see Fig. 9). The application of this micropump is to circulate fuel inside a miniaturized direct methanol fuel cell (DMFC) power system.

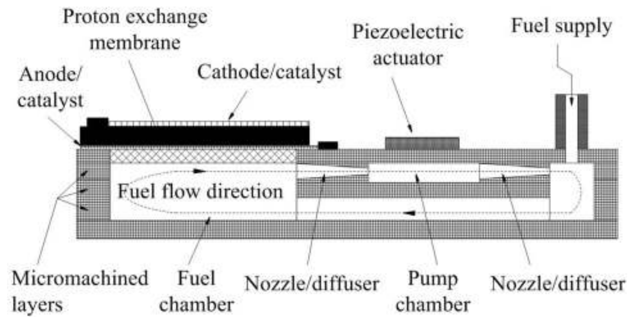

Fig. 9 Schematic of the miniaturized DMFC power system using piezoelectric valveless micropump for fuel delivery

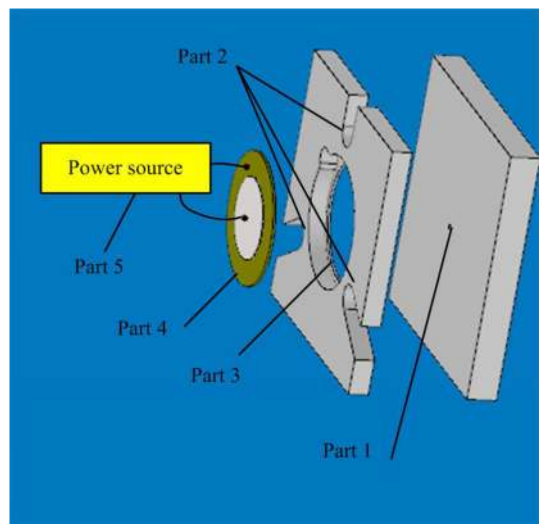

Fig. 10 Exploded view of micropump and component list. Part 1—Outlet channel of micropump. Part 2—Inlet channels of the micropump. Part 3—Chamber. Part 4—Piezoelectric buzzer(actuator). Part 5—Power driving sourc

In 2007, Cheng and Lin[24] developed a valveless piezoelectric pump with cone-shaped tubes, using four three-dimensional cone-shaped tubes with small cone angle. Among these tubes, three were evenly distributed at the side of the pump body as an inlet, in the form of diffuser; the other one was at the geometric center of the opposite side of the piezoelectric vibrator as an outlet, in the form of nozzle, with the cone angle of 10° (see Fig. 10). According to the premise assumptions, the direction of flow in the pump should be clockwise.

Verma and Chatterjee developed a valveless piezoelectric pump with cone-shaped tubes in 2011[25]. This pump had cone angle of 6.2° (see Fig. 11). According to the premise assumptions, the direction of flow in the pump should be clockwise.

All these aforementioned pumps are valveless piezoelectric pumps with cone-shaped tubes in the form of solid structure. Here, the "solid structure" refers to a three-dimensional structure that the cone-shaped tube, as a flow-

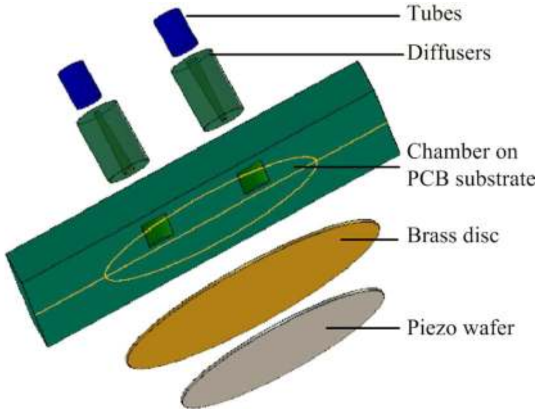

Fig. 11 Schematic of exploded view of the fabricated micropump

resistance-type non-movable valve, retains, such as cone, square cone and so on. For fluid delivery, the solid structure has the advantages of good symmetry, little disturbance, easy to control and high efficiency. However, it also has some disadvantages with respect to the structure itself, such as big duty cycle and difficulty in processing. Probably influenced a lot by the research from Stemme [1] and Gerlach [19], early valveless piezoelectric pumps with cone-shaped tubes were mostly in the form of solid.

2.2 Plane structure

In 2007, Pun, et al[26], developed a valveless piezoelectric micro-pump with cone-shaped tubes. This pump used hot stamping technology to integrate micro-tapered structure with pump cavity. And this technology helps reduce costs, improve efficiency and ensure accuracy (see Fig. 12, Fig. 13).

In 2008, Nisar, et al[27], developed a valveless piezoelectric micro-pump with a single cone flow channel (see Fig. 14).

In 2008, Cui et al. developed a valveless piezoelectric micro-pump with cone-shaped tubes[28]. This pump had a cone angle of 9.4 ° (see Fig. 15). According to the premise assumptions, the direction of flow in the pump should be clockwise.

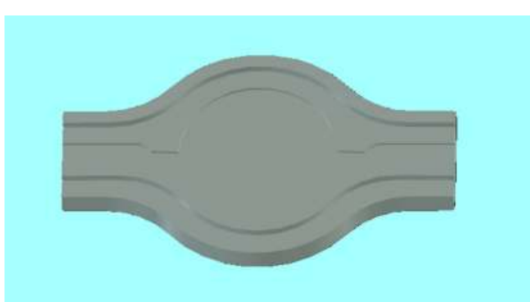

Fig. 12 Prototype of micro-pump body fabricated by HET

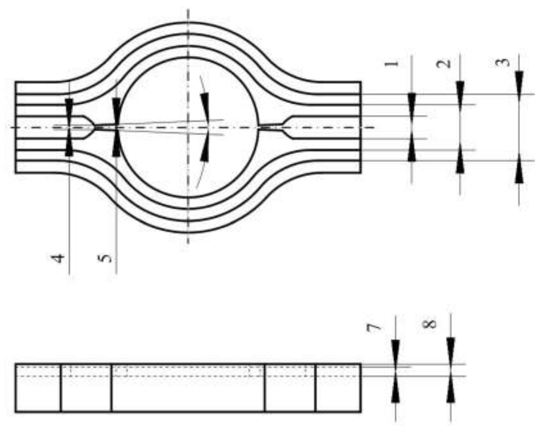

Fig. 13 Critical dimensions for quality evaluation

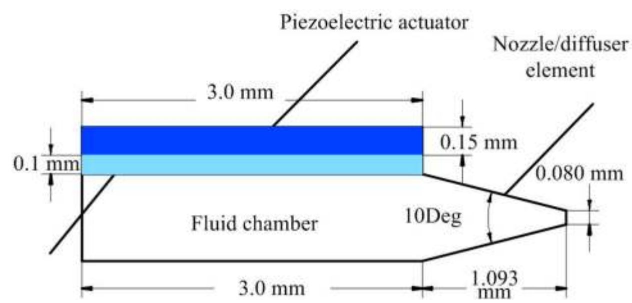

Fig. 14 Model dimension developed by Asim Nisar, et al

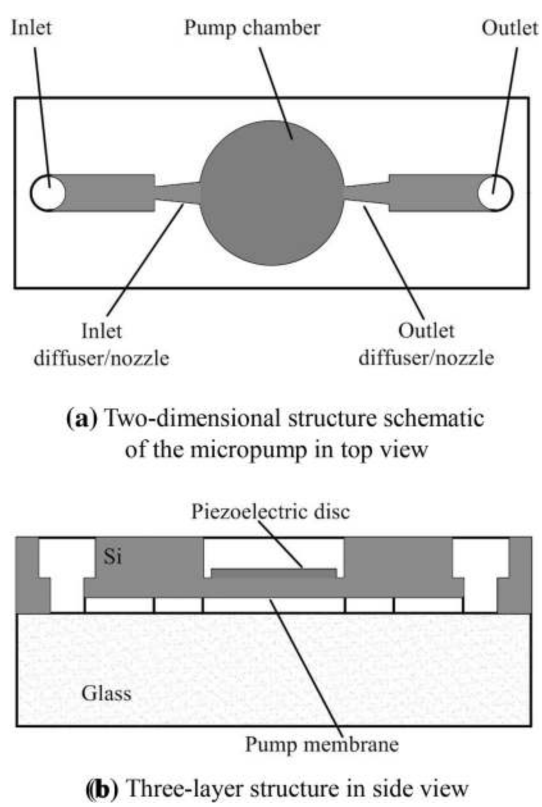

Fig. 15 Piezoelectric micropump developed by Cui et al

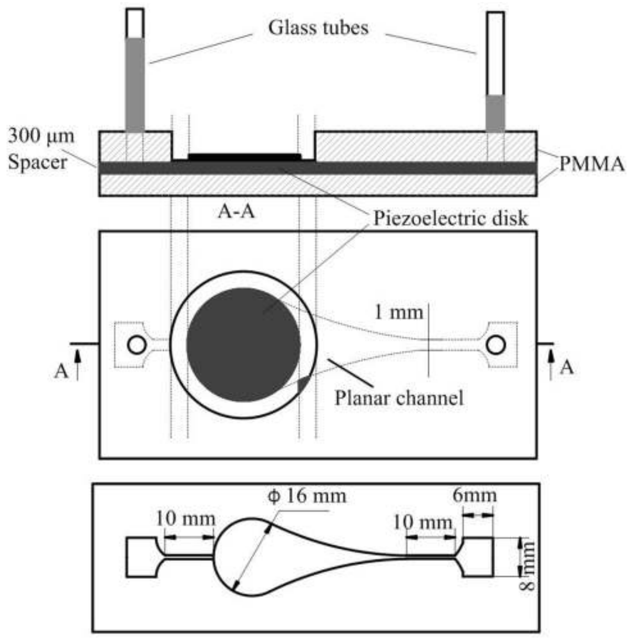

Fig. 16 Schematic of the valveless piezoelectric pump with a single raindrop-shaped tube

In 2009, Huang, et al developed a valveless piezoelectric pump with a single raindrop-shaped tube [29, 30] (see Fig. 16).

In 2009, Ha, et al [31], from Korea developed a valveless piezoelectric micro-pump with cone-shaped tubes. This pump was of the 8° cone angle (see Fig. 17). According to the premise assumptions, the direction of flow in the pump should be clockwise.

In 2012, Chandika, et al [32], developed a valveless piezoelectric pump with cone-shaped tubes. This pump had cone angle of 10° (see Fig. 18, Fig. 19). According to the premise assumptions, the direction of flow in the pump should be clockwise in Fig. 18.

In 2013, Tseng and Cheng, et al [33, 34], from Taiwan, China, developed a valveless piezoelectric micro-pump with cone-shaped tubes by using MEMS, photolithography and etching processes. This pump may have applications in the biomedical and other fields (see Fig. 20). According to the premise assumptions, the direction of flow in the pump should be clockwise in Fig. 21.

In 2015, Singh et al. from India developed a valveless piezoelectric micro-pump with cone-shaped tubes having cone angles of 10° [35] (see Fig. 22). The proposed micropump is polymer based and thus suitable for low-cost and disposable applications.

In 2017, He, et al developed a valveless piezoelectric pump with cone-shaped tubes [36]. This pump had cone angle of 7°. According to the premise assumptions, the direction of flow in the pump should be clockwise, as shown in Fig. 23.

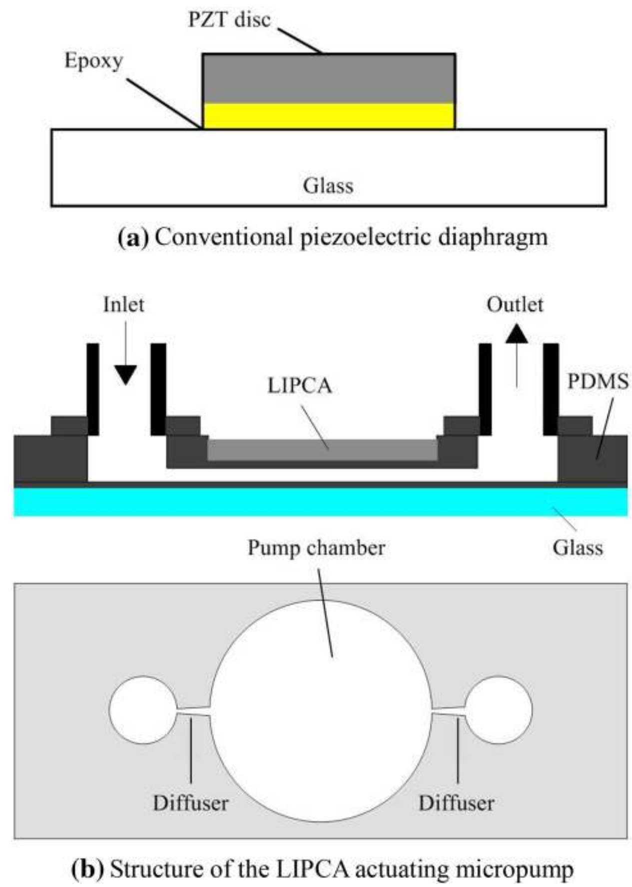

Fig. 17 Conventional diaphragm and the LIPCA actuating micropump design

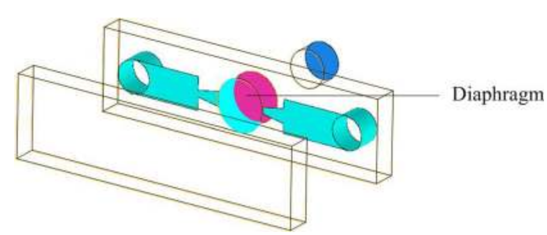

Fig. 18 Wire frame model of micropump

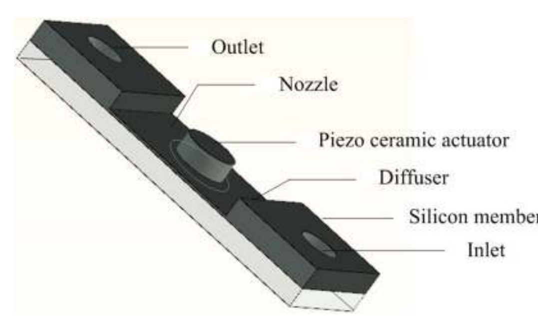

Fig. 19 3D view of the piezo driven micropump

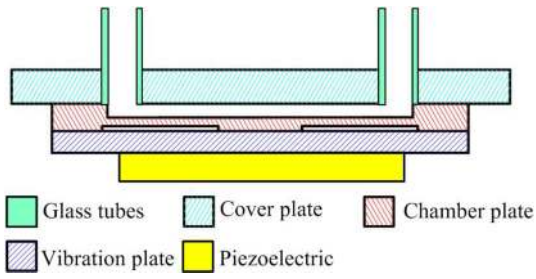

Fig. 20 Cross-section view of micropump

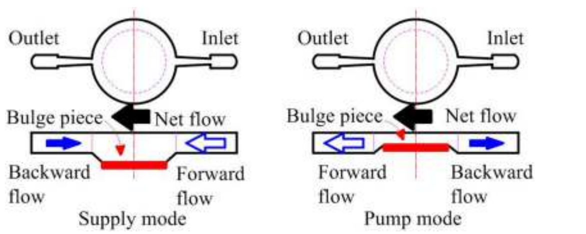

Fig. 21 Diagrams of operational principle in supply and pump mode

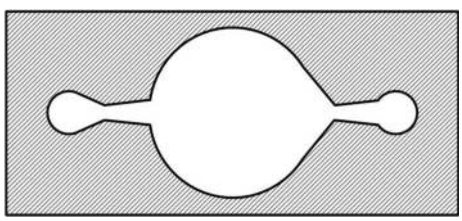

Fig. 22 Top view of the valveless piezoelectric micro-pump

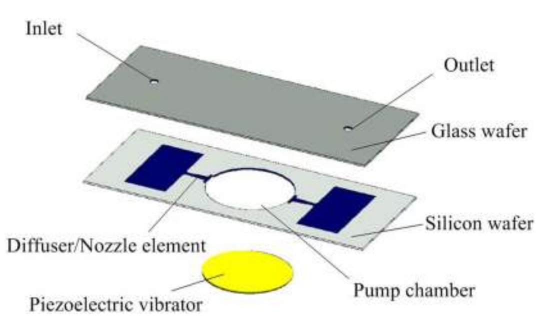

Fig. 23 Exploded view of the piezoelectric micropump

All those above are valveless piezoelectric pumps with cone-shaped tubes in the form of plane structure. The so-called "plane structure" refers to two-dimensional or two-and-a-half dimensional in-plane structure that the cone-shaped tube has, as the flow-resistance-type non-movable valve. When cutting this structure in the longitudinal direction by using the tapered plane up and down, we will always obtain new tapered planes in the same shape. (That is to say, for a cone-shaped tube in the form of plane, the new tapered shapes generated in the longitudinal direction

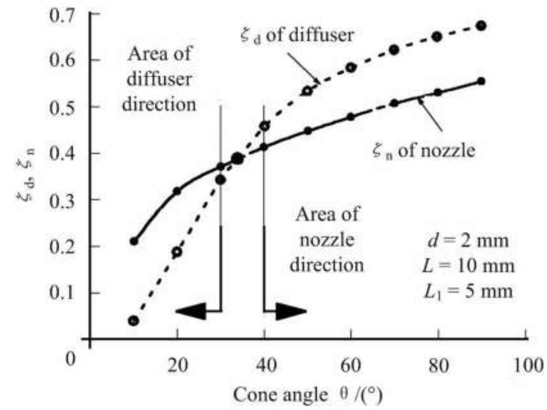

Fig. 24 Flow resistance versus cone angle

are all the same). The advantages of the plane structure include, with respect to the structure itself, small duty cycle, easy implementation of internal structure design and optimization for the cone-shaped tube, easy processing, easy realization of miniaturization. But there also exists some disadvantages with respect to fluid delivery, such as bad symmetry, large system disturbance, low efficiency, and necessary consideration of the on-way flow resistance.

What is worth mentioning in particular is that the valveless piezoelectric pump with a single raindrop-shaped tube developed by Huang, Wang and Yang [29, 30]. This pump can be used in structural design to realize the special fluid delivery or energy transfer. It can match the energy consumption between diffuser and nozzle, which may become a design direction for the valveless piezoelectric pumps with cone-shaped tubes in the future. But this structure may be not suitable to be called "cone-shaped tube" if it goes into a far more complicated form, same as the evolution of mankind itself from the ape.

2.3 Brief summary

In the past twenty years, a considerable amount of research and development has been conducted by researchers from all over the world on the topic of single-type valveless piezoelectric pumps with cone-shaped tubes, which reveals in depth the structural characteristics of the pumps (e.g., piezoelectric vibrator, diffuser/nozzles, pump chamber). Whether the pump is in the form of plane or solid structure, it always contains those characteristics.

According to the fact that the cone angle dominates the flow direction, it can be found that, the size of the cone angle of diffuser/nozzle may determine the flow resistance coefficient along tube wall, and what's more, the sign of the difference value of flow resistance coefficient between the diffuser and the nozzles determines the macroscopic flow direction of a valveless piezoelectric pump with cone-shaped tubes. Fig. 24 shows the relationship curves

Table 1 Relationship between cone angle and flow direction

Serial No.	Reference No.	Spatial structure	Cone angle θ / (°)	Flow direction	Flow direction deduced in Ref. [26]
1	[2]	Solid	5.3	Clockwise	Clockwise
2	[2]	Solid	10.7	Clockwise	Clockwise
3	[9]	Solid	70.52	Counterclockwise	Counterclockwise
4	[10]	Solid	70	Counterclockwise	Counterclockwise
5	[11]	Solid	2.15	Clockwise	Clockwise
6	[12]	Solid	35.3	Counterclockwise	Counterclockwise
7	[14]	Solid	10	Clockwise	Clockwise
8	[15]	Plane	6.2	Clockwise	Clockwise
9	[18]	Plane	9.4	Clockwise	Clockwise
10	[21]	Plane	8	Clockwise	Clockwise
11	[22]	Plane	10	Clockwise	Clockwise
12	[23][24]	Plane	10	Clockwise	Clockwise
13	[25]	Plane	10	Clockwise	Clockwise
14	[26]	Plane	7	Clockwise	Clockwise

between cone angle and flow resistance coefficient for diffuser and nozzle[37]. The statistical results of the cone angle size and the flow direction in the reference literature are shown in Table 1. Moreover, they are compared with the experiment and analysis by Zhang et al. in 2004 in Ref. [37]. Comparison results confirm the conclusion of Ref. [37], i.e., when the cone angle is small, the flow direction is clockwise; On the other hand, the flow direction is counterclockwise, although no plane structure of valveless piezoelectric pumps with cone-shaped tubes had been proposed before the Ref. [37] was written. The definitions of clockwise and counterclockwise have been given in the premise assumptions.

Eqs. (1) and (2), using the knowledge of fluid mechanics, explains the experimental results about one-way flow from the valveless piezoelectric pump with cone-shaped tubes in Fig. 23. Meanwhile, Eqs. (1) and (2) also manifests that, the cone angle that tends to maximize the value of $\lim_{\theta \to \theta_0}\left(\frac{\xi_d - \xi_n}{\xi_d + \xi_n}\right)$ may be the fundamental reason for why and when the pump reaches its maximum flow rate. Breaking the concept of classifying flow resistance into two kinds, that is, one kind that is helpful to form a unidirectional flow and the other irrelevant, the flow resistance of pump system should be indeed separated into flow resistance of diffuser, flow resistance of nozzle and on-way flow resistance of the pipeline. Since the flow resistance consumes energy when piezoelectric pump is working, the matching between driving frequency and driving voltage should be considered besides the energy supply needed to overcome all kinds of flow resistance. So far, however, very few reports have been found to deepen the knowledge and understanding of this subject. Although discussions about the matching problem between driving frequency and driving voltage

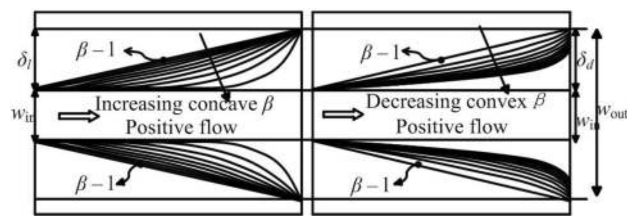

Fig. 25 Tuning of diffuser elements with concave and convex geometries

have been made by Stemme [1], Gerlach [19] and later comers, there is still a lot of work left for people to explore on the valveless piezoelectric pump with cone-shaped tubes in the view of energy matching, energy flow and energy balance, which may also become a new research direction, even a hotspot, in the near future.

$$\lim_{\theta \to \theta_0}\left(\frac{\xi_d - \xi_n}{\xi_d + \xi_n}\right) \to \max = g(\theta_0), \quad (1)$$

$$q_{V,\max} = \Delta V f g(\theta_0). \quad (2)$$

Then, let's go back to discuss the valveless piezoelectric pump with a single raindrop-shaped tube [29, 30]. When a raindrop is falling, external forces of each point on the surface of the raindrop are equal. If the inner surface of the raindrop-shaped channel is equivalent to the outer surface of the raindrop formed in the nature, then external forces generated by the on-way flow resistance of each point in the raindrop-shaped channel are also equal. In this case, the internal friction of the pump itself is minimized. According to the research on geometric tuning of convex-and-concave shape of the cone-shaped tube by Chandrasekaran and Packirisamy [38] (see Fig. 25), it can be foreseeable that some valveless piezoelectric pump with cone-shaped tubes, whose driving parameters (frequency, voltage) may consider the geometric tuning parameters of the tube as well as the fluid parameters (viscosity, density, pressure), will be created in the future.

After reviewing the above history of technology, the research on cone-shaped tube of single-type pump can be retrieved to the papers studying fire sprinklers one hundred years ago, or even earlier. In this sense, the valveless piezoelectric pumps with cone-shaped tubes can be regarded as the innovative applications of a traditional structure. From a wider-dimensional perspective, we can learn from the organism itself to develop the applications of the cone-shaped tubes.

In 1999, Owerkowicz, et al reported that the gullet of a varanid had a function similar to that of a car's turbocharger, thus assisting lung ventilation and providing sufficient supply of oxygen [39]. As the gullet plays a role of inlet channel and realizes pressure boosting, it's necessary for it to equip with the ability of fluid resistance control. It can be observed that the structure of the varanid's gullet is a kind of cone-shaped tube.

To pursue scientific discovery and technology advance, scientists create continuous innovation by inventing novel structures of valveless piezoelectric pumps with new principles. In this sense, the valveless piezoelectric pumps with cone-shaped tubes have been significantly improved. But in the sense of learning from the structures and principles of the organism itself, the improvement of the valveless piezoelectric pump with cone-shaped tubes is far from significant. A new challenge for scientists is to think about human being itself, as well as to imitate and optimize it.

3 Combined Valveless Piezoelectric Pump with Cone-shaped Tubes

3.1 Parallel structure

In 1995, Olsson, et al optimized the structure of valveless piezoelectric pump with cone-shaped tubes for efficiency increase [40]. They proposed a parallel structure composed of two valveless piezoelectric pumps with cone-shaped tubes fixed in the same plane, where the connection of cone-shaped tubes were modified from solid structure to plane structure. It is a milestone in the piezoelectric pump research. Olsson and Stemme, as pioneers in innovation of pump structure, created the first combined valveless piezoelectric pump with cone-shaped tubes. The novel structure can effectively improve output performance of a pump under the condition that the amplitude of the piezoelectric vibrator reaches its upper limit. The diffuser and nozzle in the flow channel of each single piezoelectric pump were on the same linear axis, and

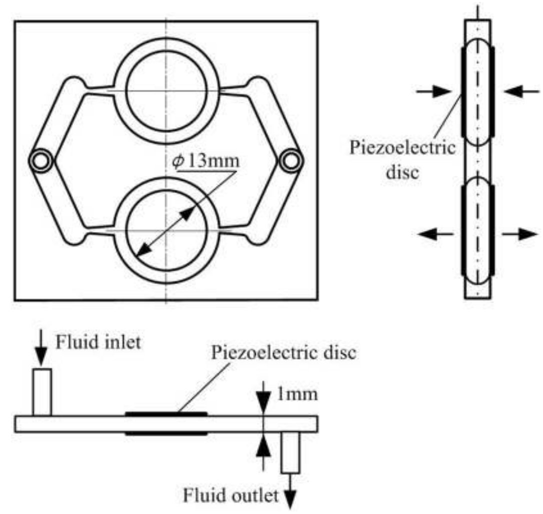

Fig. 26 Design of the new planar two-chamber pump

the axes of the two piezoelectric pumps were parallel with each other. The two piezoelectric pumps in parallel had their common inlet and outlet formed by the two angled flow channels (see Fig. 26).

The combined valveless piezoelectric pump with cone-shaped tubes was fabricated on a brass substrate with thickness of 1 mm. The diameter of single piezoelectric vibrator was 13 mm. The cross-sections of both diffuser and nozzle were square, where the narrowest size was 0.3 mm × 0.3 mm. When the two pump chambers were working in reversed phase, the maximum flow rate was 16 ml/min at the driving frequency of 540 Hz and the maximum pump pressure was 1.7 m. Compared with the performance of the two pump chambers working in a same phase, the pump flow increased by 2 times and the pressure increased by 3 times.

In 1997, Olsson, et al [41], produced a parallel-connected valveless piezoelectric micro-pump with cone-shaped tubes by using the latest technique of deep reactive ion etching (DRIE). The maximum pump pressure was 7.6 mH_2O (74 kPa) and the maximum pump flow was 2.3 mL/min. The specific parameters are shown in Table 2 (see Fig. 27 and Fig. 28).

In 1997, Tay, et al produced a parallel-connected valveless piezoelectric micro-pump with cone-shaped tubes. They used the technique of deep active ion etching to fabricate the pump channel, diffuser and nozzle in the same depth of 0.3 mm, as well as the technique of anode sputtering and technique of silicon processing. The differential pressure can reach 105 mm of water column (see Fig. 29)[42]. This micropump is proposed to integrate into micro cooling circuits for electronic components.

In 2002, Schabmueller, et al[22], from Britain developed a parallel-like valveless piezoelectric micro-pump

Table 2 Pump dimensions and measured pump performance [41]

Pump	Neck width $W1$ / µm	Diffuser length L / µm	$L/W1$	Divergence angle α / (°)	Diaphragm amplitude d_1 / µm Methanol	Max. flow Q_1 / (µL·min^{-1})	Max. pressure H_1 / mH$_2$O	Diaphragm amplitude d_2 / µm Water	Max. flow Q_2 / (µL·min^{-1})	Max. pressure H_2 / mH$_2$O
1a	20	273	13.7	9.8	0.27	314	2.76	–	–	–
2a	40	547	13.7	9.8	0.55	628	2.70	–	–	–
2b	40	720	18.0	9.8	0.34	781	3.92	–	–	–
2e	40	1000	25.0	9.8	0.40	1156	3.81	–	–	–
3a	80	1093	13.7	9.8	0.66	1537	5.57	0.64	1946	5.44
3b	80	1440	18.0	9.8	0.69	2900	5.58	0.39	1285	2.44
3c	80	1093	13.7	7.0	0.68	2693	6.17	0.72	2270	7.57
3d	80	1093	13.7	13	0.63	3427	6.00	0.58	2218	4.71

"–" Not measured

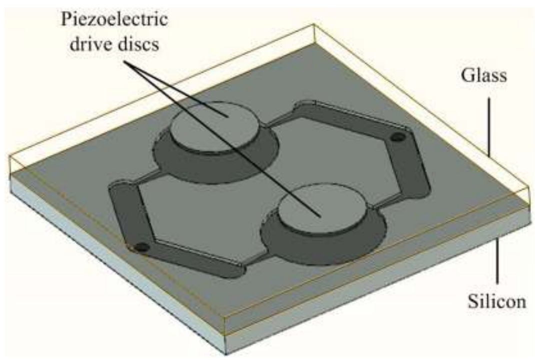

Fig. 27 Perspective view of the flat-walled diffuser pump

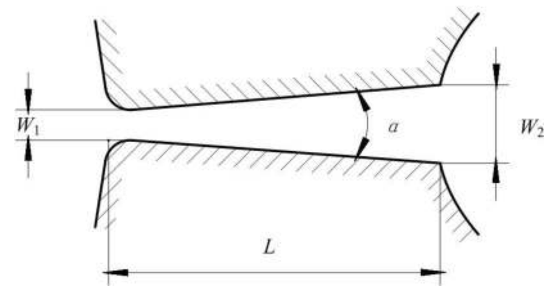

Fig. 28 Schematic top-view of a flat-wall diffuser geometry

with cone-shaped tubes, which shared the same pump chamber (see Fig. 30).

In 2004, Kim, et al developed a parallel-connected valveless piezoelectric micro-pump with cone-shaped tubes by using a low price raw material - polydimethylsiloxane[43]. This pump had its maximum flow rate of 32.9 µL/min or a differential pressure of 173 Pa at the driving frequency of 300 Hz and the driving voltage of 150 V, as shown in Fig. 31.

In 2008, Shen, et al[44], developed a parallel-connected valveless piezoelectric micro-pump with cone-shaped tubes (see Fig. 32).

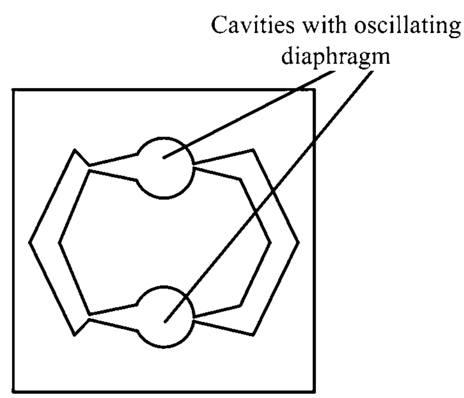

Fig. 29 Top view of the diffuser pump

3.2 Series structure

In 2008, Yang, et al[45], developed a series-connected valveless piezoelectric micro-pump with cone-shaped tubes by using the lithography and molding and bonding process. This pump works like a peristaltic pump. There were four micro- cone-shaped tubes in the same direction linked with totally three pump chambers. Each pump chamber was covered with a piezoelectric vibrator. The tapered flow tubes and pump chambers shared a same symmetrical plane, indicating that the pump is in a series structure. The fluid flows through the pump from the first inlet to the last outlet. This micro-pump could obtain a flow rate from 0.4 mm/s to 0.48 mm/s, and it obtained the maximum flow rate of 365µl/min approximately at the driving voltage of 24 V and the driving frequency of 50 Hz (see Fig. 33).

During 2009–2012, Xia and Zhang invented and investigated the valveless piezoelectric pump with an unsymmetrical slope chamber bottom. Fig. 34 and Fig. 35 show the pump structure and the structure of the

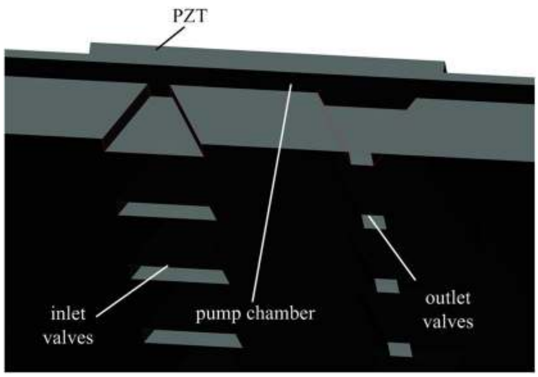

Fig. 30 Cross-section of the assembled micropump

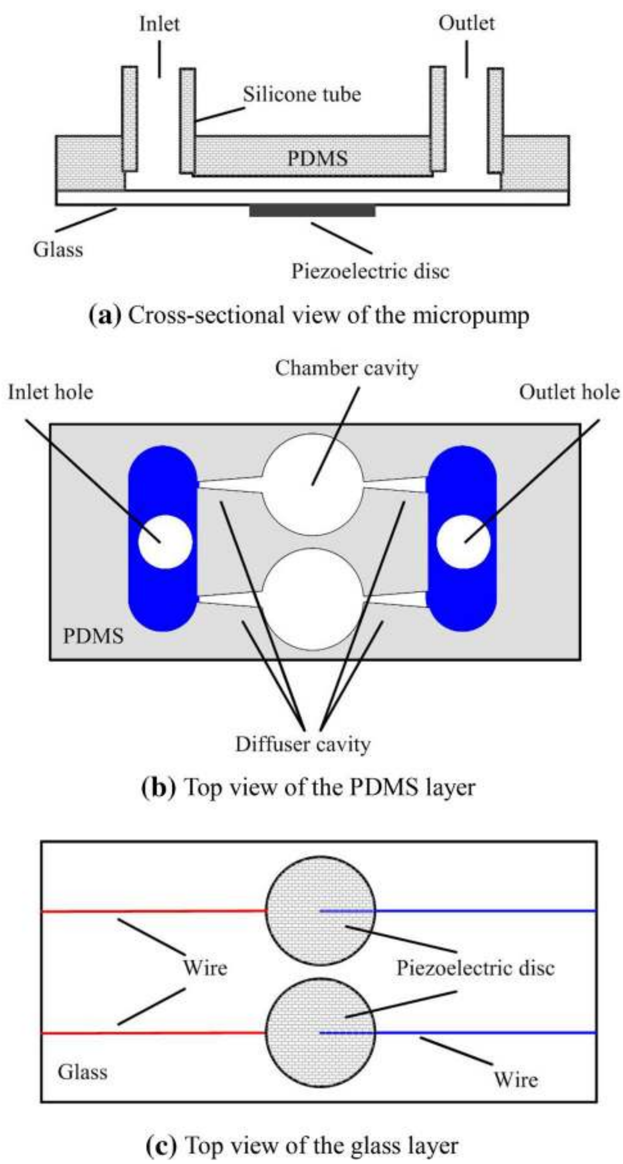

Fig. 31 Structure of the proposed micropump

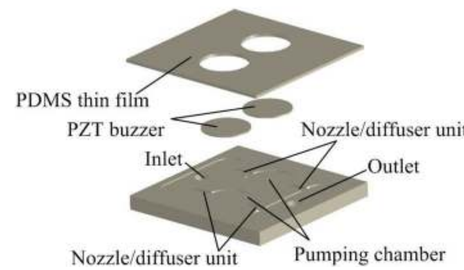

Fig. 32 3D overview of the double chamber valveless micropump

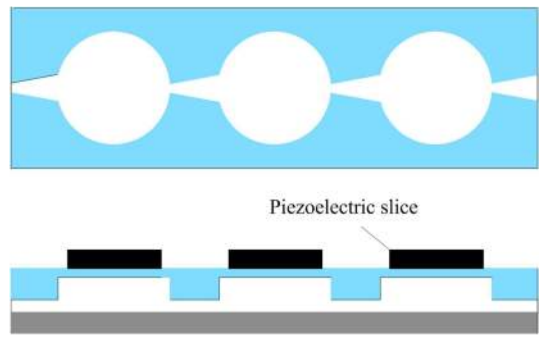

Fig. 33 Schematic diagram of the portable valve-less peristaltic micropump

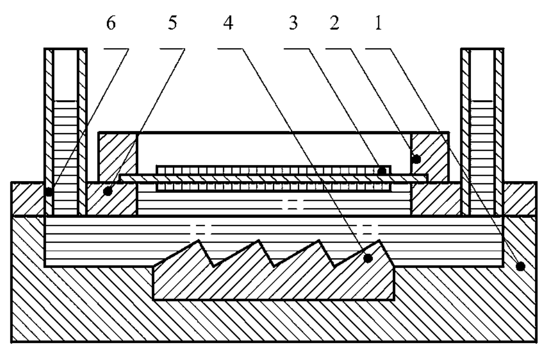

Fig. 34 Piezoelectric pump with the unsymmetrical slopes element. 1. Lucite conduit (vertical conduit); 2. Cover; 3. Upper fixing plate; 4. Unsymmetrical slopes element; 5. Piezoelectric vibrator; 6. Pump body

unsymmetrical slope chamber bottom[46–50]. The unsymmetrical slope chamber bottom is composed of a series of slopes with different inclination angles, which forms a square cone with the continuous unsymmetrical structure. From this point of view, the unsymmetrical slope chamber can be seen as an integrated structure built by repeated elements linking in series. Furthermore, the unsymmetrical slope chamber can also be considered as an integrated structure with elements linking in parallel when divided it in the direction perpendicular to the flow

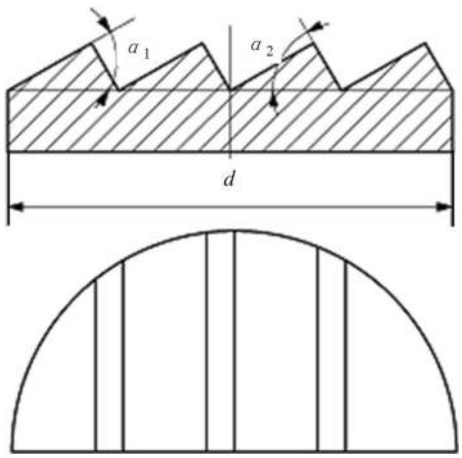

Fig. 35 Unsymmetrical slopes element

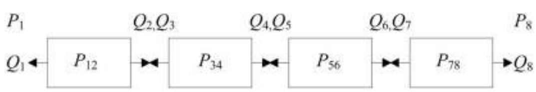

Fig. 36 Series connection of four valve-less pumps assembly

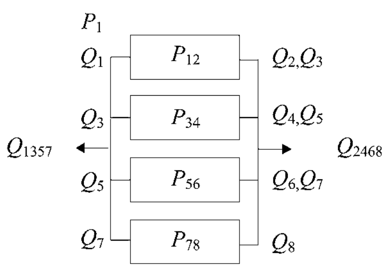

Fig. 37 Parallel connection of four valve-less pumps assembly

direction. The application of the micropump is to mix the chemical reagents in the microfluidic device.

In 2015, Ullmann, et al[51] systematically discussed the valveless piezoelectric pumps with cone-shaped tubes in a series structure and in a parallel structure from the aspects of fluid mechanics and circuit theory, and got a series of related conclusions (see Fig. 36 and Fig. 37).

3.3 Brief summary

The combined valveless piezoelectric pump with cone-shaped tubes was invented soon after the invention of single valveless piezoelectric pump with cone-shaped tubes. So, we would like to thank Olsson and Stemme et al. for their great contribution to the valveless piezoelectric pump with cone-shaped tubes, who let once again demonstrated the logic of technological progress. Since the efficiency of fluid transfer for a single valveless piezoelectric pump with cone-shaped tubes was low, the idea of making a combined valveless piezoelectric pump with cone-shaped tubes naturally came into being.

The macroscopic fluid converge refers to the fluid flow of the system during a complete cycle. At the micro level, fluid converge is the process of the diffuser and the nozzles transforming between each other during suction stage and discharge stage in a single cycle. The conversion of the diffuser and the nozzles results in the shunting and impact of the fluid at the above-mentioned concentration junction, which will cause the trend of the shunting and the impact of the fluid within the pump chamber.

This is the case of the parallel structure and synchronous phase as driving signal only. It is also necessary to discuss the case of the parallel structure and asynchronous phase as driving signal. Here, valveless piezoelectric pump with a phase difference of 180° and small cone angle (about 10°) is taken as an example. In the case of the parallel structure and asynchronous phase as driving signal, the inner and outer circulations of the flow path are generated. The inner circulation means that two independent piezoelectric pumps are driven asynchronously, and therefore, one pump is in the suction period (the pump volume becomes larger) and the other is in the discharge period (the pump volume becomes smaller). The flow between the two pumps is called inner circulation. The outer circulation means that the flow between each pump and the flow path of the external system.

Under the aforementioned complex condition, it is difficult to determine which differential pressure (flow rate) is better, the one generated by synchronous phase or the one by asynchronous phase, are better. Nevertheless, the following factors need to be discussed in detail: driving force output by piezoelectric vibrator, driving frequency which forms vibration and frequentness of inner and outer circulation, boundary condition of cone angle, boundary condition of pipe tee of confluence and diffluence, boundary condition of pump chamber, etc. In further research, researchers are trying their best to clarify the impact of these factors.

It is worthwhile to mention that the pumps shown in Fig. 30 are synchronously driven in a parallel structure[22]. They share a same pump chamber and a same driving source. The analysis of this pump is different from other valveless piezoelectric pumps with cone-shaped tubes of synchronous phase mentioned above. In this paper, the authors think its structure over and hypothesize that this pump may have the problems of vibration, shock, and inner and outer circulation, thus can be a preferred and suggested option for micro- mixer and agitator.

Up to now, few papers solely about series-connected valveless piezoelectric pump with cone-shaped tubes have been found in our retrieve data, and their research is also superficial. Series structure is a type of array to connect one

Fig. 38 Valves of the distal greater saphenous vein

pump's pump chamber and piezoelectric vibrator with another one's by connecting their cone-shaped tubes in turns. A separate unit of series-connected structure, including a group of flow tubes, piezoelectric vibrator and pump chamber, still exhibits phenomenon of vibration, and the flow in the lower level of separate unit vibrates and shocks more severely than that in the upper level. At the same time, turbulence and eddy in the lower separate unit are also severer than that in the upper level. Here, this phenomenon is defined as amplification and carrying in the series-connected valveless piezoelectric pump with cone-shaped tubes.

Amplification and carrying phenomena may bring a relevant increase of energy into the unit of the lower level. Therefore, it is necessary to consider the energy offering when designing the series-connected valveless piezoelectric pump with cone-shaped tubes. In the pump, the piezoelectric vibrators should not be designed in a series connection of exactly same vibrators, but of the vibrators with input driving energy increasing by levels. At the same time, carrying phenomenon brings the related increase of turbulence and eddy energy to the lower level of unit cone-shaped tube. So it is required to design cone-shaped tubes with Reynolds number increasing level by level, not just the simple series of the same cone-shaped tubes.

The above content is just a review of the technique history. The research of cone-shaped tubes of combined pumps can be retrieved to the papers of studying fire sprinklers connected in series at the beginning of last century. Viewed from this angle, cone-shaped tubes of combined pumps were not an innovative structure. If further consideration is given to more ancient and wider dimensions, maybe we can learn from organism itself to develop the applications of the cone-shaped tubes in the combined forms.

In 1540, human being described venous valve for the first time, and in 1603, schematic diagram of venous valve was drew for the first time, as shown in Fig. 38 and Fig. 39 [52, 53], respectively. If considering the venous valve in the type of freeze-frame moments, static venous valve is cone-shaped tubes too. The schematic diagram shown in Fig. 39 reveals the structure of these tapered flow tubes in detail. The schematic diagram shown in Fig. 38 also reveals the structure of cone-shaped tubes in combined forms. However, the static venous valves are surely more complicated than the cone-shaped tubes whether in parallel forms or in series forms.

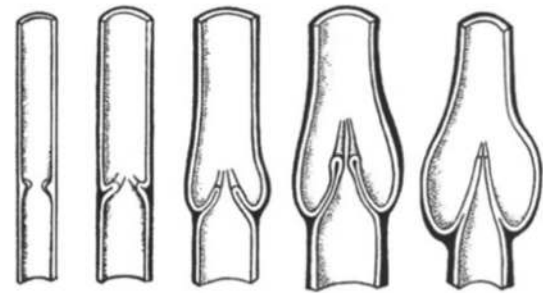

Fig. 39 Stages in the embryologic development of a typical bicuspid venous valve

4 Conclusions and Outlook

(1) The history of valveless piezoelectric pumps with cone-shaped tubes in the past two decades has been reviewed. The valveless piezoelectric pumps with cone-shaped tubes have been classified into the following categories: single valveless piezoelectric pump with cone-shaped tubes (solid structure and plane structure) and combined valveless piezoelectric pump with cone-shaped tubes (parallel structure and series structure).

(2) The functions of various types of cone-shaped tubes and pump structures have been analyzed, and future research directions of valveless piezoelectric pumps with cone-shaped tubes have been summarized and identified.

(3) The historical theory, provided by the literature, highlighted that for a valveless piezoelectric pump with cone-shaped tubes, cone angle determines the flow resistance and the flow resistance determines the flow direction. The theory has been discussed and verified by each valveless piezoelectric pump with cone-shaped tubes presented in this study.

(4) The bionics deduced from the evolution of biological structure may play an important role in the future development of valveless piezoelectric pump with cone-shaped tubes.

References

1. E Stemme, G Stemme. A valveless diffusernozzle-based fluid pump. *Sensors and Actuators A*, 1993, 39(2): 159–167.
2. L Smith. Micromachined nozzles fabricated with a replicative method//*Micromechanics Europe 1990 (MME 90)*, Berlin, Germany, November 26–27, 1990: 53–57.
3. Jian-Hui Zhang, Ying Wang, Jun Fu, et al. Development of piezoelectric pump with valve. *Transactions of Nanjing University of Aeronautics & Astronautics*, 2016, 33(3): 260–273.
4. Chao Lin, Jiu-Xiang Ji, You-Tao Tao. Structural design and control strategy analysis of micro/nano transmission platform. *Transactions of Nanjing University of Aeronautics and Astronautics*, 2014, 31(5): 484–491.
5. Jia-Qi Ren, Xiao-Bo Zhu, Guo-Zhen Chen, et al. Design and experiment of vertical motion dual-stage with piezo-actuated nanopositioning stage. *Transactions of Nanjing University of Aeronautics and Astronautics*, 2015, 32(2): 199–203.
6. Ping-Ting He, Jie Tao, Yan-Yan Zhang, et al. Effect of inhaled nano-TiO2 on lung and serum biochemical indexes of mice. *Transactions of Nanjing University of Aeronautics and Astronautics*, 2010, 27(4): 338–344.
7. Jun Huang, Jian-Hui Zhang, Wei-Dong Shi, et al. 3D FEM analyses on flow field characteristics of the valveless piezoelectric pump. *Chinese Journal of Mechanical Engineering*, 2016, 29(4): 825-831.
8. Yu-Fei Cai, Jian-Hui Zhang, Chun-Ling Zhu, et al. Theoretical calculations and experimental verification for the pumping effect caused by the dynamic micro-tapered angle. *Chinese Journal of Mechanical Engineering*, 2016, 29(3): 615–623.
9. Zhong-Hua Zhang, Jun-Wu Kan, Shu-Yun Wang, et al. Effects of driving mode on the performance of multiple-chamber piezoelectric pumps with multiple actuators. *Chinese Journal of Mechanical Engineering*, 2015, 28(5): 954-963.
10. W J Spencer, W T Corbett, L R Dominguez. An electronically controlled piezoelectric insulin pump and valves. *IEEE Transactions on Sonics and Ultrasonics*, 1978, 25(3): 153–156.
11. T Narasaki. The characteristics of bimorph vibrator pump//*Proceedings of the 13th Intersociety Energy Conversion Engineering Conference*, San Diego, USA, August 20–25, 1978: 2005–2010.
12. F C M V D Pol. *A pump based on micro-engineering techniques*. University of Twente, Enschede, 1989.
13. A Richter, A Plettner, K A Hofmann, et al. A micromachined electrohydrodynamic (EHD) pump. *Sensors & Actuators A: Physical*, 1991, 29(2): 159–168.
14. H T G V Lintel, F C M V D Pol, S Bouwstra. A piezoelectric micropump based on micromachining of silicon. *Sensors & Actuators A: Physical*, 1988, 15(2): 153–167.
15. J G Smits. Piezoelectric micropump with three valves working peristaltically. *Sensors & Actuators A: Physical*, 1990, 21(1): 203–206.
16. S Shoji, S Nakagawa, M Esashi. Micropump and sample-injector for integrated chemical analyzing systems. *Sensors & Actuators A: Physical*, 1990, 21(1):189–192.
17. M M Farooqui, A G R Evans. Microfabrication of submicron nozzles in silicon nitride. *Journal of Microelectromechanical Systems*, 1992, 1(2): 86-88.
18. F C M V D Pol, D G J Wonnink, M Elwenspoek, et al. A thermo-pneumatic actuation principle for a microminiature pump and other micromechanical devices. *Sensors & Actuators A: Physical*, 1989, 17(1–2): 139–143.
19. T Gerlach, H Wurmus. Working principle and performance of the dynamic micropump. *Sensors & Actuators A: Physical*, 1995, 50(1): 35–140.
20. G M Cheng, K Suzuki, S Hirose. A piezoelectric pump with new structure. *The 76th JSME Fall Annual Meeting*, Senndai, Japan, 1998, 5: 247–248.
21. N T Nguyen, X Y Huang. Miniature valveless pumps based on printed circuit board technique. *Sensors & Actuators A: Physical*, 2001, 88(2): 104–111.
22. C G J Schabmueller, M Koch, M E Mokhtari, et al. Self-aligning gas/liquid micropump. *Journal of Micromechanics and Microengineering*, 2002, 12(4): 420.
23. T Zhang, Q M Wang. Performance evaluation of a valveless micropump driven by a ring-type piezoelectric actuator. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 2006, 53(2): 463–473.
24. Y L Cheng, J H Lin. Manufacture of three-dimensional valveless micropump. *Journal of Materials Processing Technology*, 2007, 192: 229–236.
25. P Verma, D Chatterjee. Parametric characterization of piezoelectric valveless micropump. *Microsystem technologies*, 2011, 17(12): 1727–1737.
26. A M Pun, J H Lo, D C Louie, et al. Micro-fabrication of the non-moving part valve micro-pump by hot-embossing technology. *World Congress on Medical Physics and Biomedical Engineering 2006*, Springer Berlin Heidelberg, 2007, 1: 242–245.
27. A Nisar, N Afzulpurkar, B Mahaisavariya, et al. Multifield analysis using multiple code coupling of a MEMS based micropump with biocompatible membrane materials for biomedical applications. *2008 International Conference on BioMedical Engineering and Informatics*, Sanya, China, May 28–30, 2008: 531–535.
28. Q F Cui, C L Liu, X F Zha. Simulation and optimization of a piezoelectric micropump. *International Journal of Advanced Manufacturing Technology*, 2008, 36(5–6): 516–524.
29. X Y Huang, S S Wang, C Yang. Single-nozzle micropumps. *Proceedings of the ASME 2009 7th International Conference on Nanochannels, Microchannels and Minichannels ICNMM 2009*, Pohang, South Korea, June 22–24, 2009: 717–721.
30. S S Wang, X Y Huang, C Yang. Valveless micropump with acoustically featured pumping chamber. *Microfluidics and Nanofluidics*, 2010, 8(4): 549–555.
31. D H Ha, V P Phan, N S Goo, et al. Three-dimensional electro–fluid–structural interaction simulation for pumping performance evaluation of a valveless micropump. *Smart Materials and Structures*, 2009, 18(10): 104015.
32. S Chandika, R Asokan, K C K Vijayakumar. Flow characteristics of the diffuser/nozzle micropump—A state space approach. *Flow Measurement and Instrumentation*, 2012, 28(12): 28–34.
33. L Y Tseng, A S Yang, C Y Lee, et al. Investigation of a piezoelectric valveless micropump with an integrated stainless-steel diffuser/nozzle bulge-piece design. *Smart Materials and Structures*, 2013, 22(8): 085023.
34. C H Cheng, C K Chen. Characteristic studies of the piezoelectrically actuated valveless micropump. *Proceedings of the World Congress on Engineering*, London, U.K., July 3–5, 2013: 3–8.
35. S Singh, N Kumar, D George, et al. Analytical modeling, simulations and experimental studies of a PZT actuated planar

valveless PDMS micropump. *Sensors and Actuators A: Physical*, 2015, 225: 81–94.
36. X H He, J W Zhu, X T Zhang, et al. The analysis of internal transient flow and the performance of valveless piezoelectric micropumps with planar diffuser/nozzles elements. *Microsystem Technologies*, 2017, 23(1): 23–37.
37. Jian-Hui Zhang, Qi-Xiao Xia, Zhen Hong. Flow direction of piezoelectric pump with nozzlw/diffuse-elements. *Chinese Journal of Mechanical Engineering,* 2004, 3(1): 107–109.
38. A Chandrasekaran, M Packirisamy. Improved efficiency of microdiffuser through geometry tuning for valveless micropumps. *Journal of Fluids Engineering*, 2016, 138(3): 031101.
39. T Owerkowicz, C G Farmer, J W Hicks, et al. Contribution of gular pumping to lung ventilation in monitor lizards. *Science*, 1999, 284(5420): 1661–1663.
40. A Olsson, G Stemme, E Stemme. A valve-less planar fluid pump with two pump chambers. *Sensors and Actuators A: Physical*, 1995, 47(1): 549–556.
41. A Olsson, P Enoksson, G Stemme, et al. Micromachined flat-walled valveless diffuser pumps. *Journal of Microelectromechanical Systems*, 1997, 6(2): 161–166.
42. F E H Tay, H Li. Designing a fluid pump for microfluidic cooling systems in electronic components. *Proceedings of the 1997 1st Electronic Packaging Technology Conference*, Hawaii, USA, October 10–10, 1997: 115–118.
43. J H Kim, C J Kang, Y S Kim. A disposable polydimethylsiloxane-based diffuser micropump actuated by piezoelectric-disc. *Microelectronic Engineering*, 2004, 71(2): 119–124.
44. C Y Shen, H K Liu. Fabrication and drive test of piezoelectric PDMS valveless micro pump. *Journal of the Chinese Institute of Engineers*, 2008, 31(4): 615–623.
45. H Yang, T H Tsai. Portable valve-less peristaltic micropump design and fabrication. *Design, Test, Integration and Packaging of MEMS/MOEMS*, French Riviera, France, April 9–11, 2008: 273–278.
46. Qi-Xiao Xia, Jian-Hui Zhang, Hong Li. Valve-less piezoelectric pump with unsymmetrical slope chamber bottom. *Optics and Precision Engineering*, 2006, 14(4): 641–647. (in Chinese)
47. Qi-Xiao Xia, Jian-Hui Zhang, Hong Lei, et al. Theoretical analysis of a novel valve-less piezoelectric pump with cluster of unsymmetrical humps structure. *Optics and Precision Engineering*, 2008, 16(12): 2391–2397. (in Chinese)
48. Qi-Xiao Xia, Jian-Hui Zhang. Theoretical analysis and experimental verification on flow field of piezoelectric pump with unsymmetrical slopes element. *Chinese Journal of Mechanical Engineering*, 2009, 22(5): 735–744.
49. Jian-Hui Zhang, Qi-Xiao Xia, Yi Huang, et al. Theory and experimental verification of valveless piezoelectric pump with rotatable unsymmetrical slopes. *Science China Technological Sciences*, 2011, 54(11): 3070–3077.
50. Qi-Xiao Xia, Jian-Hui Zhang. Analysis on flow field of the valveless piezoelectric pump with two inlets and one outlet and a rotating unsymmetrical slopes element. *Chinese Journal of Mechanical Engineering*, 2012, 25(3): 474–483.
51. A Ullmann, Y Taitel. The piezoelectric valve-less pump: series and parallel connections. *Journal of Fluids Engineering*, 2015, 137(2): 021104.
52. A Caggiati, C Allegra. *Chapter 1- Historical Introduction. In: The Vein Book*. Burlington: Academic Press, 2007.
53. J Weber, R May. *Funktionelle phlebologie*. Stuttgart: Thieme, 1990.

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