applied sciences

MDPI

Review

Advances in Valveless Piezoelectric Pumps

Qiufeng Yan [1], Yongkang Yin [2], Wanting Sun [3] and Jun Fu [4,*]

1 School of Electrical Engineering, Nantong University, Nantong 226019, China; yanqf@nuaa.edu.cn
2 Shanghai Institute of Satellite Engineering, China Aerospace Science and Technology Corporation, Shanghai 201109, China; yinyongkang@nuaa.edu.cn
3 School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, China; w1sun@polyu.edu.uk
4 Jiangxi Hongdu Aviation Industry Group, Nanchang 330024, China
* Correspondence: 32920132200838@stu.xmu.edu.cn

Abstract: Piezoelectric pump design is regarded as a hot research topic in the microfluidic field, and has been applied in liquid cooling, precision machinery and other relevant domains. The valveless piezoelectric pump becomes an important branch of the piezoelectric pump, because it successfully avoids the problem of "pump-lagging of valve" during the valve piezoelectric pump processing. This paper summarizes the development of valveless piezoelectric pumps, and introduces some different configurations of valveless piezoelectric pumps. The structure and material of all kinds of valveless piezoelectric pumps are elaborated in detail, and also the output performance of the pump is evaluated and analyzed with the variations in flow rate and output pressure as reference. By comparing the flow of different types of valveless piezoelectric pumps, the application of valveless piezoelectric pumps is also illustrated. The development tendency of the valveless piezoelectric pump is prospected from the perspective of structure design and machining methods, which is expected to provide novel ideas and guidance for future research.

Keywords: valveless piezoelectric pump; flow rate; tubes

Citation: Yan, Q.; Yin, Y.; Sun, W.; Fu, J. Advances in Valveless Piezoelectric Pumps. *Appl. Sci.* **2021**, *11*, 7061. https://doi.org/10.3390/app11157061

Academic Editor: Richard Yong Qing Fu

Received: 30 June 2021
Accepted: 28 July 2021
Published: 30 July 2021

1. Introduction

Since Narasaki [1] designed the first piezoelectric pump in 1987, this started the research and expanded the application field of pumps. The converse piezoelectric effects are utilized to drive the fluid in the piezoelectric pump. With the advantages of such a simple structure [2], low power consumption [3], and no electromagnetic interference [4], the piezoelectric pump has been widely used in the fields of medical drug delivery [5–7], fuel cells [8–10], microfluidics [11–13], liquid cooling [14–16] and precision machinery [17–19] etc. According to the structural characteristics, the piezoelectric pump can be divided into two different types, i.e., valve piezoelectric pump and valveless piezoelectric pump. The valve piezoelectric pumps have the weakness of "pump-lagging of valve" due to the removable valve body. When the frequency rises to a certain value, the piezoelectric pump will be dynamically balanced and the flow rate will be rapidly dropped to zero in a macro level [20]. In addition, the valve piezoelectric pump also has the disadvantages of large pressure loss, low transmission accuracy, and non-easy miniaturization, which seriously restricts its further promotion and application.

In 1993, Stemme et al. [21] proposed the concept of a valveless piezoelectric pump with a conical flow tube for the first time, and it brings about the research boom of the piezoelectric pump into the valveless era. It should be noted that one-way flow of fluid can be achieved in the valveless piezoelectric pump to achieve using the positive and reverse flow resistance difference to perform the function of the valve. Meanwhile, the valveless piezoelectric pump can effectively solve the problems existing in the valve piezoelectric pump, which is of great concern for researchers. In the past 30 years, some researchers have designed various types of valveless piezoelectric pump. However, up to now, there is no unified classification of valveless piezoelectric pump, which is not conducive for development in the fierce market competition.

Figure 1 shows the classifications of valveless piezoelectric pumps. According to different structural characteristics, it can be divided into external flow pipe type, built-in structure type as well as a bionic valveless type. The external tube type of the valveless piezoelectric pump realizes the one-way flow of fluid by using a piezoelectric vibrator and special pipe; for instance, the nozzle/diffuser tubes [22], Y-shape tubes [23], spiral tubes [24] and special flow tubes [25], etc. Built-in structural valveless piezoelectric pump is the flow resistance structure placed inside the pump chamber, common examples include unsymmetrical slope elements [26], hemisphere-segments [27], and conical spiral cavities [28], etc. On the basis of the biological reality of the special structure, the bionic valveless piezoelectric pump is designed to achieve a one-way flow of fluid. Common structures include fishtail Bimorph [29], and built-in compliant structures [30], etc.

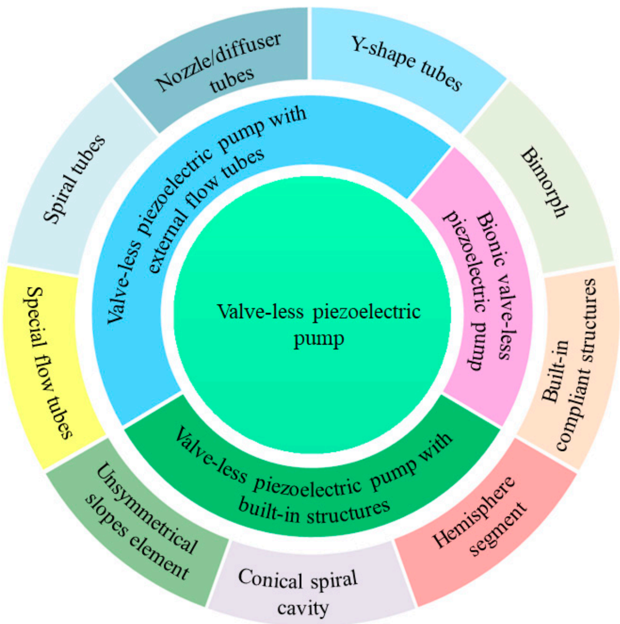

Figure 1. Classification of valveless piezoelectric pumps.

There are already many review articles summarizing the piezoelectric pump [31–33]. However, there is no research review on valveless piezoelectric pumps, in order to allow people to better grasp the development of valveless piezoelectric pumps. In this paper, based on the application of valveless piezoelectric pumps in various fields, this paper reviews the research progress. According to the description of different types of valveless piezoelectric pumps reported in the literature, the development history is introduced as follows. The influences of material properties and structure on pump performance are introduced, and the valveless piezoelectric pump is systematically summarized. Based on current research status, the future development is analyzed. The future development direction of valveless piezoelectric pump technology is predicted, and the foundation is laid for further promotion.

2. Configuration of the Valveless Piezoelectric Pump

2.1. Valveless Piezoelectric Pump with External Flow Tubes

The external flow tube type of the valveless piezoelectric pump realizes the flow resistance difference through the positive and reverse shape of the flow tube structure, and then realizes the one-way fluid pumping. With the development of modern micro-machining technology, a variety of nozzle type valveless piezoelectric pumps have emerged. Typical external flow tubes are nozzle/diffuser tubes [22], Y-shape tubes [23], spiral tubes [24], and special flow tubes [25].

2.1.1. Valveless Piezoelectric Pump with Diffuser/Nozzle Tubes

In 1993, Stemme et al. [21] proposed the first valveless piezoelectric pump using piezoelectric oscillators and conical flow tubes, which is shown in Figure 2. On this basis, Gerlach et al. [34] developed a valveless piezoelectric pump with micro-conical flow tubes based on silicon using MEMS technology. Olsson et al. [35] optimized the structure of valveless piezoelectric pumps with cone-shaped tubes for efficiency increase. 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 structures to plane structures. Nguyen et al. [36] designed and manufactured a valveless piezoelectric pump with a conical flow tube based on a printed circuit board. At the driving frequency of 100 Hz, the maximum pump flow is 3 mL/min. Chandika et al. [37] used the state space approach to predict the dynamic characteristics of the pump. The performance of the pump can be predicted by this method, which is helpful to the design of the piezoelectric pump. In order to reduce the size of the piezoelectric pump, Tseng et al. [38] used MEMS, lithography and etching processes to manufacture a valveless piezoelectric pump with a micro-conical flow tube suitable for the medical field. The pump has a maximum differential pressure of 2.9 kPa and a maximum flow rate of 0.4 mL/min. Singh et al. [39] proposed a valveless piezoelectric pump with a micro-conical flow tube of a 10 degrees cone angle, which can achieve a low flow rate. Aggarwal et al. [40] made a miniature valveless piezoelectric pump using silicon etching technology. When the driving voltage is 80 V and the driving frequency is 2.5 kHz, the output flow rate is 225.35 mL/min. Guan et al. [17] proposed a new combined driving method based on piezoelectric effect and liquid crystal reflux effect, and the maximum flow rate could reach 0.0049 mL/min.

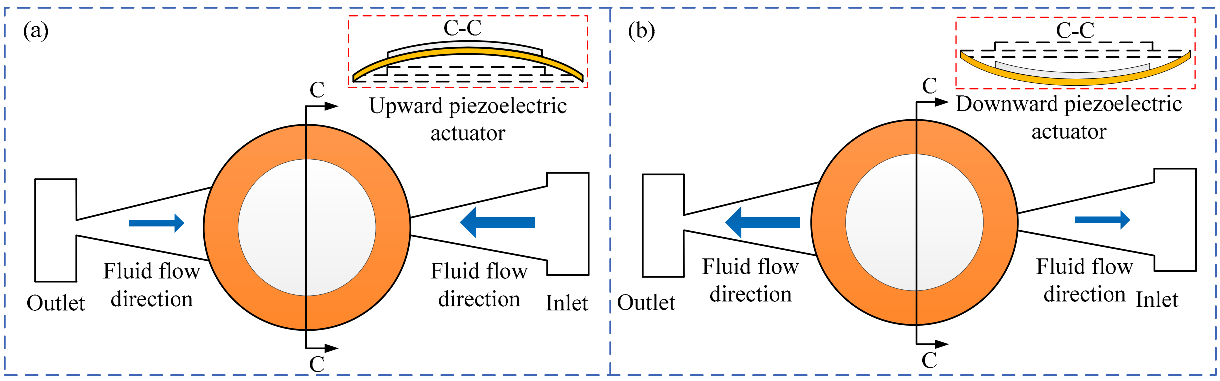

Figure 2. The working processes of valveless piezoelectric pumps with diffuser/nozzle tubes. (**a**) Suction process. (**b**) Discharge process.

In order to improve the output performance of conical flow, many scholars have studied the series and parallel pump cavities. Kim et al. [41] developed a valveless piezoelectric pump with parallel micro-tapered flow tubes using polydimethylsiloxane. Yang et al. [42] also found a valveless piezoelectric pump with a micro-conical flow tube based on series assembly using lithography, molding and bonding processes. Ullmann et al. [43] discussed the serial and parallel problems of valveless piezoelectric pumps with conical flow tubes from the aspects of hydrodynamics and circuit theory, systematically. In addition, other researchers including Azarbadegan et al. [44], Lee et al. [45], and Yang et al. [46] investigated the series and parallel connection problems of valveless piezoelectric pump cavities. Table 1 gives the summary of properties for the valveless piezoelectric pump with a diffuser/nozzle.

Table 1. Summary of properties for the valveless piezoelectric pump with external flow tubes.

First Author and Year	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
1997 [35] Olsson	Diffuser/nozzle	Si-wafer	200	3000–4000	74	2.3
2001 [36] Nguyen	Diffuser/nozzle	PCB	100	100	7	3
2013 [38] Tseng	Diffuser/nozzle	PMMA	160	400	2.9	0.4
2017 [40] Aggarwal	Diffuser/nozzle	Si-wafer	80	2520	N/A	0.2254
2019 [17] Guan	Diffuser/nozzle	PDMS	70	100	N/A	0.0049
2016 [46] Yang	Coanda effect	PMMA	300	10	3.18	0.408

2.1.2. Valveless Piezoelectric Pump with Y-Shape Tubes

Table 2 shows the summary of properties for the valveless piezoelectric pump with Y-shaped tubes. The details are as follows: Jang et al. [47] presented a design of a non-valve piezoelectric pump with a supervisor and two tubes. The pump cavity is located in the main channel close to the intersection of the three channels, and this study found that there were two complex flow phenomena inside the pump cavity. By comparison, Zhang et al. [48] further proposed a valveless piezoelectric pump with Y-shape tubes; the working principle of valveless piezoelectric pumps with Y-shape tubes is shown in Figure 3. This pump can reduce the vortex in the traditional conical flow tube, and it can be used for the transportation of living cells or long-chain polymer cells In order to further optimize the structure of the valveless piezoelectric pump with Y-shape tubes and promote its application, Huang et al. revealed that the valveless piezoelectric pump with Y-shaped flow tube, and also some other different types of valveless piezoelectric pumps, were proposed, such as multistage Y-shape treelike bifurcate tubes [49], and asymmetric channels [50]. In addition, He et al. proposed a V-shaped valveless piezoelectric pump based on the Y-shaped flow tube [51].

Table 2. Summary of properties for the valveless piezoelectric pump with Y-shape tubes.

First Author and Year	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
2013 [49] Huang	multistage Y-shape	N/A	100	9/10.3	0.55	35.6
2020 [50] Huang	asymmetrical channels	N/A	200	33/31	0.38	3.6

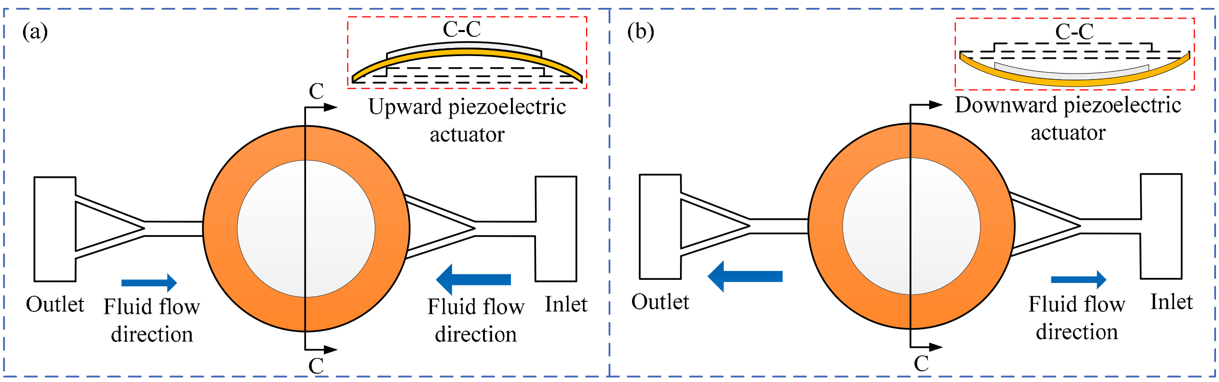

Figure 3. The working processes of valveless piezoelectric pumps with Y-shape tubes. (**a**) Suction process. (**b**) Discharge process.

2.1.3. Valveless Piezoelectric Pump with Spiral Tubes

It was found that in the northern hemisphere, the Coriolis force generated by the rotation of the Earth has an inhibiting effect on the fluid moving clockwise and a promoting effect on the fluid moving counterclockwise [52]. Dean et al. [53] obtained the existence of secondary flow channels in the curved pipe through theoretical derivation, which could enhance the mass transfer function of the fluid. Figure 4 shows the working principle of valveless piezoelectric pumps with spiral tubes. With the help of Coriolis force on the fluid in the curved pipe, Zhang et al. [24] proposed the helical tubular valveless piezoelectric pump. Through experiments, it was found that the solenoid valveless piezoelectric pump was sensitive to the angular velocity and its location, and could be used in navigation devices. However, it is difficult to process the spiral tube, which limits the further promotion of the pump. In the future, spiral tubes can be replaced by simple similar tubes, such as arc-shaped tubes.

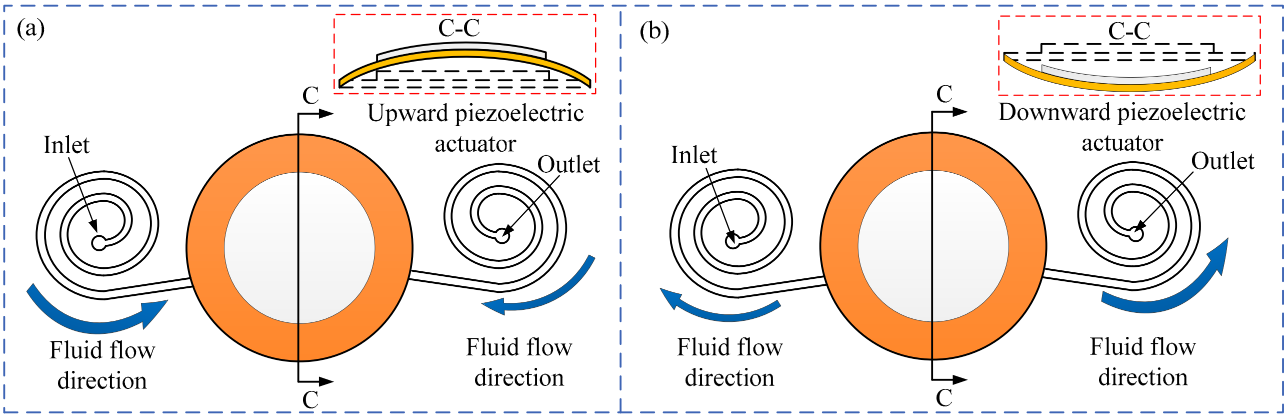

Figure 4. The working processes of valveless piezoelectric pumps with spiral tubes. (**a**) Suction process. (**b**) Discharge process.

2.1.4. Valveless Piezoelectric Pump with Special Flow Tubes

In addition to the conventional valveless piezoelectric pump with external flow tubes, scholars have also designed some valveless piezoelectric pumps with special flow tubes. Forster et al. [54] optimized the "Tesla" valve structure, made a special-shaped pipeline valveless piezoelectric pump on this basis, and studied its internal dynamic loss and pumping performance. Izzo et al. [55] developed a valveless piezoelectric pump with an anisotropic flow tube and analyzed its structure theory, providing theoretical support for the design of an anisotropic flow tube valveless piezoelectric pump. Based on the research of valveless piezoelectric pumps with diffuser/nozzle tubes, Guan et al. [56] explored a kind of valveless piezoelectric pump with the saw-tooth flow tube, with the maximum output pressure and flow rate reaching 21.3 kPa and 0.01142 mL/min, respectively. Ehrlich et al. [57] arranged the "V" and "X" shaped bulges processed by 3D printing inside the traditional conical flow pipe, and a novel type of flow blocking valveless piezoelectric pump together with the closed pump cavity was formed. He et al. [58] designed a new type of valveless piezoelectric pump by using a Canada effect, and the Canada effect can be enhanced with a streamline structure to improve the pump flow rate. When the voltage and the frequency reached 300 V and 50 Hz respectively, the optimal output pressure and flow rate of the pump were obtained, i.e., 1.75 kPa and 4.84 mL/min respectively. Table 3 shows the summary of properties for the valveless piezoelectric pump with special flow tubes.

Table 3. Summary of properties for the valveless piezoelectric pump with special flow tubes.

Figure	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
1995 [54] Forster	Tesla	N/A	150	114	N/A	0.038
2007 [55] Izzo	Tesla	N/A	100	2250/3000	1.73	0.64
2008 [56] Guan	Saw-tooth	PMMA	30	7500/8000	21.3	0.01142
2014 [57] Ehrlich	Microdiffuser elements	N/A	170	30	0.658	0.56
2019 [58] He	Canada effect	N/A	300	50	1.75	4.84

In summary, the valveless piezoelectric pump with external flow tubes is mainly designed to realize the one-way flow of liquid, which is not limited by the driving structure, and is widely used in the field of cooling systems [59], biomedicine [60], and energy applications [61]. However, due to the influence of external flow tubes, the piezoelectric pump is difficult to further miniaturize. Moreover, the flow rate of this piezoelectric pump is usually low, which cannot be used in high flow occasions.

2.2. Valveless Piezoelectric Pump with Built-in Structures

Figure 5 shows the working principle of valveless piezoelectric pumps with built-in structures. The working principle is as follows: because $\alpha 1$ is not equal to $\alpha 2$, fluid flows into or out of the chamber from the left and right conduits of the pump is different. Therefore, net flow will be generated.

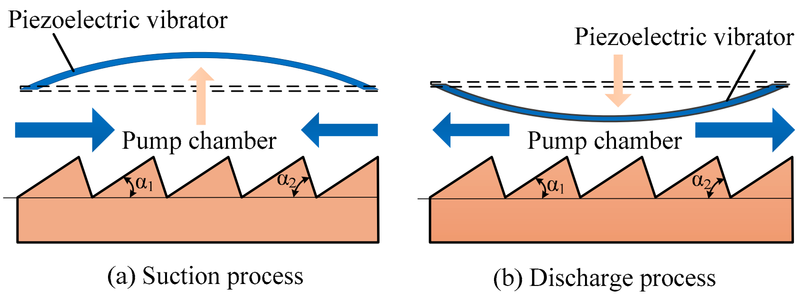

Figure 5. Working principle of a valveless piezoelectric pump with built-in structures.

In 2011, Zhang et al. [62] proposed a valveless piezoelectric pump with rotatable unsymmetrical slopes, which can realize the fusion of different fluids. This structure can control the proportion of different fluids flowing into the pump chamber by rotating the rotatable unsymmetrical slopes. Ji et al. [27] proposed a valveless piezoelectric pump with hemisphere-segment bluff-body by the principle of bluff body flow, and the flowrate of 16.4 mL/min was obtained under the voltage and frequency of 110 V and 6 Hz. He et al. [63] designed a valveless piezoelectric pump with rotatable unsymmetrical slopes by the principle of Carmen Vortex Street, which could achieve the flowrate of 220.6 mL/min and pressure of 670 Pa. In order to improve the flow rate of the pump, Zhao et al. [64] optimized the structure of hemisphere-segment bluff-body; he fabricated a valveless piezoelectric pump with a crescent-shaped structure by 3D printing, and the maximum flow rate of 286 mL/min was achieved when the voltage was 220 V at 82 Hz. Table 4 shows the summary of properties for the valveless piezoelectric pump with built-in structures.

Table 4. Summary of properties for the valveless piezoelectric pump with built-in structures.

First Author and Year	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
2011 [62] Zhang	Unsymmetrical slopes	N/A	220	50	N/A	32.32
2014 [27] Ji	Hemisphere-segment	PMMA	110/160	6	0.262	30
2019 [63] He	Dome composite structures	N/A	190	130/45	0.67	220.6
2019 [64] Zhao	Crescent-shaped structure	N/A	220	82	N/A	286

In summary, the flow resistance difference structure of the valveless piezoelectric pump with built-in structures is located in the pump chamber, and the regular flow tubes are used in the inlet and outlet, which improves the utilization of the pump chamber. This piezoelectric pump has higher integration, and it is not affected by the complex flow channel, which is easier to use in practice. Compared with the valveless piezoelectric pump with external flow tubes, the pump flow rate of this piezoelectric pump is significantly improved.

2.3. Bionic Valveless Piezoelectric Pump

Inspired by the swimming of fish, Pires et al. [29,65] employed the bending vibration of piezoelectric bimorph to simulate the swing of a fish, and then the unidirectional flow of liquid was promoted to realize the function of a pump. However, Pires et al. only imitated the structure of a fish tail, and did not conduct in-depth research on this structure. On this basis, Hu et al. [66] proposed a valveless piezoelectric pump imitating caudal-fin, where the flow rate is as much as 560% of that of experiment results carried out by Pires et al., and its working principle is shown in Figure 6. Huang et al. [67] studied the solid–liquid coupling vibration characteristics of piezoelectric bimorphs in piezoelectric underwater acoustic devices. Dong et al. [4] studied piezoelectric materials, and he designed a piezoelectric pump based on macro fiber composite, which could achieve the flow rate of 28.7 mL/min under the frequency of 15 Hz. In 2019, Bao et al. [30] proposed a piezoelectric pump with built-in compliant structures. This pump can achieve the integration of "valve-based" and "valveless" in one body. These research results provide a new idea for the research of valveless piezoelectric pumps. Table 5 shows the summary of properties for the bionic valveless piezoelectric pump.

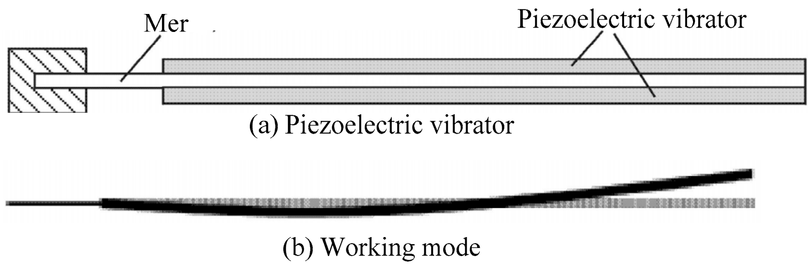

Figure 6. Working principle of a valveless piezoelectric pump imitating a caudal-fin.

Table 5. Summary of properties for the bionic valveless piezoelectric pump.

First Author and Year	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
2009 [29] Pires	Bimorph	N/A	60	320	0.12	103
2020 [4] Dong	MFC	PMMA	N/A	15	N/A	28.7
2019 [30] Bao	Compliant structure	UV epoxy	210	80	1.99	3.6

In summary, a bionic valveless piezoelectric pump mainly realizes one-way flow of fluid by imitating part of the structure of a biological body. Bionic valveless piezoelectric pumps have the advantages of simple structure, easy miniaturization, low cost, and can also solve the backflow problem of valveless piezoelectric pumps. Moreover, the pump flow of this kind of pump is usually relatively large.

2.4. Other Valveless Piezoelectric Pump

Besides, the following types of valveless piezoelectric pumps are worthy of attention. For example, Afrasiab et al. [68] designed a new valveless piezoelectric pump through a combination of the characteristics of traveling wave and barrier type valveless pumps, and the corresponding flow rate was increased by a factor of 700%. Ma et al. [69] designed a new separable valveless piezoelectric pump, and the flow rate of 9.1 mL/min was achieved under the frequency of 70 Hz. Munas et al. [70] designed a valveless piezoelectric pump with 十-shape tubes, which can be used for drug delivery and micro medical devices. Huang et al. [71] proposed a valveless piezoelectric pump with vortex diodes, and the maximum flow rate of 9.86 mL/min and pressure of 340 Pa were obtained at the voltage and frequency of 200 V and 49 Hz. Table 6 shows the summary of properties for other valveless piezoelectric pumps.

Table 6. Summary of properties for other valveless piezoelectric pumps.

First Author and Year	Type of Valveless	Structure Material	U_p ($V_{p\text{-}p}$)	f_p (Hz)	P_{max} (kPa)	Q_{max} (mL/min)
2016 [69] Ma	Diffuser/nozzle	PMMA	N/A	70	N/A	9.1
2018 [70] Munas	+-shape	PMMA	N/A	100	0.24	31.15
2019 [71] Huang	Vortex diodes	PA	200	49	0.34	9.86

3. Comparison of Various Valveless Piezoelectric Pumps

In the past 30 years, the valveless piezoelectric pump has developed rapidly. In particular, the valveless piezoelectric pump with an external flow tube of great concern to many scholars. In regard to the structure features, both the valveless piezoelectric pump with external flow tube and valveless piezoelectric pump with built-in structures can realize the unidirectional flow of liquid through the volume change of the pump chamber and the flow resistance structure. The output performance of the valveless piezoelectric pump can be controlled and regulated by optimizing the flow tube structure. In the development process of valveless piezoelectric pumps, many types of valveless piezoelectric pumps with external flow tubes have appeared, such as, valveless piezoelectric pumps with diffuser/nozzle tubes, valveless piezoelectric pumps with Y-shape tubes, valveless piezoelectric pumps with spiral tubes, and valveless piezoelectric pumps with special flow tubes. As shown in Figures 7 and 8, the flow rate of valveless piezoelectric pumps with external flow tubes usually exhibit a relative value, i.e., 35 mL/min, and sometimes can be realized at a μL/min level.

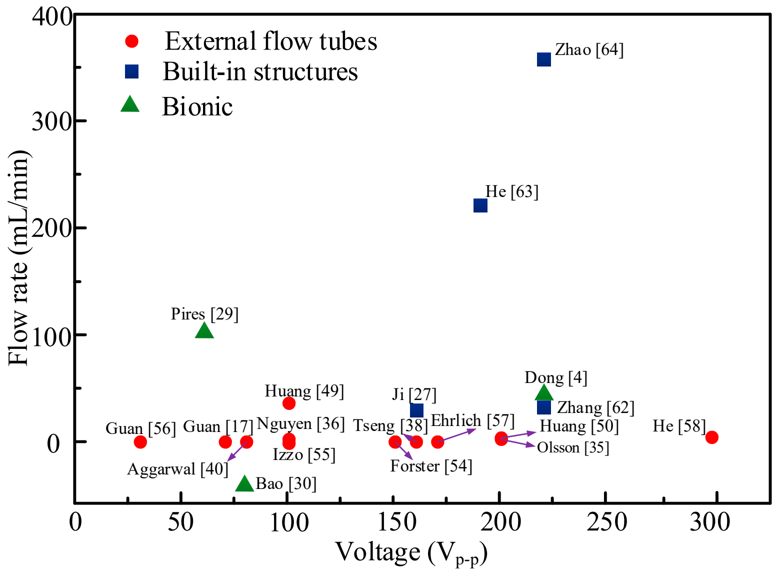

Figure 7. Maximum flow rates for valveless piezoelectric pump: flow rates versus voltages.

The flow resistance structure of valveless piezoelectric pumps with built-in structures is installed in the pump chamber, which can reduce the overall size of the valveless piezoelectric pump. The internal structure of the pump chamber was built to improve the output behavior of these pumps. It consists of valveless piezoelectric pumps with hemisphere-segment bluff-bodies, and valveless piezoelectric pumps with a crescent-shaped structure. As compared with the valveless piezoelectric pump with an external flow tube, the pump flow of a valveless piezoelectric pump with built-in structures is dramatically enhanced, and the maximum pump flow reaches 286 mL/min.

In addition, the bionic valveless piezoelectric pump is also considered to be one of the main research hotspots. The valveless piezoelectric pump imitating caudal-fin and semi-flexible valve piezoelectric pumps are the two most common bionic valveless piezoelectric pumps. The valveless piezoelectric pump imitating a caudal-fin is used to simulate a fish swimming, and make the fish static to obtain the one-way flow of liquid from front to back. The semi-flexible valve piezoelectric pump is a new breakthrough in the field of piezoelectric pumps. We can adjust the driving voltage to realize the integration of "valve-based" and "valveless" in one body.

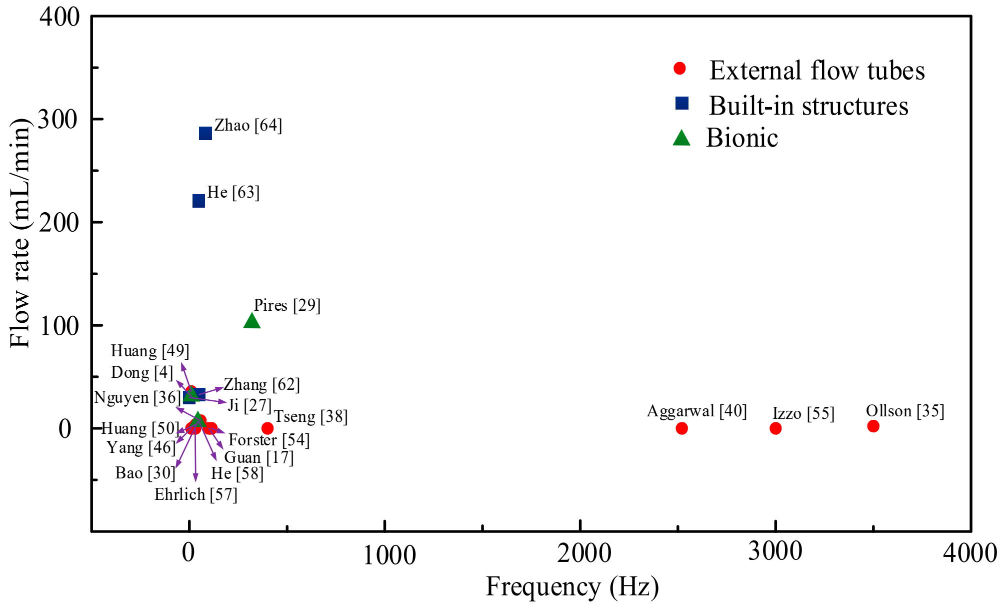

Figure 8. Maximum flow rates for valveless piezoelectric pump: flow rates versus frequencies.

4. Future Perspectives for the Valveless Piezoelectric Pump

Valveless piezoelectric pumps are used more and more widely, especially in the biomedical field. This demands that piezoelectric pump materials have biocompatibility. In the future, valveless piezoelectric pumps can be used for artificial heart and living cell delivery. However, most of the valveless piezoelectric pumps have sharp protrusions in their interior, which would have a great impact on living sells. Therefore, the optimized design of structure is important. Further, it can also be helpful to boost the performance of piezoelectric pumps.

Three-dimensional printing will be an important processing method for valveless piezoelectric pumps. The flow channel can be integrated into the pump body by using 3D printing technology, which can avoid liquid leakage. By 3D printing, the accuracy of piezoelectric pumps can further improve.

In the future, the performance of the pump can be improved by combining different flow tubes or flow resistance structures. For example, the diffuser/nozzle tube and arc-shaped tube are combined to form the variable cross section arc-shaped tube, and the diffuser/nozzle tube and the Y-shape tube are combined to form the variable cross section Y-shape tube.

Flow rate is the most important performance index of piezoelectric pumps. In order to further popularize the valveless piezoelectric pump, it is required that the piezoelectric pump has a stable flow rate. Driving voltage and driving frequency are the key factors affecting pump flow. We should provide a stable power supply to drive the piezoelectric pump. Simultaneously, the flow channel is another important factor affecting the pump flow. We should choose ultra-precision machining methods to process the flow channel. Moreover, the valveless piezoelectric pump realizes liquid flow by volume change, and cannot avoid flow fluctuation. Especially in the low-frequency valveless piezoelectric pumps, the flow fluctuation is more obvious. We can reduce this volatility by adding buffer mechanisms.

5. Conclusions

Since the valveless piezoelectric pump was firstly introduced by Stemme et al., the development of the valveless piezoelectric pump has become extraordinary rapid. According to the current research status, the valveless piezoelectric pumps are divided into three different groups, including valveless piezoelectric pump with external flow tubes, valveless piezoelectric pump with built-in structures, as well as the bionic valveless piezoelectric pump. The development course of each type of valveless piezoelectric pumps is also reviewed and summarized. Besides, the flow rate and output pressure acting as comparison parameters, the output characteristics of each valveless piezoelectric pump is analyzed. The flow rate of the valveless piezoelectric pump with external flow tubes is relatively low, usually under a value of 35mL/min, and sometimes it can even achieve the flow rate of μL/min, which is suitable for the usage in the micro flow field. The valveless piezoelectric pump with built-in structures, and the bionic valveless piezoelectric pump, exhibit a relative high flow rate, which is suitable for the application in large flow rate fields. The development prospects of valveless piezoelectric pumps is prospected from the structure design and manufacturing method. The main trend of the design of valveless piezoelectric pumps is the optimization design of structure and the combination of flow resistance structure. It is expected that the 3D printing technology would become the main processing technique for the flexible fabrication of valveless piezoelectric pumps in the future.

Author Contributions: Q.Y. and J.F. proposed and conceived of the study; Q.Y. wrote this manuscript; W.S. and Y.Y. modified this manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Nantong University.

Institutional Review Board Statement: This study did not involve humans or animals.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available in references.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Narasaki, T. Layered type bimorph vibrator pump. In Proceedings of the 13th Intersociety Energy Conversion Engineering Conference, San Diego, CA, USA, 20–25 August 1978.
2. Wu, X.; He, L.; Hou, Y.; Tian, X.; Zhao, X. Advances in passive check valve piezoelectric pumps. *Sens. Actuators A Phys.* **2021**, *323*, 112647. [CrossRef]
3. Chen, S.; Qian, C.; Cheng, W.; Kan, J.; Ji, J.; Zhang, Z.; Wang, J. A low frequency driven piezoelectric pump with flexible valve. *Sens. Actuators A Phys.* **2021**, *319*, 112567. [CrossRef]
4. Dong, J.; Liu, C.; Chen, Q.; Xu, Z.; Chen, W.; Wu, Y.; Yang, Z. Design and experimental research of piezoelectric pump based on macro fiber composite. *Sens. Actuators A Phys.* **2020**, *312*, 112123. [CrossRef]
5. Tandon, V.; Kang, W.S.; Robbins, T.A.; Spencer, A.J.; Kim, E.S.; McKenna, M.J.; Kujawa, S.G.; Fiering, J.; Pararas, E.E.L.; Mescher, M.J.; et al. Microfabricated reciprocating micropump for intracochlear drug delivery with integrated drug/fluid storage and electronically controlled dosing. *Lab Chip* **2015**, *16*, 829–846. [CrossRef]
6. Kaçar, A.; Özer, M.B.; Tascıoğlu, Y. A novel artificial pancreas: Energy efficient valve-less piezoelectric actuated closed-loop insulin pump for T1DM. *Appl. Sci.* **2020**, *10*, 5294. [CrossRef]
7. Wu, M.-H.; Huang, S.-B.; Lee, G.-B. Microfluidic cell culture systems for drug research. *Lab Chip* **2010**, *10*, 939–956. [CrossRef] [PubMed]
8. Wang, X.Y.; Ma, Y.T.; Yan, G.Y.; Huang, D.; Feng, Z.H. High flow-rate piezoelectric micropump with two fixed ends polydimethylsiloxane valves and compressible spaces. *Sens. Actuators A Phys.* **2014**, *218*, 94–104. [CrossRef]
9. Park, J.-H.; Seo, M.-Y.; Ham, Y.-B.; Yun, S.-N.; Kim, D.-I. A study on high-output piezoelectric micropumps for application in DMFC. *J. Electroceramics* **2012**, *30*, 102–107. [CrossRef]
10. Yang, X.; Zhou, Z.; Cho, H.; Luo, X. Study on a PZT-actuated diaphragm pump for air supply for micro fuel cells. *Sens. Actuators A Phys.* **2006**, *130-131*, 531–536. [CrossRef]

11. Ma, T.; Sun, S.; Li, B.; Chu, J. Piezoelectric peristaltic micropump integrated on a microfluidic chip. *Sens. Actuators A Phys.* **2019**, *292*, 90–96. [CrossRef]
12. Tanaka, Y. A Peristaltic Pump Integrated on a 100% Glass Microchip Using Computer Controlled Piezoelectric Actuators. *Micromachines* **2014**, *5*, 289–299. [CrossRef]
13. Wang, X.; Jiang, H.; Chen, Y.; Qiao, X.; Dong, L. Microblower-based microfluidic pump. *Sens. Actuators A Phys.* **2017**, *253*, 27–34. [CrossRef]
14. Tang, Y.; Jia, M.Z.; Ding, X.R.; Li, Z.T.; Wan, Z.P.; Lin, Q.H.; Fu, T. Experimental investigation on thermal management performance of an integrated heat sink with a piezoelectric micropump. *Appl. Ther. Eng.* **2019**, *161*, 114053. [CrossRef]
15. Ma, H.K.; Hou, B.R.; Lin, C.Y.; Gao, J.J. The improved performance of one-side actuating diaphragm micropump for a liquid cooling system. *Int. Commun. Heat Mass Transf.* **2008**, *35*, 957–966. [CrossRef]
16. Ma, H.-K.; Chen, B.-R.; Gao, J.-J.; Lin, C.-Y. Development of an OAPCP-micropump liquid cooling system in a laptop. *Int. Commun. Heat Mass Transf.* **2009**, *36*, 225–232. [CrossRef]
17. Guan, Y. Performance Analysis of a Microfluidic Pump Based on Combined Actuation of the Piezoelectric Effect and Liquid Crystal Backflow Effect. *Micromachines* **2019**, *10*, 584. [CrossRef]
18. Chen, S.; Xie, X.; Kan, J.; Ji, J.; Zhang, Z.; Li, J. A hydraulic-driven piezoelectric pump with separable channel for drug delivery. *Sens. Actuators A Phys.* **2019**, *295*, 210–216. [CrossRef]
19. Zhang, W.; E Eitel, R. An integrated multilayer ceramic piezoelectric micropump for microfluidic systems. *J. Intell. Mater. Syst. Struct.* **2013**, *24*, 1637–1646. [CrossRef]
20. Zhang, J.H.; Wang, D.K.; Wang, S.Y.; Akyoshi, Q. Research on piezoelectric pump-lagging of valve. *Chin. J. Mech. Eng.* **2003**, *39*, 107–110. (In Chinese) [CrossRef]
21. Stemme, E.; Stemme, G. A valueless diffuser/nozzle based fluid pump. *Sens. Actuators A Phys.* **1993**, *39*, 159–167. [CrossRef]
22. Zhang, J.H.; Xia, Q.X.; Hong, Z.; Onuki, A. Flow direction of piezoelectric pump with nozzle/diffuser-elements. *Chin. J. Mech. Eng.* **2004**, *17*, 107–109. [CrossRef]
23. Zhang, J.H.; Li, Y.L.; Liu, J.Y.; Xia, Q.X. Simulation and experiment of valve-less piezoelectric pump with Y-shape tubes. *Opt. Precis. Eng.* **2008**, *16*, 669–675.
24. Zhang, J.H.; Leng, X.F.; Zhao, C.S. A spiral-tube-type valve-less piezoelectric pump with gyroscopic effect. *Chin. Sci. Bull.* **2014**, *59*, 1885–1889. [CrossRef]
25. Morris, C.; Forster, F. Low-order modeling of resonance for fixed-valve micropumps based on first principles. *J. Microelectromechanical Syst.* **2003**, *12*, 325–334. [CrossRef]
26. Xia, Q.X.; Zhang, J.H.; Li, H. Valve-less piezoelectric pump with unsymmetrical slope chamber bottom. *Opt. Precis. Eng.* **2006**, *14*, 641–647. (In Chinese)
27. Ji, J.; Zhang, J.; Xia, Q.; Wang, S.; Huang, J.; Zhao, C. Theoretical analysis and experimental verification on valve-less piezoelectric pump with hemisphere-segment bluff-body. *Chin. J. Mech. Eng.* **2014**, *27*, 595–605. [CrossRef]
28. Cai, J.; Huang, J.; Hu, F.J.; Zhang, J.H. Research on valve-less piezoelectric pump with parallel connection conical spiral cavity. *J. Vib. Meas. Diagn.* **2013**, *33*, 29–32, 215.
29. Pires, R.F.; Vatanabe, S.L.; de Oliveira, A.R.; Nakasone, P.H.; Silva, E.C.N. Water cooling system using a piezoelectrically actuated flow pump for a medical headlight system. In Proceedings of the International Society for Optics and Photonics, San Diego, CA, USA, 19–20 March 2007; Volume 6527.
30. Bao, Q.; Zhang, J.; Tang, M.; Huang, Z.; Lai, L.; Huang, J.; Wu, C. A Novel PZT Pump with Built-in Compliant Structures. *Sensors* **2019**, *19*, 1301. [CrossRef]
31. Dereshgi, H.A.; Dal, H.; Yildiz, M.Z. Piezoelectric micropumps: State of the art review. *Microsyst. Technol.* **2021**, 1–29.
32. Zhang, J.-H.; Wang, Y.; Huang, J. Advances in Valveless Piezoelectric Pump with Cone-shaped Tubes. *Chin. J. Mech. Eng.* **2017**, *30*, 766–781. [CrossRef]
33. Yalikun, Y.; Tanaka, Y. Large-Scale Integration of All-Glass Valves on a Microfluidic Device. *Micromachines* **2016**, *7*, 83. [CrossRef]
34. Gerlach, T.; Wurmus, H. Working principle and performance of the dynamic micropump. *Sens. Actuators A Phys.* **2002**, *50*, 35–140.
35. Olsson, A.; Enoksson, P.; Stemme, G.; Stemme, E. Micromachined flat-walled valve-less diffuser pumps. *J. Microelectromechanical Syst.* **1997**, *6*, 161–166. [CrossRef]
36. Nguyen, N.T.; Huang, X. Miniature valve-less pumps based on printed circuit board technique. *Sens. Actuators A Phys.* **2001**, *88*, 104–111. [CrossRef]
37. Chandika, S.; Asokan, R.; Vijayakumar, K.C.K. Flow characteristics of the diffuser/nozzle micropump-A state space approach. *Flow Meas. Instrum.* **2012**, *28*, 28–34. [CrossRef]
38. Tseng, L.Y.; Yang, A.S.; Lee, C.Y.; Cheng, C.H. Investigation of a piezoelectric valve-less micropump with an integrated stainlesssteel diffuser/nozzle bulge-piece design. *Smart Mater. Struct.* **2013**, *22*, 085023. [CrossRef]
39. Singh, S.; Kumar, N.; George, D.; Sem, A.K. Analytical modeling, simulations and experimental studies of a PZT actuated planar valve-less PDMS micropump. *Sens. Actuators A Phys.* **2015**, *225*, 81–94. [CrossRef]
40. Aggarwal, S.; Paul, B.E.; DasGupta, A.; Chatterjee, D. Experimental characterization of piezoelectrically actuated micromachined silicon valve-less micropump. *Microfluid. Nanofluidics* **2017**, *21*, 2. [CrossRef]
41. Kim, J.H.; Kang, C.J.; Kim, Y.S. A disposable polydimethylsiloxane-based diffuser micropump actuated by piezoelectric-disc. *Microelectron. Eng.* **2004**, *71*, 119–124. [CrossRef]

42. Yang, H.; Tsai, T.H.; Hu, C.C. Portable Valve-less Peristaltic Micropump Design and Fabrication. *arXiv* **2008**, arXiv:0805.0883.
43. Ullmann, A.; Taitel, Y. The Piezoelectric Valve-Less Pump: Series and Parallel Connections. *J. Fluids Eng.* **2014**, *137*, 021104. [CrossRef]
44. Azarbadegan, A.; Cortes-Quiroz, C.; Eames, I.; Zangeneh, M. Analysis of double-chamber parallel valve-less micropumps. *Microfluid. Nanofluidics* **2010**, *9*, 171–180. [CrossRef]
45. Lee, S.C.; Hur, S.; Kang, D.; Kim, B.H.; Lee, S.J. The performance of bioinspired valve-less piezoelectric micropump with respect to viscosity change. *Bioinspiration Biomim.* **2016**, *11*, 036006. [CrossRef] [PubMed]
46. Yang, S.; He, X.H.; Yuan, S.Q.; Zhang, X.T.; Zhu, J.W.; Yan, J. A bidirectional valve-less piezoelectric micropump with double chambers based on Coanda effect. *J. Braz. Soc. Mech. Sci. Eng.* **2016**, *2*, 1–9.
47. Jang, L.S.; Chao, S.H.; Holl, M.R.; Meldrum, D.R. Microfluidic circulatory flows induced by resonant vibration of diaphragms. *Sens. Actuators A Phys.* **2005**, *122*, 141–148. [CrossRef]
48. Zhang, J.H.; Li, Y.L.; Xia, Q.X. Analysis of the pump volume flow rate and tube property of the piezoelectric valve-less pump with Y-shape tubes. *Chin. J. Mech. Eng.* **2007**, *43*, 136–141. [CrossRef]
49. Huang, J.; Zhang, J.H.; Xun, X.C.; Wang, S.Y. Theory and experimental verification on valve-less piezoelectric pump with multistage Y-shape treelike bifurcate tubes. *Chin. J. Mech. Eng.* **2013**, *26*, 462–468. [CrossRef]
50. Huang, J.; Zou, L.; Li, Z.J.; Wang, X.; Zhang, Q.; Wang, Y. Development and performance comparison of valve-less piezoelectric pumps with asymmetrical channels. *Sens. Actuators A Phys.* **2020**, *314*, 112241. [CrossRef]
51. He, X.H.; Zhang, R.; Yang, S.; Deng, X.L. Property of flow resistance for Piezoelectric pump with V-shape tube. *Trans. Chin. Soc. Agric. Mach.* **2009**, *40*, 242–246.
52. Anders, P. How do we understand the Coriolis force? *Bull. Am. Meteorol. Soc.* **1998**, *79*, 1373–1385.
53. Dean, W. XVI.Note on the motion of fluid in a curved pipe. *Lond. Edinb. Dublin Philos. Mag. J. Sci.* **1927**, *4*, 208–223. [CrossRef]
54. Forster, F.K.; Bardell, R.L.; Afromowitz, M.A.; Sharma, N.R.; Blanchard, A. Design, fabrication and testing of fixed-valve micro-pumps. *ASME Publ. FED* **1995**, *234*, 39–44.
55. Izzo, I.; Accoto, D.; Menciassi, A.; Schmitt, L.; Dario, P. Modeling and experimental validation of a piezoelectric micropump with novel no-moving-part valves. *Sens. Actuators A Phys.* **2007**, *133*, 128–140. [CrossRef]
56. Guan, Y.F.; Zhang, G.X.; Jin, J. Efficiency analysis and simulation studies of a piezoelectric micropump with novel microvalve. In Proceedings of the 2008 3rd IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Sanya, China, 6–9 January 2008; pp. 323–328.
57. Ehrlich, L.; Punch, J.; Jeffers, N.; Stafford, J. Experimental characterization of novel microdiffuser elements. *J. Phys. Conf. Ser.* **2014**, *525*, 012008. [CrossRef]
58. He, X.H.; Bian, R.Q.; Lin, N.; Xu, W.; Deng, Z.D.; Yang, S. A novel valve-less piezoelectric micropump with a bluff-body based on Coanda effect. *Microsyst. Technol.* **2019**, *25*, 2637–2647. [CrossRef]
59. Huang, J.; Zhang, J.; Wang, S.; Liu, W. Analysis of the flow rate characteristics of valveless piezoelectric pump with fractal-like Y-shape branching tubes. *Chin. J. Mech. Eng.* **2014**, *27*, 628–634. [CrossRef]
60. Eladi, P.B.; Chatterjee, D.; Dasgupta, A. Design and Development of a Piezoelectrically Actuated Micropump for Drug Delivery Application. In *Micro and Smart Devices and Systems*; Springer: New Delhi, India, 2014.
61. Dau, V.T.; Dinh, T.X. Numerical study and experimental validation of a valveless piezoelectric air blower for fluidic applications. *Sens. Actuators A Phys.* **2015**, *B221*, 1077–1083. [CrossRef]
62. Zhang, J.H.; Xia, Q.X.; Huang, Y.; Leng, X.F.; Huang, J.; Zhao, C.S. Theory and experimental verification of valve-less piezoelectric pump with rotatable unsymmetrical slopes. *Sci. China Technol. Sci.* **2011**, *54*, 3070–3077. [CrossRef]
63. He, L.P.; Zhao, D.; Li, W.; Xu, Q.W.; Cheng, G.M. Performance analysis of valve-less piezoelectric pump with dome composite structures. *Rev. Sci. Instrum.* **2019**, *90*, 6. [CrossRef] [PubMed]
64. Zhao, D.; He, L.-P.; Li, W.; Huang, Y.; Cheng, G.-M. Experimental analysis of a valve-less piezoelectric micropump with crescent-shaped structure. *J. Micromech. Microeng.* **2019**, *29*, 105004. [CrossRef]
65. de Lima, C.R.; Vatanabe, S.L.; Choi, A.; Nakasone, P.H.; Pires, R.F.; Silva, E.C.N. A biomimetic piezoelectric pump: Computational and experimental characterization. *Sens. Actuators A Phys.* **2009**, *152*, 110–118. [CrossRef]
66. Hu, X.Q.; Zhang, J.H.; Huang, Y.; Xia, Q.X.; Huang, W.Q.; Zhao, C.S. Principle and Experimental Verification of Caudal-fin-type Piezo-stack Pump with Variable-cross-section Oscillating Vibrator. *Chin. J. Mech. Eng.* **2012**, *25*, 128–136. [CrossRef]
67. Huang, Y.-H.; Hsu, H.-T. Solid–liquid coupled vibration characteristics of piezoelectric hydroacoustic devices. *Sens. Actuators A Phys.* **2016**, *238*, 177–195. [CrossRef]
68. Afrasiab, H.; Movahhedy, M.R.; Assempour, A. Proposal of a new design for valve-less micropumps. *Sci. Iran.* **2011**, *18*, 1261–1266. [CrossRef]
69. Ma, H.K.; Chen, R.H.; Yu, N.S.; Hsu, Y.H. A miniature circular pump with a piezoelectric bimorph and a disposable chamber for biomedical applications. *Sens. Actuators A Phys.* **2016**, *251*, 108–118. [CrossRef]
70. Munas, F.R.; Melroy, G.; Abeynayake, C.B.; Chathuranga, H.L.; Amarasinghe, R.; Kumarage, P.; Dau, V.T.; Dao, D.V. Development of PZT actuated valve-less micropump. *Sensors* **2018**, *18*, 1302. [CrossRef]
71. Huang, J.; Zou, L.; Tian, P.; Wang, Y.; Zhang, Q. Development of a valve-less piezoelectric pump with vortex diodes. *J. Micromech. Microeng.* **2019**, *29*, 125006. [CrossRef]