IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received February 21, 2019, accepted March 4, 2019, date of publication March 7, 2019, date of current version April 2, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2903680

Design and Experimental Verification on Characteristics of Valve-Less Piezoelectric Pump Effected by Valve Hole Spacing

JIAJIAN JI, SONG CHEN, XINYI XIE, XIAOMING WANG, JUNWU KAN, ZHONGHUA ZHANG, AND JIANPING LI
Institute of Precision Machinery and Smart Structure, Zhejiang Normal University, Jinhua 321004, China

Corresponding author: Song Chen (chensong@zjnu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 51805489, and in part by the National Innovation and Entrepreneurship Foundation of China under Grant 201810345032.

ABSTRACT Valve-less piezoelectric pumps possess the advantages of simple structure and absence of electromagnetic interference, which has accordingly drawn widespread attention. In this paper, in order to improve the performance of valve-less piezoelectric pumps, various kinds of the prototypes had been designed and fabricated to discover the relationship between the performance and the structural parameters of valve hole spacing. The prototype is comprised of a piezoelectric actuator and a pump chamber through a conical tube that connects the pump chamber with the buffer chamber. First, the flow characteristics of the valve-less pump were performed by using COMSOL Multiphysics. According to the simulation result, the decline of flow velocity around the valve holes on the side far from the center of the pump chamber may be the reasons for the performance degradation. Second, the effect of valve hole spacing on the prototype was investigated with respect to several parameters, such as the chamber height and cone angle. The experimental results indicated that the valve-less piezoelectric pump output flowrate can be improved by reducing spacing valve hole spacing. A maximum flowrate of 8.43mL/min was achieved at valve hole spacing of 3 mm, which is 13.6% and 47.1% higher than that at 15 mm and 25 mm, respectively. We finally verify the feasibility of improving the capacity of valve-less piezoelectric pumps by reducing valve hole spacing.

INDEX TERMS Valve hole spacing, valve-less piezoelectric pump, output flowrate.

I. INTRODUCTION

Valve-less piezoelectric pumps provide excellent stability and accuracy because of his simple structure, low energy dissipation and absence of electromagnetic interference, which has a wide application prospect in micro-jet, fuel delivery and biomedical application, etc. References [1]–[4] For valve-less piezoelectric pump, it is composed of PZT diaphragm and flow jet part. Between the two main components, there are many factors in output performance including channel shapes [4]–[7], chamber configuration [8], [9], structure parameters [10]–[12] and flow channel distribution [13]–[15], etc. Those above are intertwined with the flow rectify ability directly or indirectly. In order to improve the output performance of valve-less piezoelectric pumps, relevant researchers have made lots of innovations and optimization in many aspects including the above factors.

After the very first valve-less pump with nozzle/diffuser element in 1993 by Stemme and Stemme [16]. Hwang and Ji [17] studied the influence of nozzle/diffuser angle and slenderness on valve-less PZT pumps. The experimental results discovered that the best driving frequency is at 200 Hz with slenderness from 20 to 25 and nozzle/diffuser angle from 10° to 20°. By changing flow channel distribution at the inlet and outlet, Munas *et al.* [18] carried out the extension of conical tube valve-less piezoelectric pump. What the proposed design different from conventional nozzle/diffuser type is part of flow rectifier, a cross-junction structure formed by micro channels intersecting, including two inlet channels, one outlet channel and a nozzle jet. Test showed that the maximum flowrate of the novel structure pump is 31.15 mL/min at a frequency of 100 Hz.

The associate editor coordinating the review of this manuscript and approving it for publication was Yingxiang Liu.

Researchers not only focus on further parameter optimization in the proposed fluid rectification element, but also pay more attention to novel types of components with high rectification capacity. Zhang *et al.* [8] furtherly proposed multistage Y-shape treelike bifurcate tubes on basis of Y-shape pipe, and created equivalent circuit model to evaluate its functional performance. Finally, they found that the maximum flow rate of the valve-less piezoelectric pump is 1.16 mL/min with a driving voltage of 100 V and frequency of 6 Hz. Leng *et al.* [6] presented a spiral flow tube-type valve-less piezoelectric pump, and the proposed pump is sensitive to the element position caused by Coriolis force. The experimental results showed the pressure differential is 29mmH2O.

Chamber configuration is quite vital factor in micro fluid system, while the multiple chambers can not only realize promotion of energy efficiency, but also generate more steady flow. Olsson *et al.* [19] presented a planar fluid pump which consists of two pump chambers. During their work, pump performance in two different mode (anti-phase and in-phase) were verified. And the results revealed that pump capacity in anti-phase were more than twice as high as those of the in-phase oscillation mode, which of about 16 ml/min flowrate and of a maximum pressure of about 1.7mH2O at driving frequency of 540Hz. Guo *et al.* [20] proposed a novel valve-less piezoelectric micropump of parallel double chambers. They optimized nozzle/diffuser pipes' parameters, and test showed performance of the double chambers pump is 1.3 times that of the single chamber pump.

All the above approaches reported have achieved certain effect in improving the output performance of valve-less piezoelectric pump, and this kind of work is still under way. We found that people focus more on complex channel shapes and chamber configuration to enhance pump performance, but interestingly, the very simple way, the valve hole distribution in the pump chamber seemed to be overlooked. As a critical part of fluid network, the valve hole distribution affects the flow field distribution in pump chamber directly, which has further effects on output performance of valve-less pump. Therefore, it is significant to investigate effect of valve hole distribution on output flow to improve performance of valve-less piezoelectric pump. In present work, three kinds of valve-less piezoelectric pumps with different valve hole spacing are designed and fabricated. Through simulation model and experimental verification, the relationship between valve hole spacing and output flowrate on valve-less piezoelectric pump is obtained, providing reference for structural design of valve-less piezoelectric pump.

II. STRUCTURE AND WORKING PRINCIPLEI

Fig.1 has shown structure of valve-less piezoelectric pump. It is composed of piezoelectric actuator, sealing ring, pump body, cover plate, buffer chamber and conical tubes. The buffer chamber is used for connecting conical tube with inlet and outlet. The piezoelectric actuator is driven by alternating voltage to oscillate reciprocally, causing the volume of the pump chamber changed periodically. Due to the flow resistance difference of the conical tube, the unidirectional flow of the fluid is realized macroscopically.

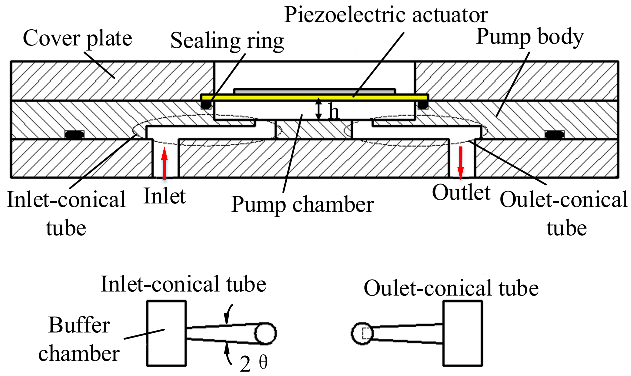


FIGURE 1. Structure of valve-less piezoelectric pump.

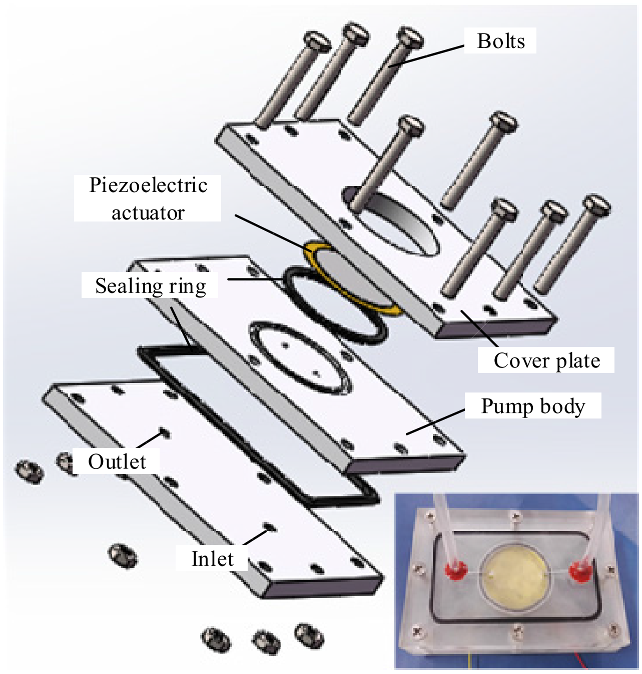


FIGURE 2. Diagram of experimental prototype.

The experimental prototypes were fabricated as shown in Fig.2. The valve-less piezoelectric pump is divided into three layers, these two conical tubes are in the back of the middle layer. The bolts and O seal rings are used to connect and seal, respectively.

Fig.3 has shown diagram of valve hole distribution. Two conical tubes are connected to pump chamber through two valve holes, which are symmetrical and equal diameter. To simplify the problem and facilitate theoretical analysis, a is adopt to represent the valve hole spacing. Three different a of valve hole spacing are set up, which were 3 mm, 15 mm and 25 mm, respectively.

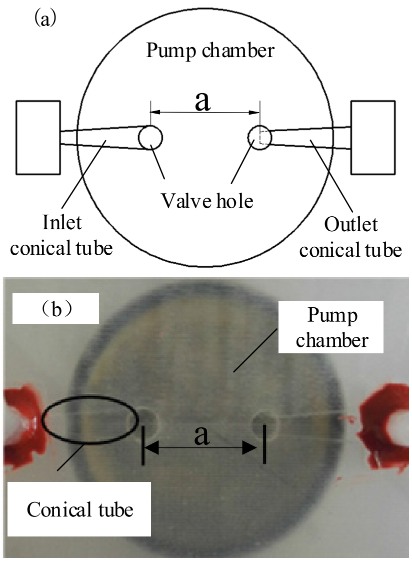


FIGURE 3. Diagram of valve hole distribution. (a) Schematic diagram of valve hole distribution. (b) Schematic diagram of valve hole distribution.

TABLE 1. Material properties of brass.

Description	Value
Density (kg/ m^{-3})	8360
Young's modulus (GPa)	125
Poisson's ratio	0.33

III. SIMULATION MODELING

In order to identify the flow characteristics, the modeling and simulation were carried out in this part. The structure model was established in SOLIDWOKRS, and the simulation was executed in COMSOL Multiphysics under the fluid-structure interaction mode on time dependent study setup.

The brass diaphragm is fixed around its perimeter, and the PZT 5H disk is bonded on top of the diaphragm. The characteristics of brass is expressed in Table1.

The calculation formula of Reynolds number is

$$Re = \frac{\rho v d}{\mu}$$

where v is the velocity of fluid medium; ρ and μ is the density and viscosity coefficient of the fluid medium, d is the equivalent diameter of channel.

We choose water as the fluid medium. So, when v is less than 0.4m/s in the proposed valve-less pump structure, the flow can be regarded as laminar flow. According to previous studies, the order of magnitude of v is about $10^{-2} \sim 10^{-4}$m/s, hence, the flow field is laminar flow. Also, Inlet and Outlet were set to open boundary. The model is meshed with the physics-controlled mesh, which is showed in the Fig.4.

The net-flow V is defined by using the global equation in COMSOL, that is

$$\frac{dV}{dt} = \sum S_{1i}v_{1i} - \sum S_{2i}v_{2i}$$

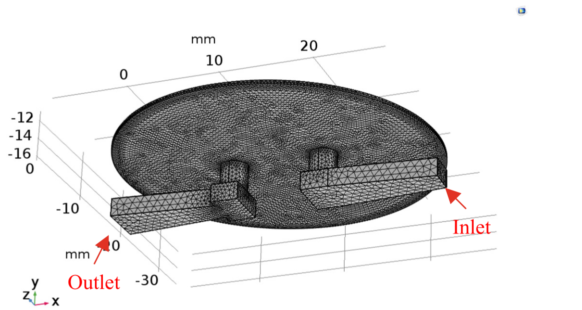


FIGURE 4. Meshed model of the valve-less pump.

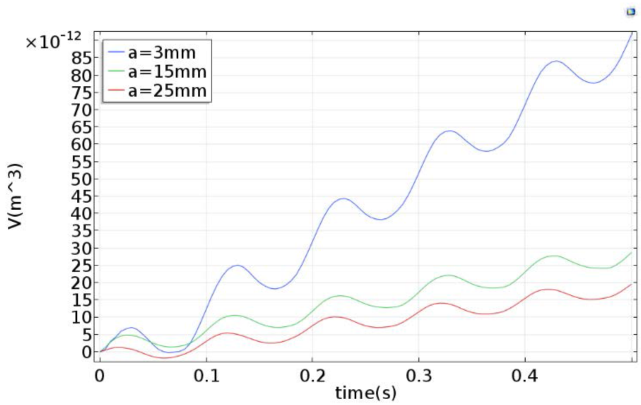


FIGURE 5. Net-flow curve of different valve hole in 0.5s.

where S_{1i} and S_{2i} is the area element in Inlet and Outlet; v_{1i} and v_{2i} is velocity on each area element.

The net-flow curve described by time is illustrated in Fig.5. The net-flow curve is fluctuating upward with law, which is completely in conformity with the characteristics of valve-less pump. Obviously, Fig.5 illustrate that the net-flow increases more rapidly when the hole spacing is 3 mm.

Following the same settings above, we get three velocity stream diagrams of different spacing at 0.2s shown in Fig.6. At this moment, the piezoelectric actuator start moving and the volume of pump chamber will decrease, resulting in the discharge of water in inlet and outlet simultaneously. According to Fig.6, with the increase of the distance between the valve holes, the flow velocity around the valve holes on the side far from the center of the pump chamber decreases. In Fig.6(c), it is obvious that there are few red areas around the valve holes on the side far from the center of the pump chamber, which may be the reasons for the performance degradation.

IV. EXPERIMENTAL SETUP

Tab.2 shows the parameters of valve-less piezoelectric pump prototype. The prototypes are made of transparent organic glass (PMMA), which is benefit for observing the fluid in conical tubes and pump chamber. In order to prove that the performance of pump can be improved by reducing valve hole spacing in different situations, chamber height and cone angle are used to simulate different situations. In addition,

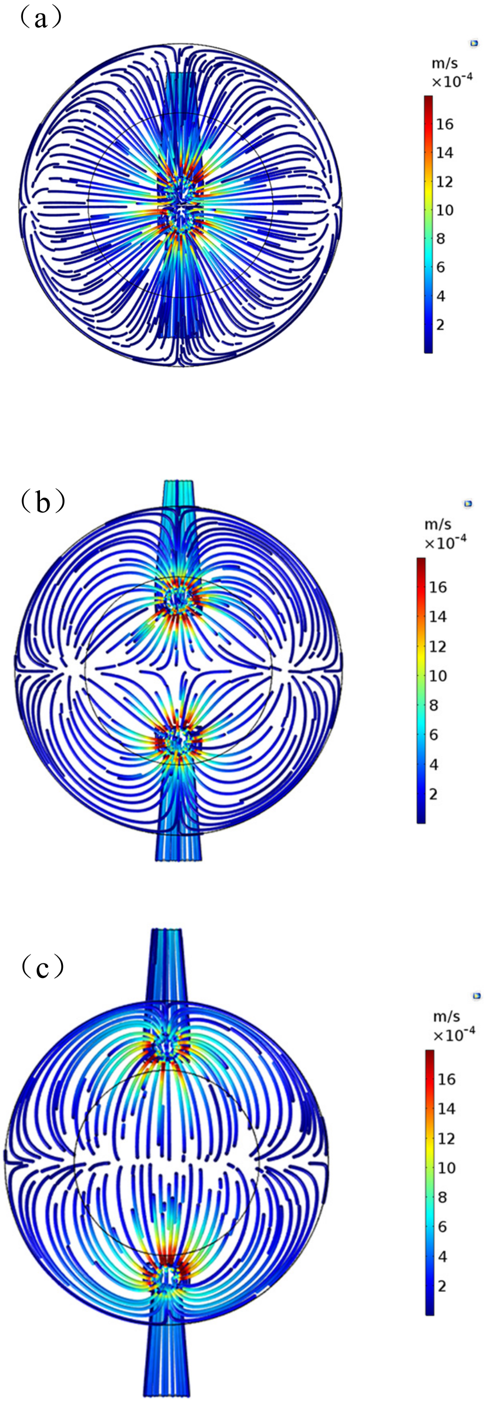


FIGURE 6. Velocity stream diagrams of different spacing at 0.2s. (a) a = 3mm. (b) a = 15mm. (c) a = 25mm.

since the main purpose of the current study is to explore the effect of valve hole spacing on performance, we simply referred to the forerunners' studies to choose a working cone angle of 8°/10°/12°, which already demonstrated excellent performance. But, when the cone angle is 8°, the output flow of prototype is too weak to reach normal working state, and cannot be used as an effective control group. Finally, the cone angle are set to 10°/12°.

TABLE 2. Parameters of piezoelectric valve-less pump prototype.

types	numerical or materials
Overall dimensions	90× 60× 6(mm)
Pump body materials	PMMA
Substrate external diameter	Φ35(mm)
The dimensions of inlet and outlet	3(mm)
Substrate thickness	0.2(mm)
Piezoceramic diameter	Φ25(mm)
Piezoceramic thickness	0.2(mm)
Chamber height (h)	0.1/0.15/0.2(mm)
Cone angle (2θ)	10°/12°
Valve hole spacing (a)	3、15、25(mm)
Voltage-driven type	Square wave

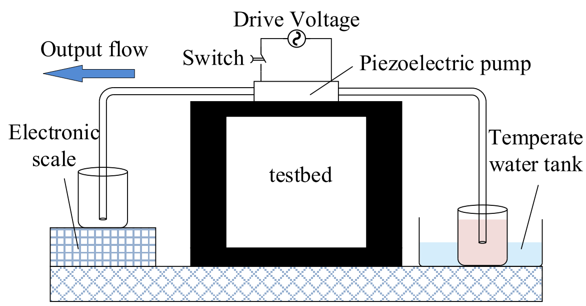


FIGURE 7. Device of flow rate experiment.

Fig.7 shows the experimental setup of the valve-less piezoelectric pump. The waveform generator (Tabor WW2074) and the power amplifier (Tabor 9400) provide with square wave driving signal for piezoelectric pump. The distilled water serves as fluid medium, and the output flowrate of piezoelectric pump is tested by electronic scale. For reducing effect of bubbles, the working medium is kept at 55∼60° by the constant temperature water tank during experiment. The output flow of piezoelectric pumps with three different valve holes spacing are conducted under different parameter combinations. Initially, when driving voltage is at a fixed (300Vpp), in the different frequency (1∼30Hz) output flow is measured, and then at a fixed frequency, the output flow is measured under different voltage measurement (200∼400Vpp).

V. EXPERIMENTAL RESULT AND ANALYSIS

To validate the theoretical model, the effect of valve hole spacing on prototype was investigated with chamber height and cone angle.

A. PERFORMANCE IMPACT EXPERIMENT BY VALVE HOLE SPACING AT DIFFERENT CONE ANGLE

In order to analyze performance impacted by valve hole spacing at different cone angel, we keep the driven-voltage under 300Vpp. Fig.8 shows the relationship of flowrate with frequency at different cone angle. According to the flowrate curve of piezoelectric pump at cone angle of 10° in Fig.8(a), the maximum flowrate with valve hole spacing of 3mm reached 8.43ml/min. And it is 13.6% and 47.1% higher than that of the 15mm and 25mm valve hole spacing, respectively.

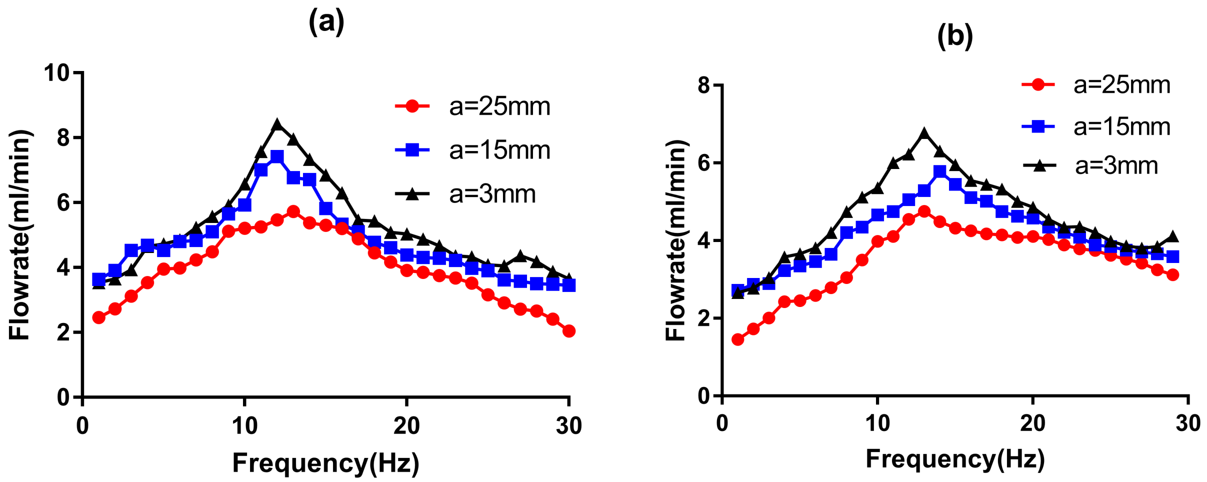


FIGURE 8. Measured flowrate with frequency at different cone angle and chamber height of 0.15mm. (a) Cone angle of 10°. (b) Cone angle of 12°.

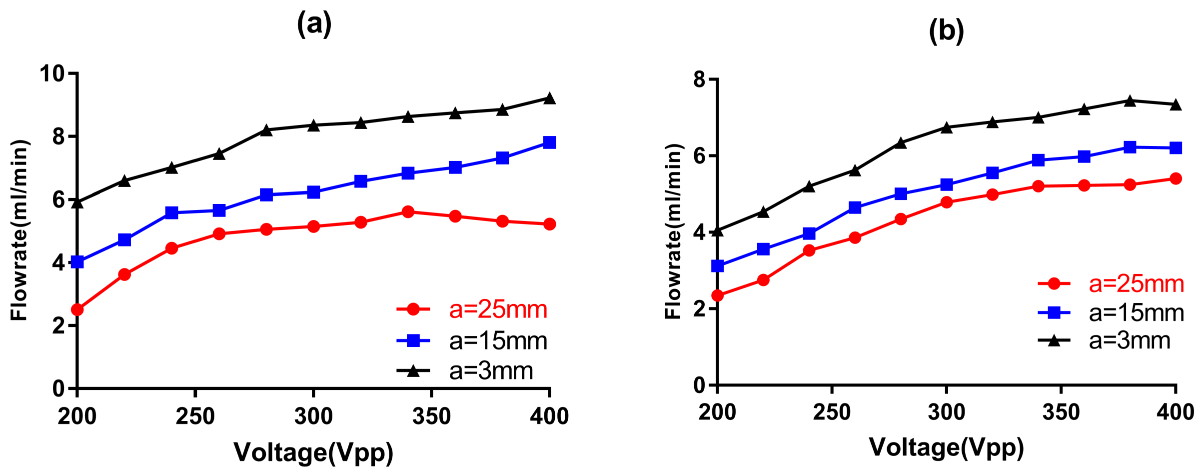


FIGURE 9. Measured flowrate with voltage at different cone angle and chamber height of 0.15mm. (a) Cone angle of 10° at 12Hz. (b) Cone angle of 12° at 13Hz.

From Fig.8 (b), the valve hole spacing of 3mm also shows the best output performance, which is 17.3% and 49% higher than that of the 15mm and 25mm, respectively. This is consistent with the simulation results. By comparing Fig.8(a) with Fig.8(b), it is worth mentioning that the cone angle of 10° have better performance than cone angle of 12°. This is the same with the relevant research results.

We continue to investigate the voltage properties. The measured flowrate with voltage at cone angle of 10° and 12° can be seen in Fig.9. It is easy to see the performance of the 3 mm spacing prototype is higher than that of the other two groups from beginning to end, which achieved the best output flowrate of 9.23ml /min driven at 400Vpp. Similarly, the cone angle of 10° shows superior capability in this project.

B. PERFORMANCE IMPACT EXPERIMENT BY VALVE HOLE SPACING AT DIFFERENT CHAMBER HEIGHT

Based on the above test, prototype with cone angle of 10° overall performance is better from longitudinal comparison, the cone angle of 10° is selected. On the case of different chamber height, we analyze the influence of three different kinds of valve hole spacing on output flowrate. Fig.10 shows the relationship between output flowrate and valve hole spacing with frequency at different chamber heights. From Fig.10(a), as the spacing of valve holes decreases, the maximum flowrate of 4.3ml/min, 4.92ml/min, and 5.39ml/min are obtained, respectively. In Fig10(b), the maximum flowrate is 5.45ml/min, 6.15ml/min and 7.25ml/min, respectively. Through the comparison of Fig.10(a), Fig.8(a) and Fig.10(b), we find that the chamber height of 0.15mm may be more suitable under the same conditions (cone angel of 10°).

On the basis of the above experiment, the comparison test under different voltages were carried out. Fig.10(a) is that output flow curve with chamber height of 0.1 mm, the calculated results show that the maximum flowrate of 3mm increased by 20.7% and 45.5% compared with that of 15mm and 25mm, respectively. Fig.10(b) is similar to above, the spacing of 3mm shows the best capability.

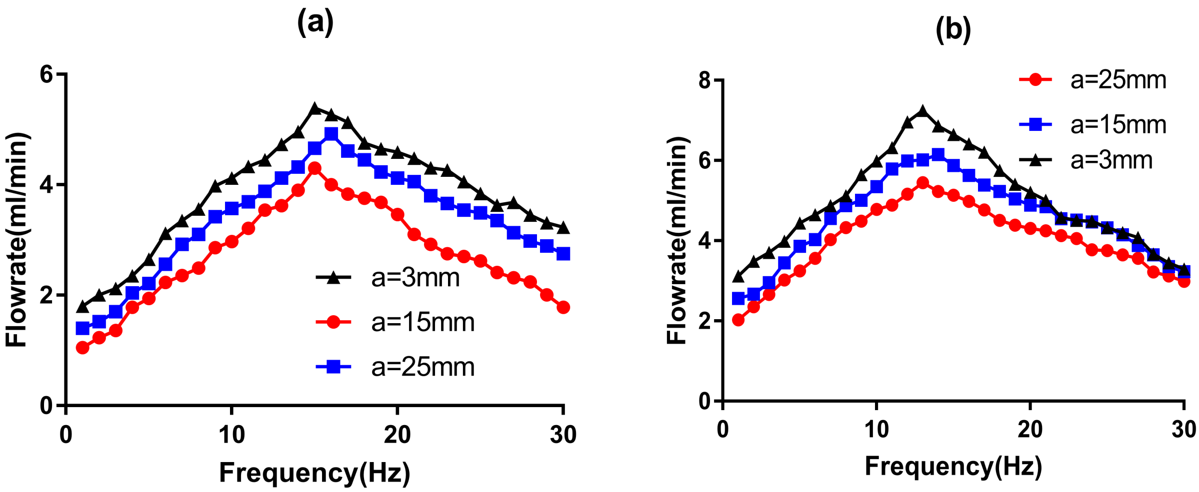


FIGURE 10. Measured flowrate with frequency at different chamber height and cone angle of 10°. (a) Chamber height of 0.1mm. (b) Chamber height of 0.2mm.

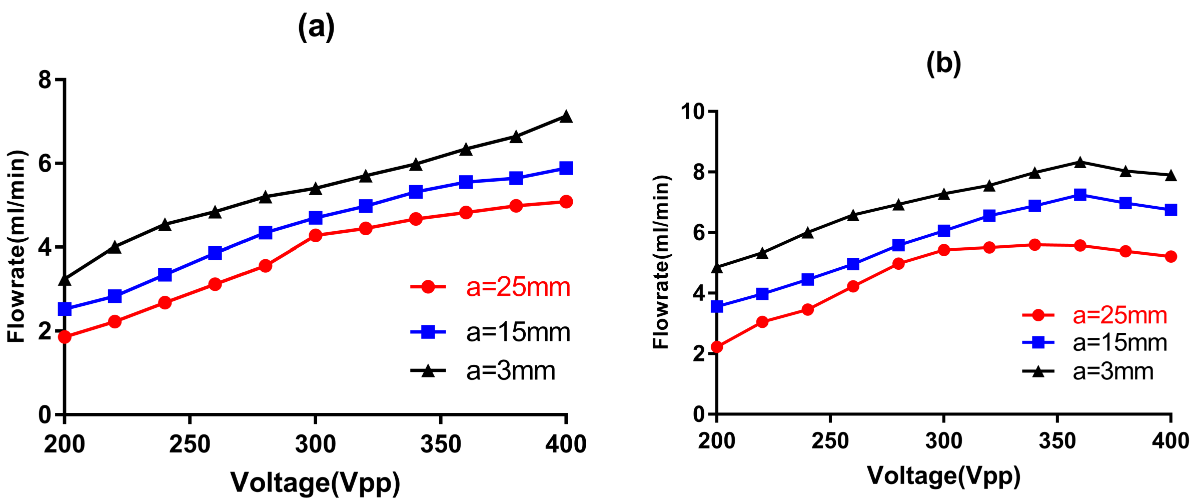


FIGURE 11. Measured flowrate with voltage at different chamber height and cone angle of 10°. (a) Chamber height of 0.1mm at 15Hz. (b) Chamber height of 0.2mm at 13Hz.

There is a big gap in output performance of piezoelectric pumps between different valve hole spacing, which reflects a certain rule of influence. The output effect of piezoelectric pump with the minimum valve hole spacing (3mm) is better than that with valve hole spacing (15mm and 25mm), which is a high rate of improvement. The correctness of simulation result is verified by experiment.

VI. CONCLUSION

From two aspects of conical tube flow resistance and plate gap flow pressure drop, a theoretical model was established. According to theoretical model, it is found that the output flow performance can be improved by reducing valve hole spacing.

In order to effectively analyze influence law of valve hole spacing on output performance, combination tests with different chamber height and different cone angle were used to simulate different situations. A maximum flowrate of 8.43mL/min was achieved at valve hole spacing of 3 mm, which is 13.6% and 47.1% higher than that at 15 mm and 25 mm, respectively. The output flow performance increases significantly with the decrease of valve hole spacing(3mm,15mm,25mm), which is basically the same with theoretical analysis.

REFERENCES

[1] S. Aggarwal, B. E. Paul, A. DasGupta, and D. Chatterjee, "Experimental characterization of piezoelectrically actuated micromachined silicon valveless micropump," *Microfluidics Nanofluidics*, vol. 21, no. 1, Dec. 2016.

[2] P. Kawun, S. Leahy, and Y. Lai, "A thin PDMS nozzle/diffuser micropump for biomedical applications," *Sens. Actuators A, Phys.*, vol. 249, pp. 149–154, Oct. 2016.

[3] K. Li, J. Liu, W. Chen, and L. Zhang, "Influences of excitation on droplet spreading characteristics ejected by piezoelectric micro-jet," *IEEE Access*, vol. 6, pp. 25930–25938, 2018.

[4] S. Yang, X. He, S. Yuan, J. Zhu, and Z. Deng, "A valveless piezoelectric micropump with a Coanda jet element," *Sens. Actuators A, Phys.*, vol. 230, pp. 74–82, Jul. 2015.

[5] J. Huang, J. Zhang, S. Wang, and W. Liu, "Analysis of the flow rate characteristics of valveless piezoelectric pump with fractal-like Y-shape branching tubes," *Chin. J. Mech. Eng.*, vol. 27, no. 3, pp. 628–634, May 2014.

[6] X.-F. Leng, J.-H. Zhang, Y. Jiang, J.-Y. Zhang, X.-C. Sun, and X.-G. Lin, "Theory and experimental verification of spiral flow tube-type valveless piezoelectric pump with gyroscopic effect," *Sens. Actuators A, Phys.*, vol. 195, pp. 1–6, Jun. 2013.

[7] J.-H. Zhang, Y. Wang, and J. Huang, "Advances in valveless piezoelectric pump with cone-shaped tubes," *Chin. J. Mech. Eng.*, vol. 30, no. 4, pp. 766–781, Jul. 2017.

[8] J. Zhang, Y. Wang, and J. Huang, "Equivalent circuit modeling for a valveless piezoelectric pump," *Sensors*, vol. 18, no. 9, p. 2881, Sep. 2018.

[9] C.-H. Cheng, A.-S. Yang, C.-J. Lin, and W.-J. Huang, "Characteristic studies of a novel piezoelectric impedance micropump," *Microsyst. Technol.*, vol. 23, no. 6, pp. 1709–1717, Jun. 2017.

[10] T. Sato *et al.*, "Electrohydrodynamic conduction pump with asymmetrical electrode structures in the microchannels," *Chem. Lett.*, vol. 46, no. 7, pp. 950–952, 2017.

[11] A. Olsson, P. Enoksson, G. Stemme, and E. Stemme, "Micromachined flat-walled valveless diffuser pumps," *J. Microelectromech. Syst.*, vol. 6, no. 2, pp. 161–166, Jun. 1997.

[12] W. Hilber, S. Clara, and B. Jakoby, "Microfluidic pumping utilizing a PDMS membrane with an integrated nonuniform open-porous foam," *IEEE Sensors J.*, vol. 15, no. 9, pp. 5109–5114, 2015.

[13] A. Nisar, N. Afzulpurkar, B. Mahaisavariya, and A. Tuantranont, "MEMS-based micropumps in drug delivery and biomedical applications," *Sens. Actuators B, Chem.*, vol. 130, no. 2, pp. 917–942, 2008.

[14] X. He, W. Xu, N. Lin, B. B. Uzoejinwa, and Z. Deng, "Dynamics modeling and vibration analysis of a piezoelectric diaphragm applied in valveless micropump," *J. Sound Vibrat.*, vol. 405, pp. 133–143, Sep. 2017.

[15] M. Shirkosh, Y. Hojjat, and H. Sadeghian, "A new design of electrostatic traveling wave (ETW) micropump and the effect of parameters on the flow rate," *Flow Meas. Instrum.*, vol. 48, pp. 8–14, Apr. 2016.

[16] E. Stemme, "A valveless diffuser/nozzle-based fluid pump," *Sens. Actuators A, Phys.*, vol. 39, no. 2, pp. 159–167, Nov. 1993.

[17] S.-F. Hwang and Y.-M. Ji, "Experimental investigation on the design of nozzle/diffuser for micropumps," *Int. J. Precis. Eng. Manuf.*, vol. 15, no. 4, pp. 717–723, Apr. 2014.

[18] F. R. Munas *et al.*, "Development of PZT actuated valveless micropump," *Sensors*, vol. 18, no. 5, p. 1302, Apr. 2018.

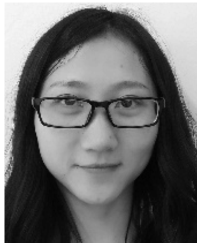
[19] A. Olsson, G. Stemme, and E. Stemme, "A valve-less planar fluid pump with two pump chambers," *Sens. Actuators A, Phys.*, vol. 47, nos. 1–3, pp. 549–556, 1995.

[20] L. Guo, W. Yan, Y. Xu, and Y. Chen, "Valveless piezoelectric micropump of parallel double chambers," *Int. J. Precis. Eng. Manuf.*, vol. 13, no. 5, pp. 771–776, May 2012.

JIAJIAN JI is currently pursuing the degree in mechanical design manufacturing and automation with Zhejiang Normal University. Since 2017, he has been involved with different projects related to piezoelectric valveless micropumps and testing.

SONG CHEN received the B.S. degree from Zhejiang Normal University, China, in 2011, and the Ph.D. degree from Jilin University, in 2016. He is currently a Lecturer with Zhejiang Normal University. His research interests include piezoelectric actuators and piezoelectric micropumps.

XINYI XIE is currently pursuing the degree in mechanical design manufacturing and automation with Zhejiang Normal University. Her research interests mainly include piezoelectric micropumps.



XIAOMING WANG is currently pursuing the degree in mechanical design manufacturing and automation with Zhejiang Normal University. Her research interests mainly include piezoelectric micropumps.

JUNWU KAN received the B.S. degree from the Jilin University of Technology, China, in 1988, and the M.S. and Ph.D. degrees in mechanical engineering from the College of Mechanical Science and Engineering, Jilin University, in 2000 and 2003, respectively. In 2000, he was with the Piezoelectric Actuator Group of Prof. Suzuki, Yamagata University, Japan. After returning from Japan, he continued to work on the research and development of the piezoelectric energy harvesting and piezoelectric actuators, particularly the piezoelectric energy harvesting. He is currently a Professor with Zhejiang Normal University.

ZHONGHUA ZHANG received the B.S. degree in mechanical engineering and the M.S. degree in mechanical and electrical engineering from Liaoning Technical University, China, in 2002 and 2005, respectively, and the Ph.D. degree in mechanical and electrical engineering from the Dalian University of Technology, China, in 2009. He is currently an Associate Professor with Zhejiang Normal University, China. He is also an Academic Visitor with the University of Southampton, U.K., where he is devoting himself to the research work of piezoelectric energy harvesting. He has published over 30 scientific papers. His main research interests include piezoelectric energy harvesting, piezoelectric pumps, and integration technology of sensors and actuators.

JIANPING LI was born in Jiangsu, China, in 1987. He received the B.S. and Ph.D. degrees from the School of Mechanical Science and Engineering, Jilin University, Changchun, China, in 2011 and 2016, respectively. In 2016, he was a Postdoctoral Fellow with the Japan Society for the Promotion of Science. In 2018, he was with Zhejiang Normal University. His current research interests include piezoelectric actuators and the application of electrical impedance spectroscopy in biomedical science.