# Developments and Applications of Microfluidic Pumps and Valves

HSIAO CHI SONIJA HONG [1,†], Leying Wu [2,*,†], Xiang Yan [3,†], Sitan Wang [4,†]

[1] School of Guangdong Country Garden School, Foshan, China

[2] School of Qibao Dwight High School, Shanghai China

[3] High School Affiliated to Nanjing Normal University of Jiangning Campus, Nanjing China

[4] School of Chengdu Jiaxiang Foreign Languages School, Chengdu, China

* Corresponding Author Email: lywu_coco@qibaodwight.org

† These authors contributed equally.

**Abstract.** Microfluidic technology is used a lot in modern engineering. Microfluidic pumps and valves are key topics of microfluidic research today. Microfluidic pumps and valves have long life of equipment with low power waste. They can transport liquids like water and oil. Microfluidic pumps and valves are widely used in household appliances, cooling systems and medical devices. However, there is still a research gap on the improvement of the performance of the microfluidic pumps and valves. Therefore, this paper summarizes the recent developments and applications of the design and optimization techniques for micropumps and microvalves. The basic principle of topology optimization technique for micro-pumps and valves and its applications are detailed. Research findings are summarized. Suggestions are put forward to provide useful guidelines for future research. Overall, this paper can be served as a useful reference for those who would like to know the optimization design method of microfluidic pumps and valves.

**Keywords:** Microfluidic device, pumps, valves.

## 1. Introduction

The phrase "microfluidic pumps" is more specifically defined as pumps having functional dimensions in the micron range. Microfluidic pumps are equipment which can operate and regulate small volumes of fluid. The interest in this novel pump has been sparked by their tiny overall dimension, relatively high cost, and enhanced metering accuracy comparison to conventional pumps. Numerous industrial uses for microfluidic pumps include the shipment of tiny amounts of adhesive during production processes, biomedical applications such as implantable or portable drug carriers, implementations in chemical sensing, chemically powered micropump for ecological risk tracking, and chemically powered micropump for portable drug delivery devices. Microfluidic pumps can be classified according to various criteria. In this paper, pump with or without valve parts will be discussed.

Valved micropumps generally work by using periodic changes in chamber volume and the action of a one-way valve gate [1]. The pump body is mainly composed of the driving membrane, pump chamber and inlet/outlet valves. And the drive will be based on different drive methods (piezoelectric drive, electrostatic drive, and thermal drive, etc.). K. Au et al. [2] examined various microvalves and micropumps designs that can be used in bioelectromechanical systems and provided a comprehensive overview. It is suggested that device characteristics must be considered before deciding whether certain device is appropriate to apply to a biomedical design. Zhang et al. [3] investigated thickness-averaged approximation and finite element calculations of the periodic flow of a piezoelectric microfluidic pump using a water wave model, which can reasonably describe the basic characteristics of the internal flow of the micropump. It is noted that the difference in fluid kinetic energy changes in different flow directions of diffusion tubes is the main source of the directional flow of the periodic flow of the microfluidic pump. Li et al. [4] investigated a study on micropumps and microvalves and discussed their structural design, braking principles, and implementation performance through the current state of research. Li found that micropumps and microvalves have the potential for integration and mass production due to their low energy consumption, small size, and fast response. Moreover, microfluidic control systems also have the potential to realize applications in engineering, medical-biological and other fields, such as semiconductor processing and electrical humidity phenomena. Bo et al. [5] addressed the key issues of Micro-DPIV technology by using the transient flow field at the outlet of the valveless micropump as the detection target, establishing the optimal operating state of the micropump through the periodical interval sampling technique, and adding fluorescence microscopy settings as well as tracer particles. In addition, it is concluded that Micro-DPIV is one of the most effective techniques in microfluidic field detection, and the technique can provide experimental verification and technical guidance from technical difficulties such as flow field distribution, device performance detection, flow channel structure design and optimization, respectively.

The objective of this paper is to present a summary of advanced technologies and uses for microfluidic pumps and valves. Section 2 introduces optimization of various kind of microfluidic pumps and microfluidic valves. Conclusion and prospects are presented in Section 3.

## 2. Main body

### 2.1. Microfluidic Pump

For valveless micropumps that are actuated by membrane vibration, Deng et al. [6] suggested a powerful topology optimization technique. The number and positions of actuation elements, the phase difference, and the drive frequency were adjusted in the micropump channel to raise the output net flow rate of the liquid. There were exhibited numerous innovative valveless micropumps.

As shown in Figure 1, the valveless micropump acts as a bimorph actuator with a waveform voltage applied to piezoelectric and membrane. Thus, the pumping chambers produce sequential suction and injection flows along of the major channel sidewalls. Therefore, by optimizing the net flux, the performance of the micropump can be optimized.

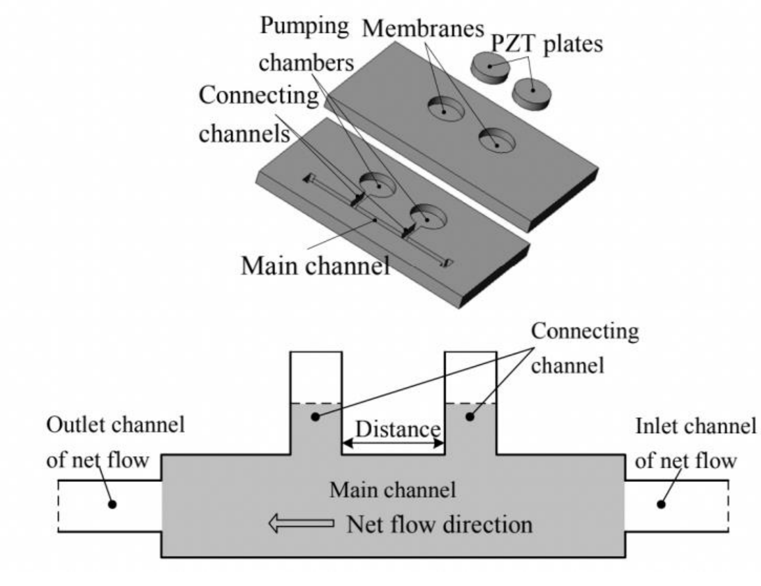
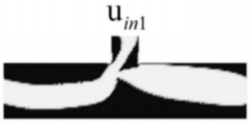
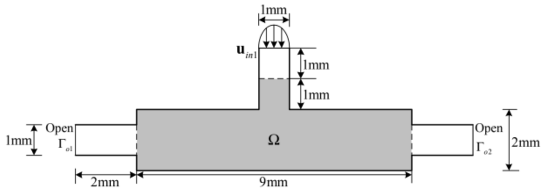



**Figure 1.** Valveless micropump optimization design

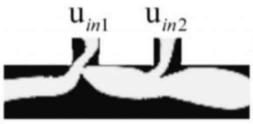
Figure 2 (a), (b) and (c) are the improved layouts of the main channel, while Figure 2 (d), (e) and (f) are the initial valveless micropump designs.



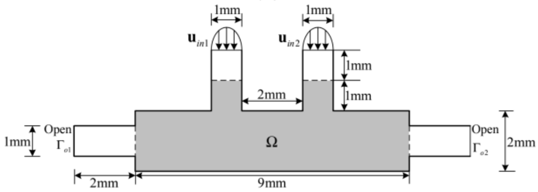

(a) Net flux being 1



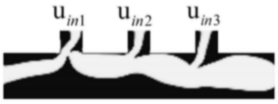

(d) Initial pump with one actuation element



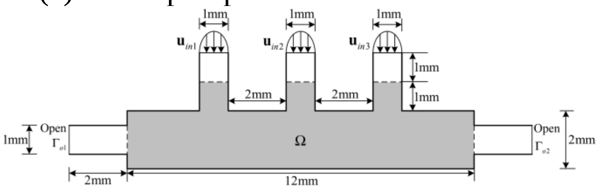

(b) Net flux being 2.2




(e) Initial pump with two actuation elements



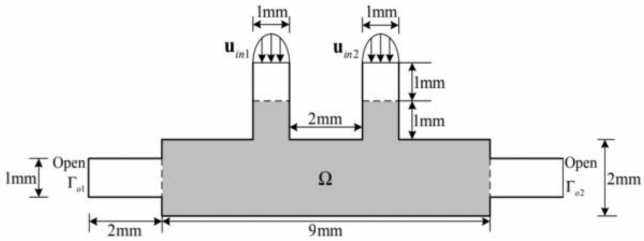

(c) Net flux being 3.4



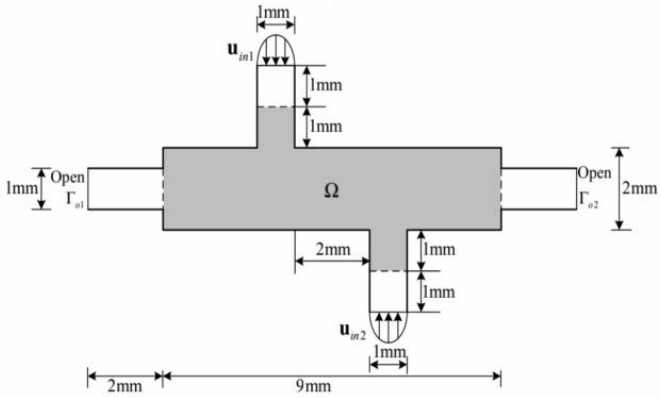

(f) Initial pump with three actuation elements

**Figure 2.** Comparison diagram of the original and optimized design domains for valveless micropumps with different numbers of actuating elements

The relative position and phase difference of the actuation pulse will also have an impact on the performance of micropump, and the basic main channel including two elements is depicted in Figure 3.




(a) Micropump with two actuation elements on the same side




(b) Micropump with two opposite-side actuation elements

**Figure 3.** Initial layout of domains of valveless micropumps

According to Figure 4, the optimized micropump will have a greater value of pumping net fluxes with the actuation elements on the single side of the main channel, and π/3 is the ideal phase difference for the main channel with two elements. Plotting of the net flux values uses a polar coordinate system. Overall, it can be concluded that three actuation elements will have a larger pumping net flux than those with two if the phase difference is chosen wisely.

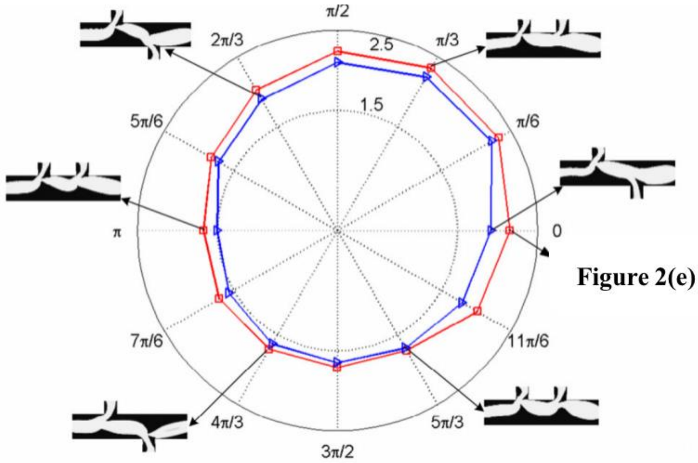
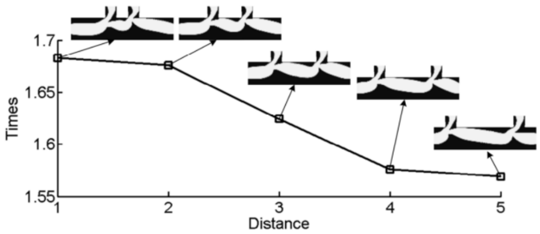
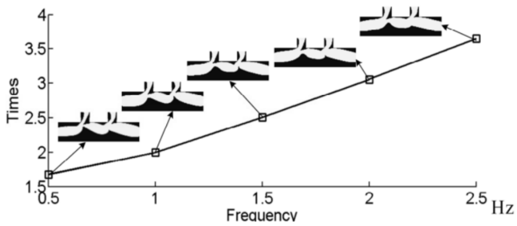



**Figure 4.** Optimized micropumps at the same sidewall or both sidewalls of the main channel are consistent with various phase differences

Figure 5 (a) demonstrates the impact on the values of net flux by modifying the gap between two actuation elements since it also influences the configuration of the main channel and the efficiency of the micropump. A valveless micropump with a greater actuation frequency produces a higher pumping net flow, as evidenced by Figure 5 (b).




(a) Optimized micropumps with various distances between 2 actuation elements




(b) Optimized micropumps actuated by different frequencies

**Figure 5.** Data plot of micropumps with two actuation elements

In conclusion, the subject matter is distinctive, as it is a rare case where optimization is applied to valveless micropumps in a non-steady flow situation while the usual Tesla steady flow is used. Moreover, the specific analysis and experimental validation of the performance system of valveless micropumps is not detailed. Therefore, in-depth investigation should be carried out to find out the effect of non-steady flow on the performance of the valveless micropumps.

M M Gregersen exposed induced charge electroosmosis (ICEO) devices to topology optimization [7]. The efficiency of the pump is increased as a result of the improvement that this technology brings to the dielectric shape. Utilizing this method results in the dielectric shape being adjusted, which in turn results in an increase in the pump's overall efficiency. According to the findings of Squires and Bazant's investigation [8] ICEO flow may be generated when a solid object is immersed in an electrolytic solution while simultaneously being polarized by an external electric field.

Before this point, the component establishes a potential difference with the bulk of the electrolyte that is dependent on its position in the system. However, due to the presence of counter ions in the electrolyte, this potential is blocked, which results an electric double layer on the surface. After being electrocuted in the ensuing external electric field that was tangential to the object surface, the ions of the diffusive component of the layer started pulling the fluid with viscous forces. This was because the external electric field was tangential to the object surface.

As a direct result of this, the actual slip velocity on the outer surface of the double layer may be computed. The model system is shown in Figure 6. This system is made up of a parallel plate capacitor that is controlled by the difference of a harmonic oscillating voltage. Additionally, this capacitor is made up by a dielectric solid with a electrolyte. The ICEO companies that are external to the system flow over the dielectric surfaces of a solid dielectric that has been manufactured and seated in the electrolyte. The goal of the topology and geometry of the dielectric solid are designed to provide highest flow in the direction perpendicular to the electric field applied.

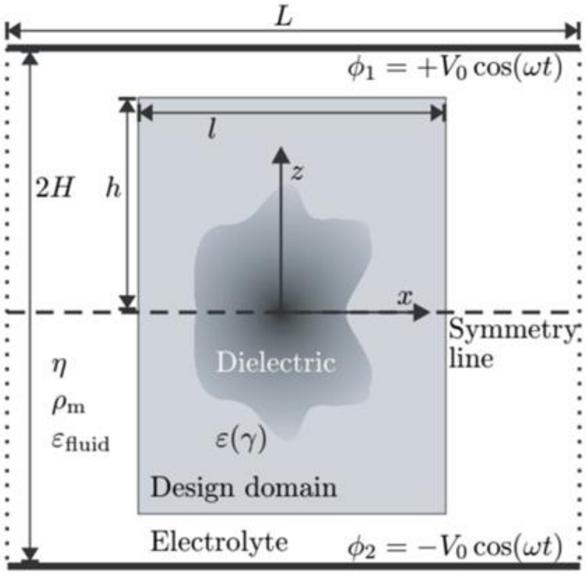
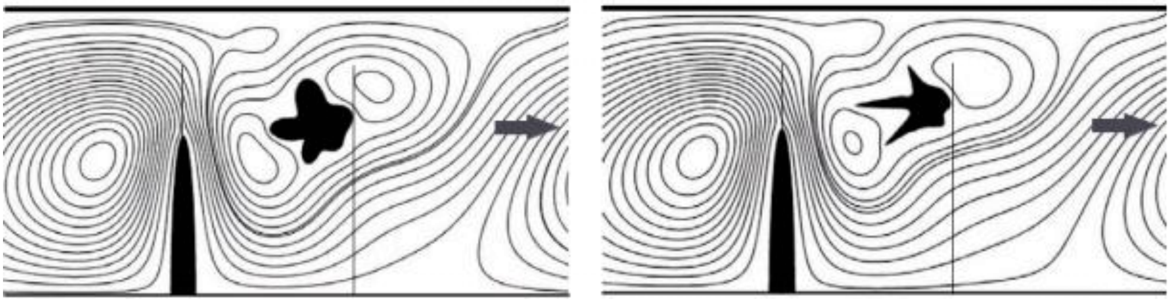



**Figure 6.** Is a drawing of the electrolytic capacitor's rectangular cross-section

In the left-top corner of the design domain, it is shown that the topology-optimized form would benefit from far more flow movement between the two dielectric islands than is now occurring. The area between the aisles was infilled by the dielectric substance, and the flow was measured in order to establish the relevance of this division. It seems that the flow rate has only been significantly lowered as a result of this topological change. Therefore, the essential topology of the dielectric solid in the upper half domain is comprised of the development of one center island that is located straddling the antisymmetric line and one satellite island that is located near to the tip of the center island. The result of optimizing the form of this two-piece assembly is shown in Figure 7. The flow rate is 1.92 x 10-3, which is about 2.5 times more than the flow rate that would be produced by a straightforward triangle shape (0.46 x 10-3).



(a) streamline pattern for a two-piece geometry (b) streamline pattern for a modified two-piece geometry

**Figure 7.** Streamline of typical two-piece geometries

Figure 7 (a) illustrates the streamline pattern for a two-piece geometry. This pattern was computed using the conventional ICEO model. In order to establish the form of the hard-walled dielectric solid, a technique called shape optimization with 16 directed angles is applied (dark one). The flow rate is

1.92 x 10-3. Compared with to Figure 7(a), the form of the dielectric solid in Figure 7 (b) has been modified. The flow rate is equal to Q = 1.52 x 10-3 now.

In general, the study demonstrates how directly linked topologies and basic forms of the dielectric solids may be modified into multiple connected topologies of intricate shapes in order to considerably enhance real ICEO-based devices. In the future, research could focus on developing more sophisticated shapes for dielectric solids to enhance the performance of the electronic devices.

### 2.2. Microfluidic Valve

Deng et al. [9] optimized the fluidic resistance of a stationary component low microvalves Reynolds numbers. Particularly as compared to the standard Tesla valve, the optimized valves minimize the fluidic resistance for the forward flow and reverse flow. Typically, a higher Reynolds number is preferred because it represents the low viscosity of a fluid. Experiments are conducted to test the number representation of the diodicity of fluidic resistance, which is a microvalve's capacity to permit forward flow while obstructing backward flow in a planned periodic valve.

The experiment regarding optimizing channel topology for low and intermediate Reynolds values using the finite element technique (FEM) was put out. As seen in Figure 8, the domain is selected at a 45° angle in contrast to the traditional Tesla valve. It is found out that when the Reynolds number was below 100, the diodicity increased by a maximum of 57%, with the low Reynolds number range showing the best performance.

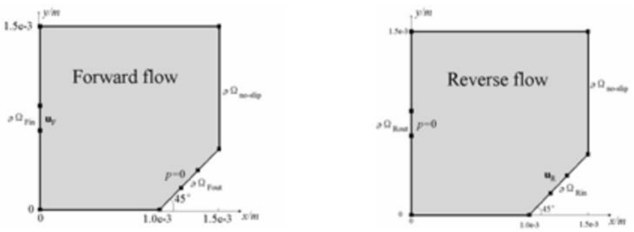



**Figure 8.** The forward and reverse flow valve's boundaries and the design domain

Figure 9 depicts the micro valve's optimization procedure. Figures 9 (a), (b), and (c) show the iterative optimization's intermediate topologies, and Figure 9 (d) shows the NMP valve's ideal topology, with the optimized fluidic channel represented by the white-colored subdomain. It is clearly shown in the picture that the valves are becoming straighter with the process of optimization which reaches the purpose of decreasing the resistance force to make fluid pass through.

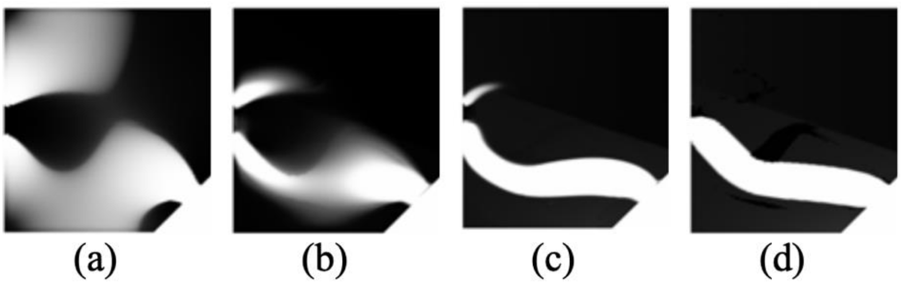



**Figure 9.** The topology evolving process of the NMP valve

Figure 10 illustrates a comparison of diodicity for various Reynolds numbers. Better diodicity of the valve is indicated by a lower diodicity rating. It is possible to see the advantage of the valve with a low Reynolds number.

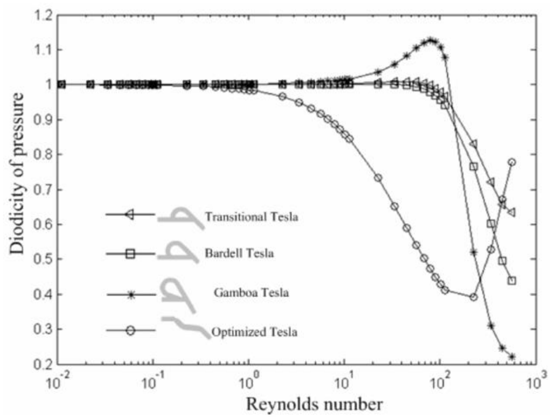
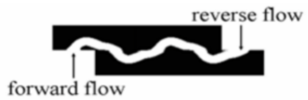



**Figure 10.** Comparison of diodicity with different Reynolds numbers

The design of periodic microvalves is frequently used in microfluidic devices because they can achieve different flow resistance. After using the optimized model, the calves with 2 or 12 periodicity are shown in Figure 11 (a) and (b) respectively.




(a) valve with 2 periodicity


(b) valve with 12 periodicity

**Figure 11.** The optimal topology of the NMP valve

The optimized valve has a different layout than a conventional Tesla valve, and its diodicity has increased by up to 57%. The experimental confirmation that a microvalve is a 3D structure mentions one of the experiment's flaws. However, the glass-fabricated two-dimensional domain served as the initial implementation site for the non-moving component fluidic resistance microvalves. In the future, this could be enhanced by utilizing three-dimensional technology.

### 2.3. Optimization Design of Micro Venturi Diode

Liu et al. [10] pointed out that all-inclusive key design factors of Micro Venturi diodes have significant impact on the outcome of the diode effect. A novel method is proposed to produce Venturi diodes for steady Newtonian flows.

Figure 12 shows that forward pressure drop is lower than of the reverse direction in the micro-Venturi diode. The diodicity parameter can measure and record the diodicity effect of a micro-Venturi diode. A lower effect of diode is indicated by a higher value of the diodicity parameter. Two fluxes with opposite directions should be equal in this experiment.

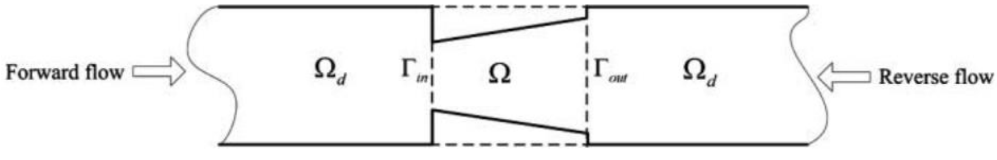
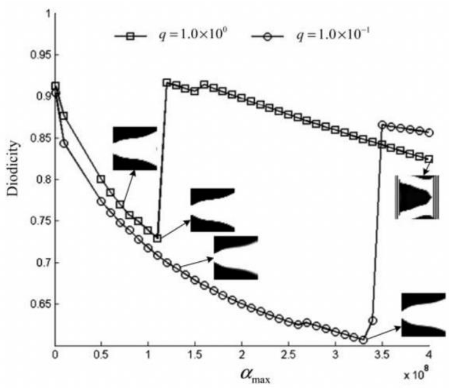
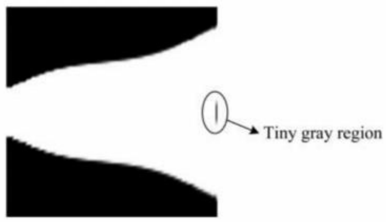



**Figure 12.** Schematic of the micro-Venturi diode

Figure 13 (a) shows the results with figure and pattern given by solving the optimization model. (1) The optimization outcome should have less diodicity, (2) it should have a distinct black-white type border so that it can be made using materials that are readily available for microfluidics, as illustrated in Figure 13 (b). These two criteria are used to determine the design parameters with the most plausible values.




(a) Values of diodicity




(b) An optimal design with a tiny grey region

**Figure 13.** Values of diodicity and the optimized micro-Venturi diode

The effect of the ratio between length and width is investigated. The design of several micro-Venturi diodes for the original design domains shown in Figure 14 under that the length ratio should be fixed between 0.5 and 1.5. Figure 14 shows that as the length over width is lower, the effect of diodicity will be better.

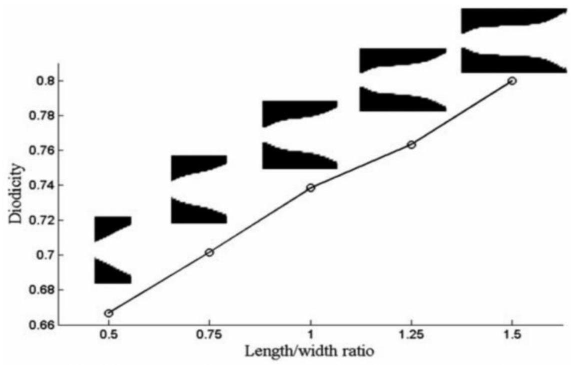



**Figure 14.** Different ratio of length or width influences the diodicity effect in micro-Venturi diode

Volume fraction on the diodes is a feature that could influence diodicity. The volume of the optimized micro-Venturi diode also has upper constraints as illustrated in Figure 15 when the length to breadth of the design domain is increased. This demonstrates that the volume constraint can be disregarded during the optimization of the micro-Venturi diodes.

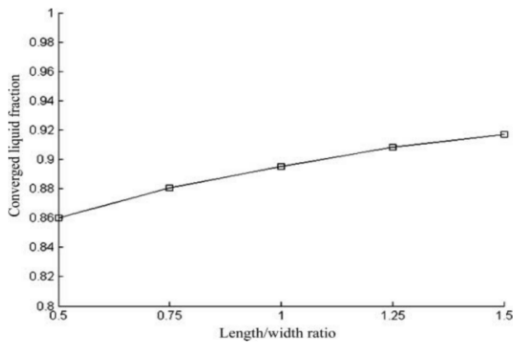



**Figure 15.** The converged liquid fraction with various ratios of length to width

The ideal value of the diodicity is determined by the original design domain's length to breadth ratio and the volume restriction. The two features must keep in constant to prevent influencing the result of effect of Reynolds number. For the optimization model considering both single and multiple Reynolds numbers, Figure 16 illustrates the reason of Reynolds number could affect figure of diodicity. It concludes that the Reynolds number has an great impact on the diodicity.

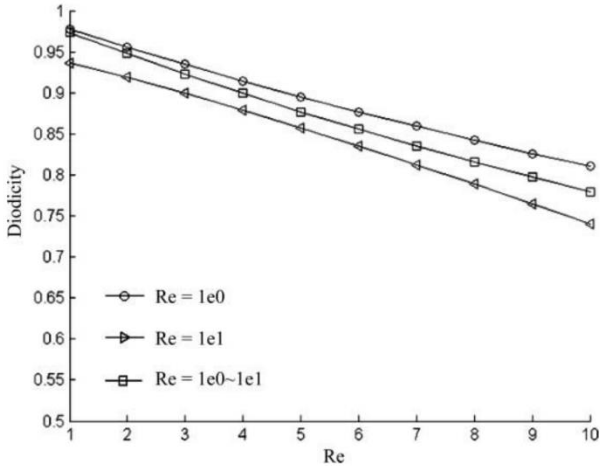



**Figure 16.** Effects of Reynolds number on the diodicity

In conclusion, this paper points out four methods to improve the diodicity effect of micro-Venturi diodes, namely ratio length to width, the volume constraint in model, Reynolds numbers and curved micro-Venturi diodes. It has been used widely in Petroleum, chemical, electric power and metallurgy field.

## 3. Conclusion

This paper summarized the recent advances in the optimization of valveless micropumps, induced-charge electro-osmotic micropumps, no-moving fluidic resistance pumps, and Venturi diode in terms of the topography and relations with Reynold numbers separately.

Following is a summary of the findings. The output net flux is influenced by the quantity and locations of actuation elements, driving phase variations and frequency. Additional actuation elements with the right driving phases will be able to generate higher output net flux than pumps utilizing single actuation element, and the output net flux can be further increased by utilizing higher driving frequency. Secondly, multiple connected topologies of complicated shapes other than simply linked topologies and shapes of the dielectric solids is helpful to enhance the performance of the actual ICEO-based devices. Thirdly, the resistance was decreased and the diodicity was increased by up to 57% using the optimized no-moving fluidic micro valves. Finally, the ratio of length, the volume, the Reynolds number, and the curved micro-Venturi diodes are the critical aspects of micro-Venturi diode optimization at low Reynolds number.

Putting those improved valves into use and creating further uses of those technologies to improve people's lives could prove to be crucial areas for future study. For instance, the medical industry might be a substantial application for those technologies, assisting patients in managing blood clots in biotic vascular fields.

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