Asymmetrical flow effect applied to pumping performance of simple duct channel

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A B S T R A C T

In this study, a simple pumping system, composed of a piezoelectric buzzer imbedded in a duct channel, was used to study the effect of longitudinal flow asymmetry on pumping performance in view of its importance in the design of valveless pumping systems, in spite of the fact that this has rarely been addressed before. The physical features of flow asymmetry caused by the Liebau effect, during the asymmetrical or asynchronous vibration of a buzzer in the course of space and time, can generate net mass flow and result in a pumping performance that has been confirmed experimentally. The degree of transversal asymmetry of a buzzer in space and time positively correlates with longitudinal asymmetry for pumping performance. This principle should be useful when designing valveless pumping systems, especially for applications for fields like bio-medicine, bio-chemistry, and environmental testing. Since this pumping system uses simple components, no moving valve structure will not damage any biological particles in a transmission process.

1. Introduction

Many kinds of valveless pump designs have been addressed in literature. Regarding “valveless” pumps, the mechnofluidic one-way valves are replaced by fluidic diodes. A diode is a device exhibiting different hydrodynamic properties for different directions of the flow. The effect is characterized by diodity—the ratio of dissipation in the reverse and forward flow direction [1]. The flow channels at the inlets and the outlets of valveless reciprocating pumps are designed to give different flow resistances in the forward and the reverse directions. Many principles of valveless reciprocating pumps have been investigated at an early stage [2–5]. One of valveless reciprocating pumps was the valveless diffuser pump presented in 1993 [6,7]. The opening angle of the diffusers was less than 20° and the diffuser direction was in a forward flow direction. In 1994, a valveless nozzle pump with an opening angle of 70.5° was presented [8,9]. The pump worked in the opposite direction and was compared to the valveless diffuser pump presented earlier, which had its forward direction in the direction of the diverging wall. In the diffuser pump, diffuser elements were used as rectification elements. Wear and fatigue were therefore eliminated since the diffuser pump had no moving parts and the risk of valve clogging was also reduced.

In general, a common micropump scheme is a reciprocating diaphragm with two passive check valves [10–12]. Other schemes include diffusers [13,14], electrohydrodynamics [15,16], rotary pumps [17], and gear pumps [18]. In diaphragm pumps, fluidic transport is attained by alternately under-pressuring and over-pressuring the pump chamber, resulting in a supply mode and pump mode, respectively. In these modes, pumping occurs only when the adequacy of pressure difference is produced that overcomes the cracking pressure of rectifying valves. Microactuators are limited by small stroke capabilities, low cracking pressures, reverse leakages, and flow resistances are highly desirable characteristics of check valves. So, Shoji et al. [19] and Smith and Hök [20] have demonstrated valves for use with micropumps; however, both valves have exhibited a certain degree of reverse leakage and had limited flow rates. Modified forms of Parylene check valves [21] satisfied the above requirements and possessed the additional advantage of negligible stiction and surface tension effects. The geometric configuration of a moving membrane element in a check valve, in addition to the low Young’s modulus of Parylene, results in high deflections and a negligible flow resistance. Notably, flow resistance features of the check valve were roughly identical to those of a plain orifice. Unlike valveless pumps, pumps designed with these valves are capable of reverse blocking, even in a neutral state [13–16]. It is also necessary to minimize the pressure required to deflect the pumping membrane. Since only weak forces are available, a membrane material with a low Young’s modulus is optimal. Silicone rubber has a low Young’s modulus, and due to its large elongation properties, it has been utilized as a mem-
brane material in microvalves [22] and micropumps [23]. Thus, large deflections and efficient use of pump chamber volume are achieved. Moreover, the nozzle/diffuser element [6] of a valveless micropump has a net transport of fluid from an inlet to an outlet due to the difference in the flow resistances in the diffuser and nozzle. As passive check valves are subject to wear, clogging, and fatigue [24], nozzle/diffuser elements have recently become common in micropumps. Many micropump systems have been developed by means of various principles of actuation and valve types; however, few studies have examined the effect of asymmetrical flow on pumping performance. In this study a duct channel with a piezoelectric buzzer as a vibrator element was utilized to investigate the effect of flow asymmetry on pumping performance in different asymmetrical situations and asynchronous vibration modes of a vibrator.

2. Numerical method and geometric model

This study performed simulations with the application of CFD-ACE+ software (CFD Research Corporation, Huntsville, AL, USA), a multi-physics package based on Finite-Volume techniques. The program was run on a 2.4-GHz Pentium IV processor with 1 GB of RAM memory. Mesh-independent test runs were performed before the study. An upwind method for solving the quadrilateral grid of 9000 cells was used as the 2D computational domain inside the micro-channel.

Although operated in a laminar flow regime, a fine mesh was needed to accommodate the detailed features of the sorting mechanism. Each run took 2 h to be completed.

A flow model designed with the CFD-ACE+ software was used in the simulation.

2.1. Flow model

The governing equations for the flow model are mathematical statements of mass and momentum conservation laws for flow physics. These two laws can be applied to develop a set of equations (known as the Navier–Stokes equations) that allow CFD-ACE+ to solve a flow model numerically.

For processing the mesh, a quadrilateral grid was made. The convergent condition was assumed to be in the range of $10^{-20}$ for numerical results.

Finally, a sine wave with an amplitude of 10 $\mu$m and a frequency of 10 Hz was used as the vibration mode to imitate the realistic operation of the piezoelectric buzzer. For boundary conditions, the outlet reference pressure was set as zero for gage pressure. In addition, 200 samples in a period (peak to peak) were taken for a time step test of the numerical scheme to ensure inherent stability conditions.

2.2. Geometric model

In this study, the components of the valveless micropump mainly included the duct channel, compression chamber, piezoelectric buzzer, acrylic plates and an inlet/outlet channel. The duct channel, compression chamber and piezoelectric buzzer were then covered with the upper and lower acrylic plates and sealed with glue to produce a complete micropump chip like the one shown in Fig. 1. Here, the transversal flow in the compression chamber would be actuated by the piezoelectric buzzer, and then flow through the connecting duct channel, which induces the longitudinal flow motion due to the periodic vibration of the buzzer. The film of the piezoelectric buzzer, whose diameter and thickness are, respectively, 20 and 0.12 mm, only covered a length of 2 mm for sealing. The total length was 100 mm for one side of the duct channel. In addition, the width, $D$, was set at 1 mm and the depth, $H$, was set at 1 mm for the duct channel. To provide a driving force for the piezoelectric buzzer, a sine wave generated by a function generator (TG1010A), with a resolution of 0.1 mHz and amplified for 50 folds by voltage amplifier (TEGAM 2350), would be utilized to drive transversal flow motion in the compression chamber, resulting in the longitudinal flow motion during the periodic vibration of the buzzer. The input voltage, whose initial value was $7 V$, and the piezoelectric buzzer frequency whose value was 10 Hz, were used to carry out the experiment. Here, the inlet/outlet channel would be connected with the same water tank for decreasing the head loss and increasing the accuracy of the flow rate. Finally, a gas bubble imbedded in the duct channel would be used for the convenience of flow visualization in periodic vibrations.

The Reynolds number, Re, based on the net mass flow and channel width $D$, was set at $Re=0–0.02$. The flow direction along the positive X-axis was set as the forward flow, and vice versa. An index of net mass flow rate was utilized to investigate the effect of longitudinal flow asymmetry and the asynchronous vibration mode of the vibrator on the duct channel. In this study, pure water and methanol at room temperature were used as the model fluids in the simulations. Deionized water was used as a substitute for pure water in this experiment.

To determine the effect of an asymmetrical flow pumping system on the duct channel, a piezoelectric buzzer embedded in the sidewall of the duct channel was situated asymmetrically in the middle of the duct channel. The piezoelectric buzzer was composed of a single phase power supply/function generator (signal input).

To assess the performance of the assembled micropump, a tank was placed at the inlet and outlet to store deionized water. Prior to the test, the duct channel, chamber, and two tubs with an inside diameter of 1 mm were filled with water. The amount of flow pumped could be calculated by measuring the distance of the bubble motion in the duct channel during a specific period.
As for the valveless pumping effect, the Liebau phenomenon is the occurrence of valveless pumping through the application of a periodic source at a place which lies asymmetrically with respect to the system configuration [1,26]. In fact, in 1985 Takagi and Takahashi proposed a model for rigid pipes and verified the occurrence of valveless pumping in real experiments and numerical simulations. This evidence shows that the application of a periodic force which acts asymmetrically gives rise to net flow [27–32]. Hence, the transversal flow asymmetry of the duct channel induced by the Liebau effect would be inferred when the compression chamber flow was driven by a periodic vibration of a piezoelectric buzzer [25]. Regarding the laws of the conservation of mass and energy, when transversal flow of a compression chamber is driven by the piezoelectric buzzer, it induces a longitudinal flow in the duct channel. Therefore, the flow resistance originating from the different pressures in the forward and reverse flow direction at the inlet and outlet of the flow channel would be different because of the occurrence of the Liebau effect. The longitudinal asymmetric flow would transform a potential energy in a timely fashion, e.g., pressure to kinetic energy, and e.g., flow velocity. Finally, the net flow rate would be produced in a periodic actuating process.

3. Results and discussions

Numerous designs for non-moving valves in a pumping system based on changing the flow structure were addressed. Basically, these kinds of valveless pumping systems should originate from the flow asymmetrical features [13–16,27–32]; however, they were rarely noted and addressed. In this study, a duct channel with a piezoelectric buzzer acting as a vibrator was employed to study the effect of flow asymmetry. To assess the transversal asymmetrical effect of the duct flow field induced by the buzzer, two cases with asymmetrical placements of the buzzer (indicated by an arrow) embedded in one sidewall of the duct channel (Fig. 2) were examined first. The flow velocity distribution for cases 1 and 2 both demonstrates an asymmetrical character due to the Liebau effect. The longitudinal asymmetric flow would transform a potential energy in a timely fashion, e.g., pressure to kinetic energy, and e.g., flow velocity. Finally, the net flow rate would be produced in a periodic actuating process.

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Comparing the results of cases 5 and 6, a longitudinal flow asymmetrical phenomenon in case 5 seems to be obvious because the transversal flow asymmetry, originating from the asymmetry in space and time, would be enlarged by the Liebau effect in the periodic vibration. Hence, a better pumping performance would be expected. By contrast, case 6 indicates that the asymmetrical feature of space would be resisted by the symmetry of time for...
Fig. 4. Symmetrical flow velocity distribution versus the out-of-phase (case 3) and in-phase (case 4) vibration modes for the two buzzers embedded in a symmetrical configuration. The red arrow indicates the location of the buzzers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 5. Symmetrical flow velocity distribution versus the out-of-phase (case 5) and in-phase (case 6) vibration mode for two buzzers embedded in an asymmetrical configuration, with respect to the middle of the duct channel. The red arrow indicates the location of the buzzers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 6. The net mass flow rate per cycle changes with time for different locations and vibration modes of the buzzers. Unit of mass flow rate per cycle: kg/s.

...the in-phase vibration mode. Therefore, no net flow volume was obtained [31]. This ratiocination needed to be further confirmed by Fig. 6. The transient phenomena in all cases studied would occur, and the dynamic variations of the flow rate would undergo a transition process, but the flow appears to be in a steady state form after 15 cycles of vibration waves. The lines in cases 1 and 2 have the same values; nevertheless, with opposite signs, since net mass flow rate results from the flow symmetry of the duct channel in specific cases in which the buzzer installation was imbedded. This data demonstrates that the characteristics of the asymmetrical situation of the buzzer in the duct channel would result in a longitudinal asymmetric flow, and a net flow rate would be obtained since the flow in the compression chamber would be transferred into a transversal asymmetrical flow by the Liebau effect in a periodic vibration of the buzzer. In another aspect, the out-of-phase (case 3) and in-phase (case 4) vibration modes of the buzzer situated in the middle of the duct channel show that the flow made by cases 3 and 4 (Fig. 4) did not generate a net mass flow because of the longitudinal flow symmetry. This result indicates that a pumping system with an in-phase vibration mode and a symmetrical situation of the buzzer is also unable to produce a net mass flow [31]. The characteristics of a longitudinal asymmetrical flow originating from the asymmetri-
cal space of an actuator (piezoelectric buzzer) have been observed and experimentally confirmed. Furthermore, the flow rate of case 5 with the out-of-phase vibration mode and asymmetrical situation of the buzzer would double the flow rates of cases 1 and 2. It is crucial to further investigate the physics behind the introduction of the net flow. To address the effect of flow inertia on the mass flow rate, two fluids, pure water and methanol, were used since they have a higher and lower flow inertia, respectively. The results were executed using case 1 and are shown in Fig. 7. The results suggest that the mass flow rate produced by water, which possesses a higher inertia, is larger than that of methanol. Hence, it is logical to presume that a higher inertia flow results in a larger mass flow rate. It then also suggests that flow at a larger Reynolds number will also produce a larger mass flow rate. However, more effort in determining the relation between Reynolds numbers and mass flow rates will be needed to take a further step to accurately determine the magnitude of the effect of inertia on a viscous force. Additionally, to clearly present the correlation between the transversal flow asymmetry induced by an actuator in space and time and the pumping capability, three types of pumping systems, whose amplitude of vibration and driving frequency is 20 μm and 50 Hz, respectively, were used as actuators and are shown in Fig. 8. In this study, a micro-nozzle with a throat width of 500 μm would be applied to the pumping system. Type 1 is a duct channel without a nozzle. Furthermore, type 2 incorporates one nozzle (indicated by the arrow) that is imbedded in one side of the channel. Type 3 indicates that two nozzles (indicated by arrows) are imbedded in the same side of the duct channel. Therefore, the asymmetric phenomenon of type 2 is stronger than that of type 1. Also, the effect in type 3 is stronger than that in type 2. The flow asymmetry would then be used to explain the pumping performance of the duct channel.

The simulation results show that the mass flow rates are $2.8628 \times 10^{-5}$ kg/s for type 1, $1.9740 \times 10^{-3}$ kg/s for type 2, and $6.4262 \times 10^{-3}$ kg/s for type 3. Thus, type 3 produced the largest mass flow rate. This evidence indicates that the more asymmetrical the actuator situation is, the larger the pumping flow rate will be [28]. Also, Fig. 9 shows the mass flow rate produced by different actuator frequencies in case 1. The results shown in Fig. 9 indicate that increasing the vibration frequency will enhance the mass flow rate [26]. Therefore, a more transversal asymmetrical flow in space and time induced by the Liebau effect in the periodic vibration of the buzzer would be transferred into a more longitudinal asymmetrical flow, producing a larger mass flow rate [28]. These experimental
case 1 (Fig. 2). The input signal for the piezoelectric buzzer was con-

stantial and out-of-phase/in-phase vibration mode for the pumping system was investigated to study pumping performance. Useful findings obtained by numerical analysis and confirmed experimentally are as follows.

In view of the conservation of mass and energy, the longitudinal asymmetrical flow which resulted from the transversal asymmetry of space and in time (out-of-phase) would be induced by the Liebau effect in periodic vibration, resulting in a net mass flow and possessing a pumping capability. As the asymmetry of the actuator in space and time is increased, the longitudinal flow asymmetry and the pumping performance also increase. This principle should prove useful when designing valveless pumping systems, especially for applications such as in bio-medicine, bio-chemistry, and environmental testing. Since this pumping system uses simple components and has no moving valve structure, it cannot damage biological particles in the transmission process and is very suitable for bio-applications.

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**References**

[5] V. Tesaf, Fluidic jet-type rectifier: experimental study of generated output pres-
[12] R. Zengerle, A. Richer, H. Sandmaier, A micro membrane pump with electro-
[15] G. Fuhr, R. Hagedorn, T. Muller, W. Benecke, B. Wagner, Water of pumping solu-


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