Journal of Engineering Science and Technology
Vol. 12, No. 2 (2017) 451 - 459

ON THE ANALYSIS OF IMPEDANCE-DRIVEN REVERSE FLOW DYNAMICS

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Abstract

Impedance pump is a simple valve-less pumping mechanism, where an elastic tube is joined to a more rigid tube, at both ends. By inducing a periodic asymmetrical compression on the elastic tube will produce a unidirectional flow within the system. This pumping concept offers a low energy, low noise alternative, which makes it an effective driving mechanism, especially for micro-fluidic systems. In addition, the wave-based mechanism through which pumping occurs infers many benefits in terms of simplicity of design and manufacturing. Adjustment of simple parameters such as the excitation frequencies or compression locations will reverse the direction of flow, providing a very versatile range of flow outputs. This paper describes the experimental analysis of such impedance-driven flow with emphasis on the dynamical study of the reverse flow in open-loop environment. In this study, tapered section with converging steps is introduced at both ends of the elastic tube to amplify the magnitude of reverse flow. Study conducted shows that the reverse peak flow is rather significant with estimate of 23% lower than the forward peak flow. The flow dynamics on the other hand has shown to exhibit different characteristics as per the forward peak flow. The flow characteristics is then studied and showed that the tapered sections altered the impedance within the system and hence induce a higher flow in the reverse direction.

Keywords: Impedance-driven, Reverse flow, Dynamics.

1. Introduction

Impedance pump is a type of valve-less pumping device, in which it utilizes a bio-inspired mechanism for pumping of fluid, based on resonant wave interactions along an elastic tube [1]. By inducing a periodic asymmetrical compression on the elastic tube will produce a unidirectional flow due to the mismatch of fluid impedances within

Nomenclatures

A_i	cross-sectional area of adapter, where *i*=1,2,3,4, m^2
C	tube elasticity, $m^5\ N^{-1}$
L	fluid inductance, $N\ s^2\ m^{-5}$
P_i	fluid pressure within adapter, where *i*=1,2,3,4, $N\ m^{-2}$
P_n	normalized pressure head
Q_n	normalized flow rate
r	nominal radius of elastic tube, m
R	fluid resistance, $N\ m^{-5}$
S	fluid reactance, $N\ m^{-5}$
v_i	fluid velocity within adapter, where *i*=1,2,3,4, $m\ s^{-1}$
Z	fluid impedance, $N\ m^{-5}$

Greek Symbols

α	Womersley number
μ	coefficient of fluid viscosity
ρ	density of fluid
ω	angular excitation frequency

the system [2-10]. The first demonstration of valve-less pumping through an impedance pump, was demonstrated by Liebau [11, 12] in 1954, using an elastic tube connected to reservoirs at different heights.

Hickerson [5] in 2005, conducted a comprehensive experimental study on impedance pump performance, demonstrating its intrinsic behaviours. It showed that an open-loop system can create and sustain a pressure head, and that an elastic material is not a necessary condition for impedance-driven flow. Following Hickerson’s work in 2005, Bringley et al. [6] in 2008, performed an experimental study, and formulated a simple mathematical model, described by ordinary differential equations, which further enhanced the understanding of the flow behaviours, through simple modelling. Jung [13] in 2007, developed a simplified lumped model of impedance pump, in which the system is governed by ordinary differential equations for the study of pressure and flow, with time-dependent elasticity, viscosity and inertia. Timmermann and Ottesen [8] in 2009, performed numerical simulations linking various parameters and showed that the eigenfrequencies of the system constitute the resonant frequencies and the horizontal slope frequencies.

Loumes [10] in 2007, introduced the concept of multilayer impedance pump in which the flow output and inner wall motion are found to be maximal when the pump is excited at the resonant frequency, while only a small excitation is needed to produce a significant flow. Loumes’ work brought a breakthrough in enhancing efficient pumping, where lesser effort is required to generate a similar magnitude of flow. A multi-pincher impedance pump was studied using a one-dimensional numerical simulation by Rosenfield and Avrahami [14] in 2010 and showed that flow rates can be significantly increased when using a sequential array of compression mechanisms operating in resonant frequencies with the appropriate phase between them. Lee et al. [15-18] in recent years developed a two-stage open-loop impedance pump and showed that the flow may significantly improve while maintaining similar energy consumption.

With reference to the current available literatures, most authors reported reversal of flow at lower excitation frequencies. The magnitude of the flow is, however, demonstrated to be very minimal, as compared to the forwarding flow. This paper describes the experimental analysis of such impedance-driven flow with emphasis on the dynamical study of the reverse flow in open-loop environment. Tapered section with converging steps is introduced at both ends of the elastic tube to amplify the reverse flow. The experimental setup for this analysis is explicitly described in the following section.

2. Experimental Methods and Materials

Experimental approach is chosen in this study such that the pump's bulk flow responses can be explicitly measured and analyzed. In this study, the location of compression is fixed at 10% tube length from left end of the elastic tube. The experiment is repeated seven times and averaged data is plotted, with uncertainty measured at 0.2 at resonance. Analyses on pressure-flow of both reversing and forwarding flow are highly emphasized in this work.

The experiment is conducted utilizing a single-stage impedance pump as shown in Fig. 1. The pump consists of two reservoirs with cross-sectional area of 6400 mm^2 and height of 300 mm, a natural rubber latex tube, two tapered sections with converging steps and single compression mechanism. The pump is constructed of one natural rubber latex tube with nominal diameter of 29 mm and thickness of 0.08 mm, held horizontally. The tube's ends are connected to the tapered sections, then fixed and attached to two reservoirs at each end of the tapered sections. Water with standard properties at 25ºC is used as the working fluid. The tapered sections, as shown in Fig. 2, are assembled using a Brass Gas Cylinder Adapter, a PVC Male x Female Reduction Nipple, and a PVC Male Thread Adapter. The compression mechanism is built of a 12 V-DC motor with compression width of 30 mm. Contact between the compression mechanism and tube only happens during compression.

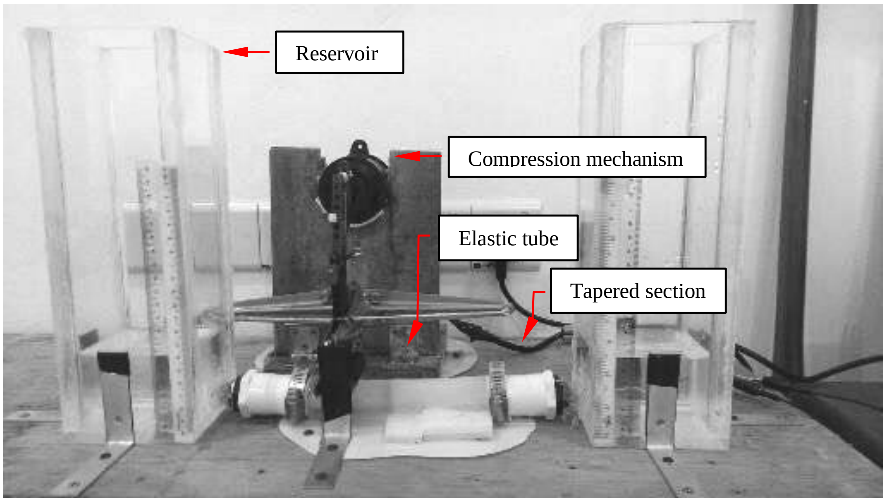


Fig. 1. A single-stage open-loop impedance pump.

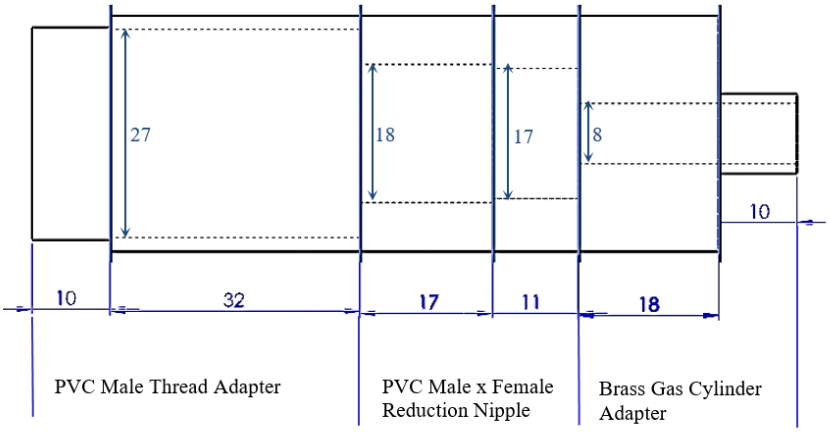


Fig. 2. Converging tapered steps (dimensions in mm).

The analyses of the flow dynamics are in its non-dimensional form. The manipulating variable in this experiment are the excitation frequencies, presented as Womersley number, as expressed in Eq. (1)

$$\alpha = r\sqrt{\frac{\rho\omega}{\mu}} \tag{1}$$

Flow rates and pressure heads for excitation frequencies ranging from 10 Hz to 145 Hz are recorded and studied. The flow rates are normalized against the highest flow rate induced, denoting the forward peak flow as one, as expressed in Eq. (2)

$$Q_n = \frac{Q_{instantaneous}}{Q_{forward,maximum}} \tag{2}$$

where $Q_{instantaneous}$ is the instantaneous flow rate and $Q_{forward,maximum}$ is the maximum forwarding flow rate (in the positive direction).

As for the pressure-flow diagram, the normalized flow rates is used and, the pressure heads is normalized against the maximum pressure head obtained where zero flow is reached, as expressed in Eq. (3)

$$P_n = \frac{P_{instantaneous}}{P_{forward,maximum}} \tag{3}$$

where $P_{instantaneous}$ is the instantaneous pressure head and $P_{forward,maximum}$ is the maximum forwarding pressure head (in the positive direction).

Plotting the normalized pressure-flow diagram will enable a more vivid illustration on the significance of flow reversal, in the form of ratio, with respect to the forwarding peak flow.

3. Results and Discussion

The flow rates of a single-stage impedance pump with respect to varying excitation frequencies are measured and analyzed. Figure 3(a) shows the plot of averaged flow rates against excitation frequencies and Fig. 3(b) shows the normalized flow rates against Womersley numbers. Represented in its non-dimensional form Womersley number, reversing flow is observed at $\alpha \leq 80$, with an approximate of 23% lower in peak flow as compared to the forward peak flow. In comparison to Lee et al. [18], with rather comparable experimental setup, lower reversing flow was observed at the similar Womersley number of 55 with only an approximate of 20% of the forward peak flow magnitude was recorded. In this setup, with tapered sections of converging steps introduced, the reversing flow is significantly augmented with estimated increase of 75% in its magnitude.

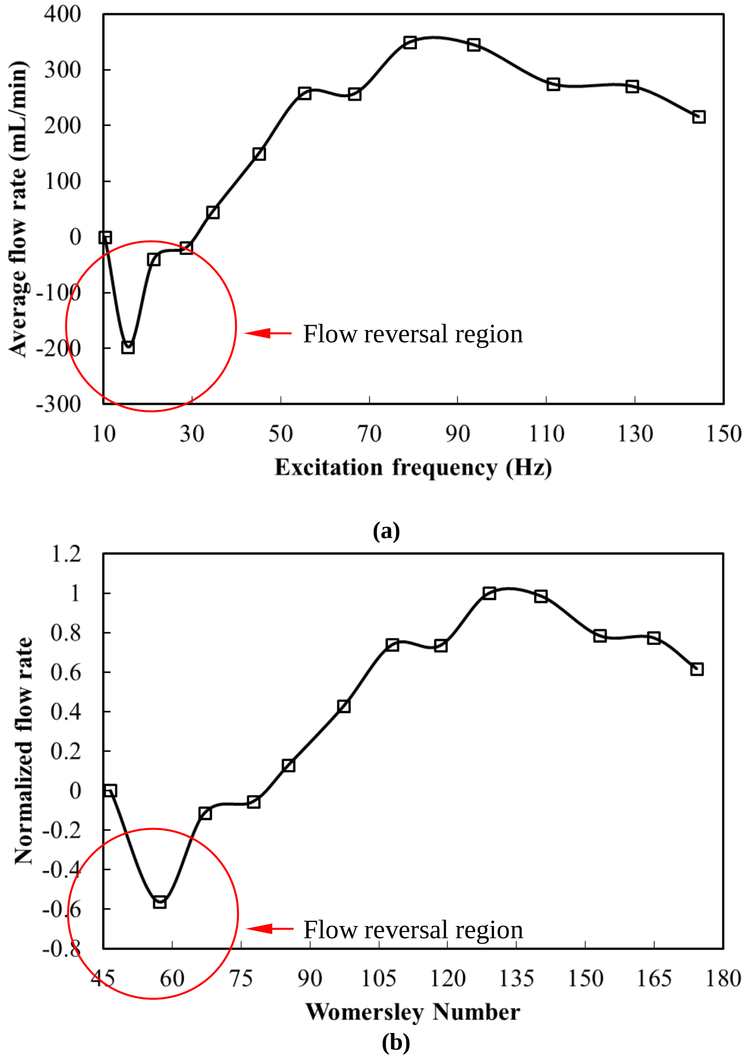
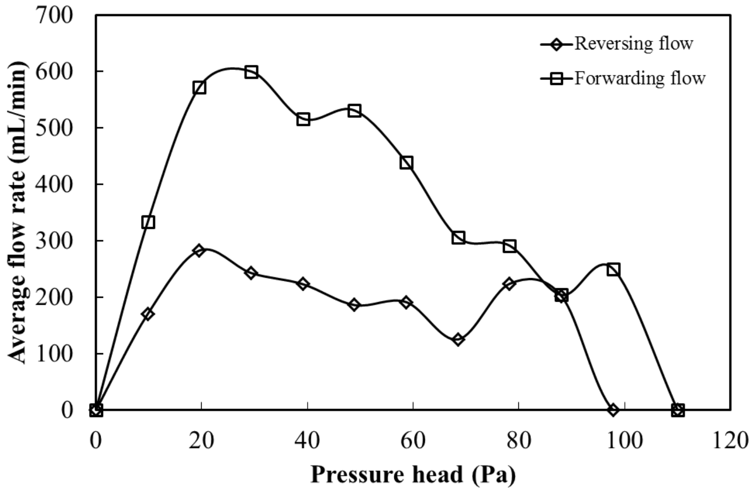
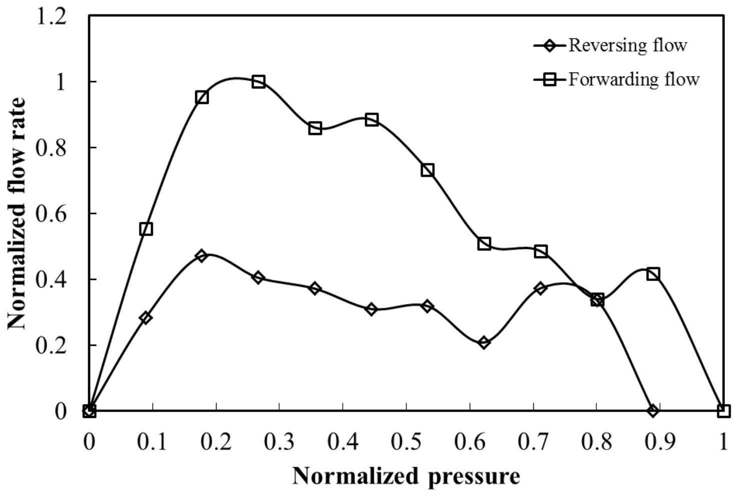


Fig. 3. (a) Avearged flow rates against excitation frequencies and (b) Normalized flow rates against Womersley numbers.

The flow characteristics of the reversing and forwarding flow are highly emphasized as shown in Fig. 4(a) the average flow rates against the pressure heads and Fig. 4(b), in its non-dimensional form, the normalized flow rates against the normalized pressures. In Fig. 4, it is shown the both flow exhibits rather similar pressure-flow pattern. The reversing flows shown to exhibit lower pressure heads attained as compared to the forwarding flow. The dynamics of the reversing flow is however shown to be fluctuating along the normalized flow of 0.33, with maximum flow rate of 0.45 and minimum of 0.2 are recorded. For the forwarding flow on the other hand has an obvious increase in flow at normalized pressure of 0.2. The lowest flow recorded for a forwarding flow is 0.33.



(a)



(b)

Fig. 4. (a) Avearged flow rates against pressure heads and (b) Normalized flow rates against normalized pressures for reversing and forwarding flow.

Based on the observation, it may therefore be deduced that for a reversing flow, the stability of flow is less and with high fluctuation. This phenomenon may due to the drastic shift of impedance diffence along the elastic tube, in particular the alteration of the fluid impedances in the tapered sections. This phenomenon is best described using Eq. (4). The effect of impedance has also been widely discussed in [19].

$$Z = R + iS \tag{4}$$

where *Z* denotes the fluid impedance; *R* is the fluid resistance, in the form of fluid viscosity; and *S* is the fluid reactance, a hindrance towards oscillating fluid wave.

The tapered sections, serve as a step-up controller to alter the characteristic impedance within the system, in which the impedance mismatch between the elastic tube and reservoir can be significantly increased, hence a greater reversal of flow is observed. This is made possible due to the transition of fluid reactance. Fluid reactance is expressed as,

$$S = \omega L - \frac{1}{\omega C} \tag{5}$$

where it is driven by both fluid inertia and elasticity of tube. As the tapered sections are made of solid material, hence the elasticity component in the equation can be taken out, leaving only

$$S = \omega L \tag{6}$$

As the fluid inertia is purely dependent on the excitation frequency, therefore, is can be assumed that the fluid reactance effect is neglibile at low excitation frequencies. This leaves Eq. (4) with only a single fluid resistance component. With reference to Fig. 5 and Continuity Equation, the following expressions can then be established,

$$\begin{aligned} &A_1 v_1 = A_2 v_2 = A_3 v_3 = A_4 v_4 \\ &\text{where } A_1 > A_2 > A_3 > A_4 \\ &\text{hence } v_4 > v_3 > v_2 > v_1 \\ &\text{and } P_1 > P_2 > P_3 > P_4 \end{aligned} \tag{7}$$

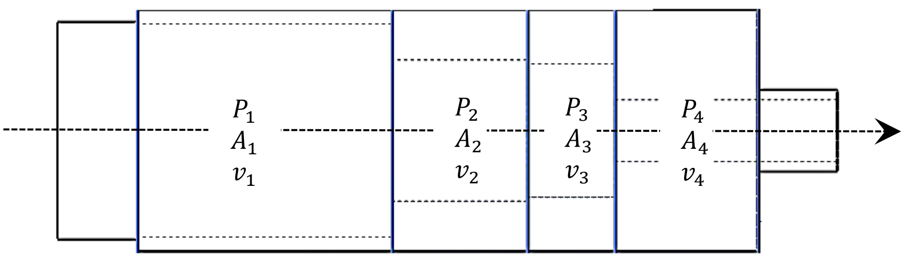


Fig. 5. Direction of flow in the converging tapered steps.

With larger ΔP_{1-4}, a higher velocity is induced. Hence, a higher reverse flow is demonstrated. However, it should be noted that a mismatch between ΔP_{atm-4} and ΔP_{1-4} may occurs, hence fluctuation of flow is observed. As opposed to the conventional uniform diameter adapter where only ΔP_{atm-1} existed, hence a more stable flow is observed.

4. Conclusions

In this study, tapered sections with converging steps are introduced into the conventional system as reported in Refs. [15-18]. As conclusing remark, the introduction of tapered sections with converging steps has greatly enhance the magnitude of the reversing flow. The reversing flow is shown to be greatly enhanced with 75% higher as compared to Ref. [18]. The reverse peak flow is recorded to be 23% lower than the forward peak flow. In addition, the reversing flow has also shown to be fluctuating, as a result of drastic shift of impedance diffence along the flexible media, in particular the alteration of the fluid impedances in the tapered sections.

Recommendation for Future Work

Initial experiments were conducted in work to study the effect of tapered sections on impedance-driven flow dynamics. A more systematic step up/down ratio of tapered sections can be further studied for optimized flow outputs.

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