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EXPERIMENTAL STUDIES OF NOZZLE/DIFFUSER MICROPUMPS USING ENHANCEMENT STRUCTURE

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ABSTRACT

This study conducts an experimental study concerning the improvement of nozzle/diffuser micropump design subject to enhanced structures. A total of three micropumps, including two enhancement structurs having two-fin or obstacle structure and one conventional micro nozzle/diffuser design. It is found that the pressure drops across the designed micro nozzles/diffusers are increased considerably when the obstacle or fin structure are added. The resultant maximum flow rates are 42.08 mm^3/s and 50.15 mm^3/s for conventional micro nozzle/diffuser and added two-fin structure in micro nozzle/diffuser operated at a frequency of 350 Hz. It is found that the mass flowrate for two-fin design surpasses that of conventional one when the frequency is below 400 Hz but the trend is reversed with a further increase of frequency. This is because the maximum efficiency ratio improvement for added two-fin is appreciably higher than the other design at a lower operating frequency. In the meantime, despite the efficiency ratio of the obstacle structure also reveals a similar trend as that of two-fin design, its significant pressure drop (flow resistance) had offset its superiority at low operating frequency, thereby leading to a least flowrate throughout the test range.

Keywords: Micro pump, diffusers, nozzles, Enhancement, Pressure drop.

NOMENCLATURE

A	Cross sectional area (m^2)
C	Perimeter (m)
Dh	Hydraulic diameter (m)
f	Friction factor
H	Depth (m)
L	Length (m)
$\dot{m}$	Mass flowrate (kg/s)
Re	Re number
$\bar{u}$	Mean velocity (m/s)
V	Velocity (m/s)
W	Throat width (m)
x	Position from the neck (m)
θ	Opening angle (deg)
α	Aspect ratio
μ	Dynamic viscosity (N-s/ m^2)
η	ratio of the loss coefficient of nozzle and diffuser
ε	static rectification efficiency
ξ	Total pressure loss coefficient
ρ	Density (kg/m^3)
ΔP	Pressure drop (Pa)

Subscripts and Superscripts

1	Region 1
2	Region 2
3	Region 3
x	Position of neck
d, diff	Diffuser
n, nozzle	Nozzle
+	Positive
-	Negative

INTRODUCTION

Micro-pump is an essential key component in microfludic systems. Active valve having actuator is often adopted in the micro-pump design. However, concerns of clogging, wear, and fatigue of the active valve is always a problem in designing the micro-pump. Hence, a novel idea with valve-less diffuser pump was first proposed by Van De Pol [1]. Stemme and Stemme [2] later made the concept a step forward into a workable and practical micropump. Unlike those using passive check valves [3-4] or active check valves [5-6], the design uses diffusers as flow directing elements. Wear and fatigue in the valves are eliminated since the diffuser elements have no moving parts. The risk of clogging is also reduced. The valve-less diffuser pump consists of two diffuser elements connected to a pump chamber with an oscillating diaphragm. The key components of the micropump are the flow directing diffuser elements. Despite its simple and robust nature, the nozzle/diffuser micropump suffers from low efficiency. In this regard, it is of crucial importance to seek some augmentation to improve the efficiency for this kind micro-pump. However, the published literature about the micro nozzle/diffuser is mainly focused on the manufacturing technology as well as its performance [7-8] or on simulating the performance of micropump [9-10] with micro nozzle/diffuser valve. Yet there is very rare attention toward the improved performance using enhanced structure. Yang et al. [11] characterizes and analyzes the performances of five micro diffusers/nozzles of having enhancement structures with one of conventional micro nozzle/diffuser valve. The maximum improvement of the loss coefficient ratio is about 16 %. However, this study is applicable only to valve performance. The objective of is study is to incorporate the associate concepts into micropumps, examining the performance of the micropumps subject to these enhancement.

EXPERIMENTAL SETUP

A total of three types of micro nozzle/diffuser and implemented into the micropump. The geometries of the test micro- diffuser/nozzle structure and their detailed dimensions are show in Fig. 1. Figure 1(a) denotes the conventional design with an opening angle of 20 ° opening angle, Fig. 1(b) is the two-fin structure with the same opening angle, and Fig. 1(c) is with the obstacle structure. The test samples were fabricated using the deep reactive ion etching (DRIE). The SEM photo showing the fabricated sample is given in Fig. 2. The inlet and outlet hole are drilled using laser machining on glass wafer. Finally the silicon wafer is anodically bonded to the glass wafer.

The test samples were then placed at a test rig to examine its performance. A schematic of the test rig is shown in Fig. 3. The main objective of the experimental setup is to measure the total pressure drop across the nozzle/diffuser. The test facility is based on a one-through design, and water is used as the working fluid. A syringe is used to store water and maintain the pressure of the system. During the experiment, water flows in series to a infusion pump (KDS, Model 100, that provides flow rates from 0.1 μL/hr to 519 mL/hr), a filter and check valve, the test section, and finally into a beaker seated upon an electronic balance (AND Model GF2000, with weighing capacity up to 2100 g and its minimum weighing value of 0.01 g). Measurements of the water flow rate were double-checked constantly by catching-and-weighting scheme at the outlet of the test apparatus. The pressure drop across the test section is measured by a precision differential pressure transducer (YOKOGAWA EJA110A differential pressure transducers having an adjustable span of 1300 to 13000 Pa). The system pressure is measured by an accurate pressure transducer (YOKOGAWA FP101 pressure transducers). Notice that the uncertainties of the pressure transducer, differential pressure transducer are 0.5% and 0.3%, respectively. The system temperature is measured by a resistance temperature device (RTD). The RTD was pre-calibrated by a quartz thermometer with a calibrated accuracy of 0.1 ºC. In the experiment, the derived typical uncertainty of the pressure loss coefficient is less than 5%. The total pressure drop ΔP of micro nozzle/diffuser is often in terms of the pressure loss coefficient ξ, i.e.

$$\Delta P = \xi \times \frac{1}{2}\rho \bar{u}^2 \tag{1}$$

The most common way to evaluate the micropump performance is via efficiency ratio of the nozzle/diffuser element as follows

$$\eta = \frac{\xi_{nozzle}}{\xi_{diff}} \tag{2}$$

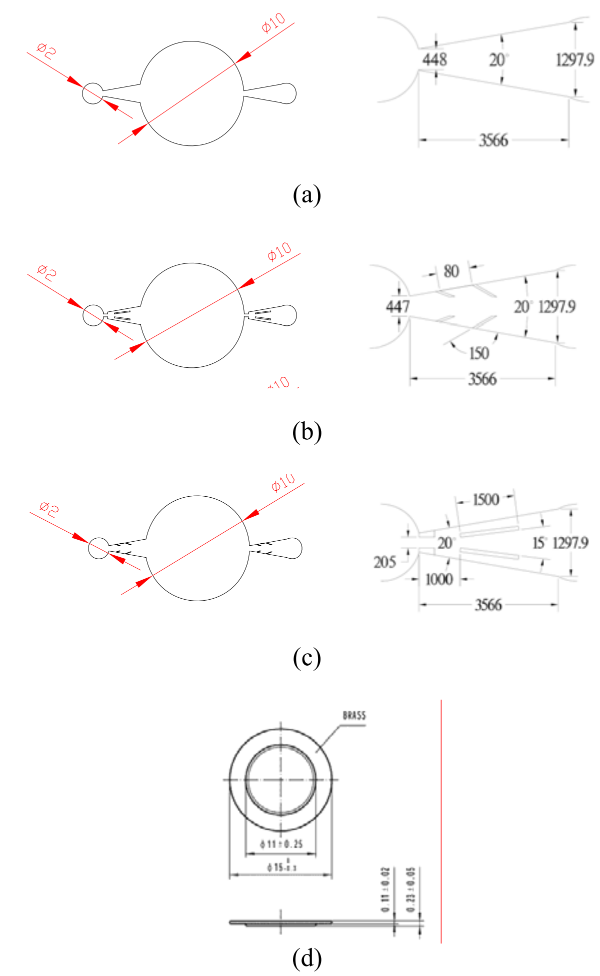

Fig. 1. Detailed geometry of the test micro nozzle/diffuser and piezoelectric disks

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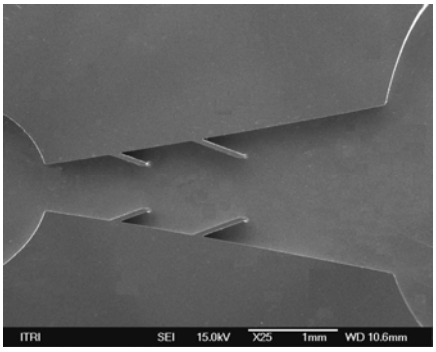
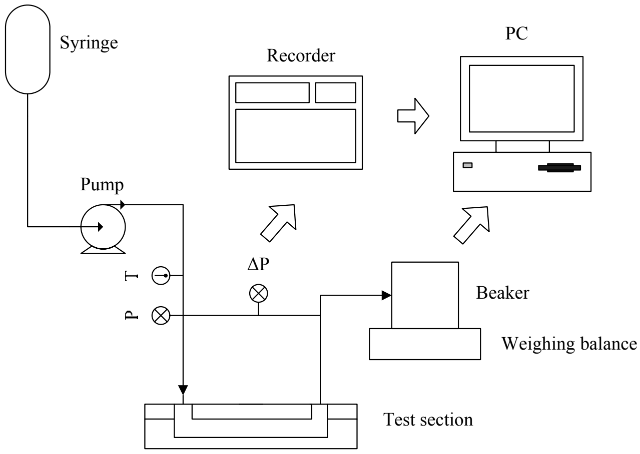
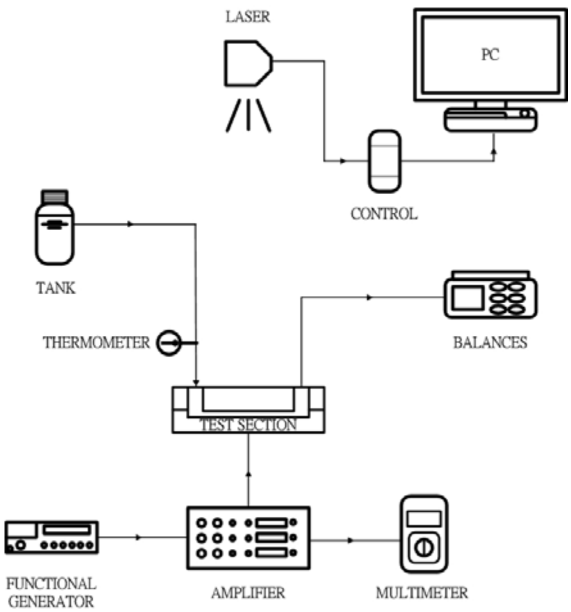


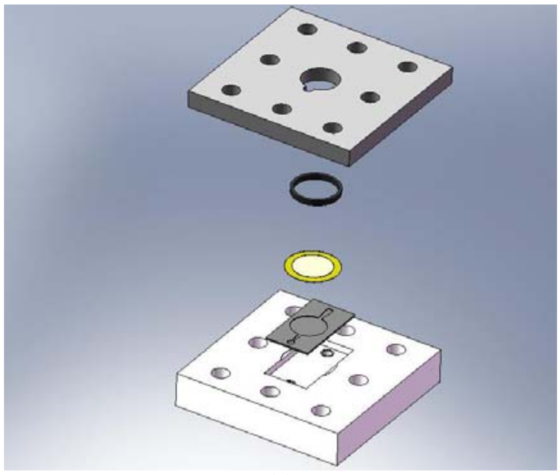
Fig. 2. The SEM photo of obstacle tested sample.



(a)



(b)



(c)

Fig. 3. Schematic diagram of the experimental setup of (a)micro nozzle/diffuser (b)micropump (c)test section.

The schematic of the mircopump testing facility is shown in Fig. 3(b). A function generator (GW Instek, GFG-8216A with controlled frequency ranging from 0.3Hz to 3MHz) is used to generate control signal for the piezo element. The generated signal is further amplified by an amplifier (Piezomechanik Gmbh, SVR500-3). The corresponding voltage is from -100 to 500 V. The amplitude of the piezo membrane can be measured by laser displacement sensor (Keyence, LK-G30) with measurement range of ± 5 mm and an accuracy of ± 0.01μm). The mass delivered by the micropump is measured by a precision electronic balance (A&D, GF-2000, with minimum detectable mass weight of 0.01g). The measured mass weight is then divided by the collected time to become mass flowrate.

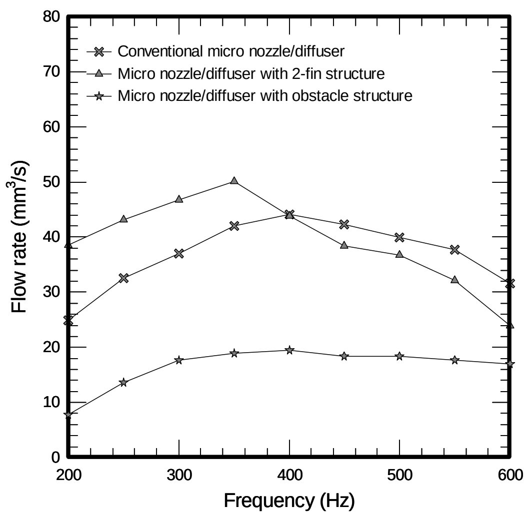


Fig. 4. Frequency vs. flow rate for micropumps.

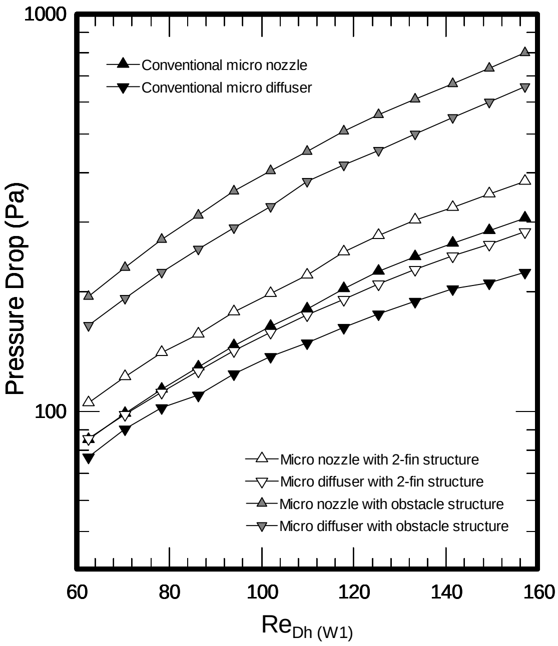


Fig 5. Pressure drop vs. Reynolds number for micro nozzle/diffuser.

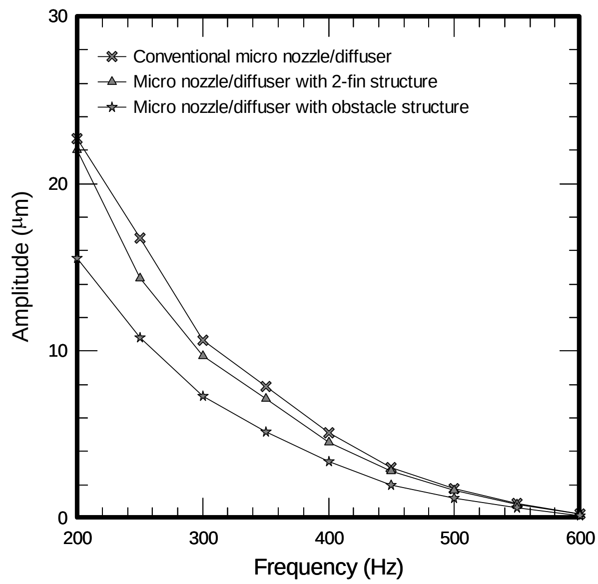


Fig. 6. Frequency vs. amplitude for conventional micro nozzle/diffuser.

RESULTS AND DISCUSSION

Test results of mass flowrate vs. frequency for all the test micropumps are plotted in Fig. 4 at a fixed voltage of 50 V. As depicted in the figure, the flowrate for all three micropumps is firstly increased with the rise of frequency and peaks at a frequency around 350~400 Hz. The corresponding maxima for the conventional, two-fin, and obstacle structure are 42.08 mm^3/s, 50.15 mm^3/s and 18.96 mm^3/s, respectively. However, the obstacle structure shows the smallest flowrate among the test samples. In the meantime, the flowrate for the two-fin structure exceeds that of conventional design when the frequency is below 400 Hz but is lower than the conventional one when the frequency surpasses 400 Hz. Apparently, the performance of micropumps is related to the micro structures. Firstly, the presence of enhanced structure like the present two-fin structure or obstacles will give rise to more pressure drops. This can be made clear from Fig. 5 where the obstacle cast significant pressure drop, followed by the 2-fin structure and conventional comes in third. The much higher pressure drop leads to a sharp rise of flow resistance, thereby reducing the vibrating amplitudes. Accordingly, the smallest flowrate is encountered for the obstacle structure. Upon this situation, the maximum amplitude of conventional micro nozzle/diffuser and added obstacle structure are 22.69 μm and 15.56 μm.

However, as opposed to the added obstacle structure in micro nozzle/diffuser, despite the pressure drop for the 2-fin structure still exceeds that of conventional one, the flowrate for the two-fin design is superior to the conventional one when the operating frequency is below 400 Hz. For further comparison of the performance for the test samples, the pressure drops are then in terms of dimensionless efficiency ratio vs. the Reynolds number. The Reynolds numbers are based on throat width of the test samples without enhancement. Test results are shown in Fig. 7, the ordinate of the figure is η/η_{no1}. A value above unity indicates that the efficiency ratio for enhancement design exceeds that of conventional nozzle/diffuser at the same Reynolds number. The results shown in this figure denotes that the micro nozzle/diffuser with adding fins shows considerable improvement in performance at low Reynolds number region. The maximum efficiency ratio improvement is about 15 %. As a consequence, the added two-fins structure in micro nozzle/diffuser shows a higher mass flowrate when the frequency is below 400 Hz. However, in conventional micro nozzle/diffuser, the loss coefficient for the nozzle at the exit is higher due to free jet flow accompanied with some additional pressure recovery for diffuser, leading to a higher efficiency at the higher Reynolds number region [7]. In the meantime, as shown in Fig. 5, the added fin offers additional pressure as compared to the conventional design. This is more pronounced when the Reynolds number is increased. In summary of these effects result in a higher mass flowrate for the conventional design at the higher operating frequency.

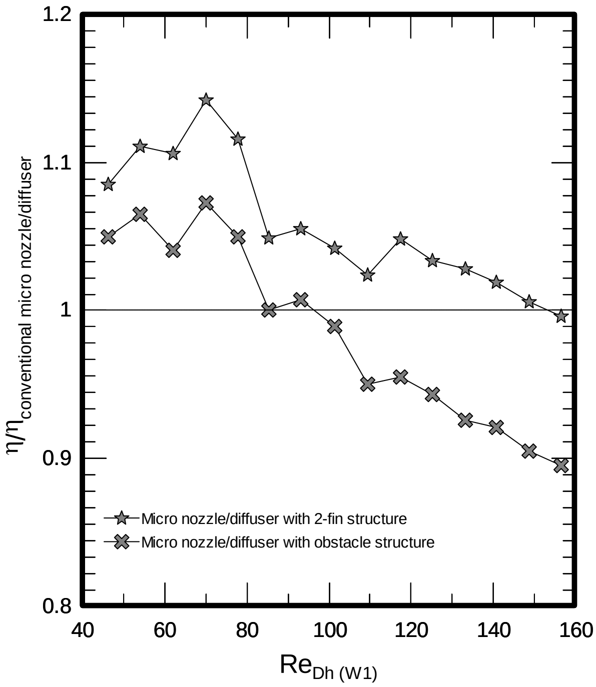


Fig. 7. The efficiency ratio between conventional micro nozzle/diffuser vs. Reynolds number.

CONCLUSIONS

This study characterizes and analyzes the performances of micro pumps with two types of enhancement structures, including one two-fin and obstacle structure, and the conventional micro nozzle/diffuser design. The pressure drops across the designed micro nozzles/diffusers are found to be increased considerably when the obstacle and fin structure are added. The resultant maximum flow rates are 42.08 mm^3/s and 50.15 mm^3/s for conventional micro nozzle/diffuser and added two-fin structure in micro nozzle/diffuser operated at a frequency of 350 Hz. It is found that the flowrate for the two-fin design is higher than the conventional one when the frequency is below 400 Hz whereas the trend is reversed when the frequency is above 400 Hz. This is because the maximum efficiency ratio improvement for added two-fin is appreciably higher than the conventional one at a lower operating frequency but the trend gradually reduced when the operating frequency is further increased. In the meantime, despite the efficiency ratio of the obstacle structure also reveals a similar trend as that of two-fin design, its significant pressure drop (flow resistance) had offset its superiority at low operating frequency, thereby leading to a smallest flowrate throughout the test range. Upon this situation, the maximum amplitude of conventional micro nozzle/diffuser and added obstacle structure are 22.69 μm and 15.56 μm.

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