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Performance Comparison between Planar and Pyramidal Microdiffuser for Valveless Micropump

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Abstract The microdiffuser is the most important component of the valveless micropump and its design plays a role in the valveless micropump performance to direct the flow in a proper direction. A planar microdiffuser valveless micropump has been compared with a pyramidal microdiffuser valveless micropump using 3-D CFD simulations. Both planar and pyramidal microdiffuser has a throat hydraulic diameter of 0.6865*mm* and diffuser half angle of 6.65°. The dynamic mesh was applied under different actuation frequency of the micropump diaphragm (8, 50, 100, 200, 500, 1000, and 2000*Hz*). The net flow rate and the rectification efficiency were calculated for the two valveless micropumps. The results showed that the pyramidal microdiffuser performance was better than the planar microdiffuser for frequency $f \geq 200Hz$ as the net flow rate generated by pyramidal microdiffuser was higher than that by planar microdiffuser. The highest net flow rate of 18.3$\mu L/min$ was achieved by the pyramidal microdiffuser at rectification efficiency of 0.35% and actuation frequency of 2000*Hz.*

Keywords: Valveless Micropump, Microdiffusers, CFD Simulation, Rectification Efficiency

1. Introduction

A micropump as an internal flow system often utilizes microdiffusers to decelerate the flow to recover static pressure and direct the flow in the proper direction. Based on the Bernoulli's principle the function of a microdiffuser is to recover the pressure across the gradually enlarged cross-sectional area by transforming the kinetic energy into potential energy. The performance of the microdiffuser is mainly depending on the microdiffuser rectification efficiency χ. The three main types of valveless microdiffusers are planar, pyramidal, and conical as shown in Fig. 1. The best conical microdiffuser is 10 to 80 percent longer than the best planar microdiffuser under the same inlet working conditions (White, 1986). Therefore, according to space limitation the planar microdiffuser performance is better than conical microdiffuser.

In the recent years, some of research efforts have been performed to study the planar microdiffuser element for valveless micropump (Chen-li and Zone Han, 2007; Olsson et al., 1997; Olsson et al., 2000). Because of the design complexity of micropumps and limited knowledge of the device physics on microscale (Wang et al., 2006), little work was performed to investigate the pyramidal microdiffuser and its rectification efficiency comparing with planar microdiffuser.

The work presented here is a full 3-D CFD simulation of a complete assembled micropump utilizing two different micro-valves. The coolant net outlet flow rate as the most important objective for internal flow systems such as micropumps has been calculated and the rectification efficiency for each microdiffuser type has been investigated in relation to the flow rate. The simulation has been performed applying dynamic mesh under constant diaphragm deflection amplitude of

6μm and different actuation frequency of (8, 50, 100, 200, 500, 1000, and 2000Hz).

2. Diffuser-nozzle element

2.1 Rectification efficiency

The rectification efficiency χ of the microdiffuser is the most effective parameter on the micropump flow rate among other factors such as deflection amplitude and oscillation frequency of the diaphragm (Singhal et al., 2004). The rectification efficiency of a micropump is the ability of the micropump to direct the flow in a certain direction. The higher rectification efficiency gives the better flow directing ability of the micropump.

$$x = \frac{(Q_+ - Q_-)}{(Q_+ + Q_-)} \tag{1}$$

where Q_+ and Q_- are the flow rate in the positive and negative direction respectively.

2.2 Microdiffuser-micronozzle efficiency

The microdiffuser-micronozzle efficiency η is defined as the ratio of the total pressure loss coefficient for flow in the negative direction ξ_{neg} to that for the flow in the positive direction ξ_{pos}.

$$\eta = \frac{\xi_{neg}}{\xi_{pos}} \tag{2}$$

where the total pressure loss coefficient for the flow through a gradually expanding diffuser, gradually contracting nozzle, or sudden expansion or contraction in an internal flow system is defined as the ratio of pressure drop ΔP to the velocity head upstream through the device (Stemme and Stemme, 1993).

$$\xi = \frac{\Delta P}{\frac{1}{2}\rho \upsilon_{throat}^2} \tag{3}$$

2.3 Flow governing equations

The equations of motion for three dimensional, incompressible, viscous, and unsteady state flow in Cartesian (x-y-z) co-ordinates have been used to simulate the laminar flow inside the valveless micropump (Versteeg and Malalasekera, 1995).

3.3.1 Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho U) = 0 \tag{4}$$

3.3.2 Navier-Stokes Equations

x-momentum

$$\frac{\partial(\rho u)}{\partial t} + \nabla \cdot (\rho u U) = -\frac{\partial P}{\partial x} + \nabla \cdot (\mu \nabla u) \tag{5.1}$$

y-momentum

$$\frac{\partial(\rho v)}{\partial t} + \nabla \cdot (\rho v U) = -\frac{\partial P}{\partial y} + \nabla \cdot (\mu \nabla v) \tag{5.2}$$

Z-momentum

$$\frac{\partial(\rho w)}{\partial t} + \nabla \cdot (\rho w U) = -\frac{\partial P}{\partial z} + \nabla \cdot (\mu \nabla w) \tag{5.3}$$

where P, ΔP, U, μ, ρ, and ∇ are pressure, pressure difference, velocity vector ($=ui + vj + wk$), dynamic viscosity, fluid density, and standard spatial grad operator respectively.

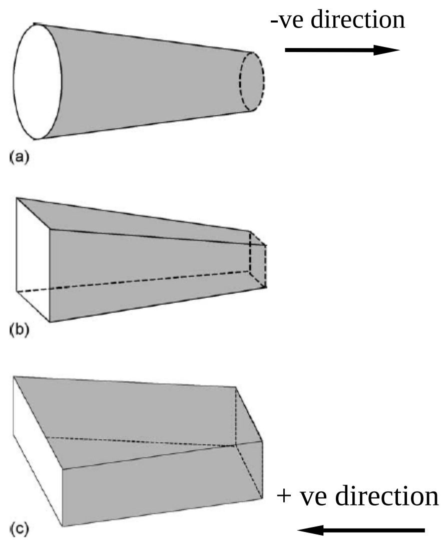

Fig.1. Schematic of (a) conical, (b) pyramidal, (c) planar microdiffuser elements (Singhal et al., 2004).

3. Models Geometry

The micropump model used in this study consists of a pump chamber, microdiffusers, a diaphragm and actuator. The isometric view is depicted in Fig. 2 and the geometric dimensions of the micropump models are illustrated in Table 1. The only difference between the two micropump models is the microdiffuser type.

4. CFD Simulation

To run the simulation for the current study the Fluent solver (FLUENT, 2005) has been used to solve the flow after generating the 3-D geometry and the mesh by Gambit as an operator interface (GAMBIT, 2005). The mesh for the planar microdiffuser type consists of 342199 cells and for the pyramidal microdiffuser type consists of 325779 cells.

The inlet and outlet boundary condition have been set to be inlet-vent and outlet-vent respectively. All the walls of the micropump have been set to be fixed except for the diaphragm which is an oscillating wall governed by the compiled user defined function. The working fluid is water in liquid phase at 25°C. The flow is assumed to be unsteady, viscous, and laminar with no slip conditions near the walls. The time step size Δt for unsteady flow has been set to change according to the frequency f change and the number of time steps N by applying the relation (Yao et al., 2007).

$$\Delta t = \frac{1}{f \times N} \tag{6}$$

The micropump diaphragm assumed to oscillate in a sinusoidal fashion and simulated by:

$$y(r,t) = (1 - \frac{\pi r}{D}) \times A \sin(2\pi f t) \tag{7}$$

where y, r, t, A, D, and f are maximum deflection, the radial distance, flow time, initial deflection amplitude, diaphragm diameter, and frequency respectively.

Table 1
Geometric dimensions of the micropump (dimensions in *mm*.)

	Planar	**Pyramidal**
In/out chamber length	3.95	3.95
In/out chamber width	1.6	1.6
Throat hydraulic diameter	0.6865	0.6865
Diffuser wide port width	1.6	1.6
Diffuser half angle	6.65	6.65
Pump chamber diameter	6.0	6.0
Base groove diameter	5.0	5.0
Base groove height	0.1	0.1
Actuator diameter	5.0	5.0
Micropump size(L*W*T)	22.4*6.0*1.6	22.4*6.0*1.6

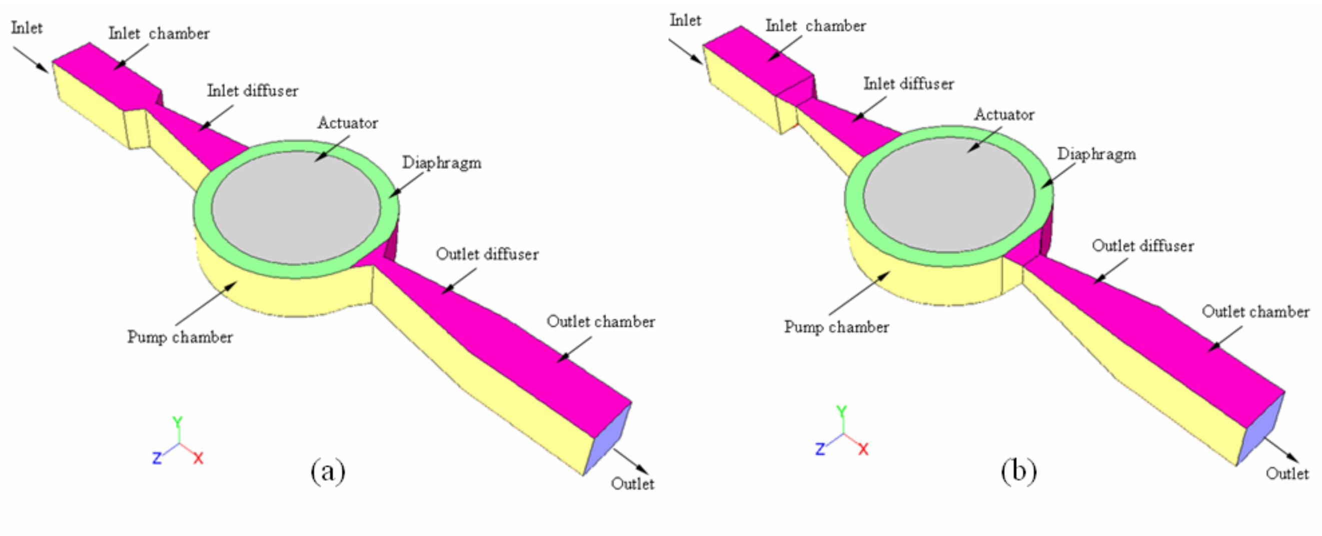

Fig. 2. Isometric view of the Micropumps: (a) planar microdiffuser type, (b) Pyramidal microdiffuser type.

4.1 Validation

The CFD simulation by Fluent solver has been validated by the flow visualization from the experimental work of (Chen-li and Zone Han, 2007). A combined structure and unstructured mesh of 53173 elements has been used to perform the simulation. The inlet boundary condition set to be pressure inlet of 550pa gauge pressure, the outlet boundary condition set to be pressure outlet of 0pa gauge pressure and Reynolds number was 20.2. The streamtraces resulted from CFD work showed a reasonable qualitative and quantitative agreement with that from experimental work as shown in Fig. 3 and Table 2.

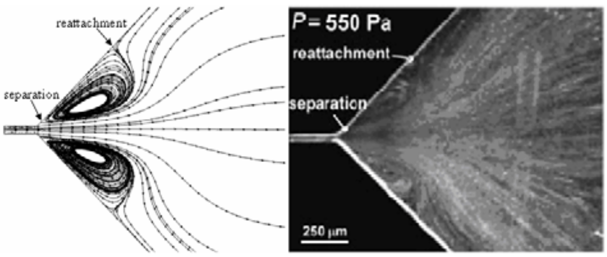

Fig. 3. Diffuser flow separation comparison.

Table 2
Separation and reattachment point locations
(measured from diffuser throat)

	Separation (μm)	Reattachment (μm)
Experimental	60	810
CFD	66	840

5. Simulation Results and Discussion

To compare the performance of planar and pyramidal diffuser micropump the net flow rate $\dot{Q}_{net}$ and the microdiffuser rectification efficiency x have been calculated for different actuation frequency during a complete oscillating cycle (pump phase and supply phase). For the first half of the oscillation cycle (pump phase) under the maximum downward deflection of the diaphragm; according to the pump principle (Stemme and Stemme, 1993); the micropump should conduct more flow through the outlet port than that through the inlet port. In contrast, for the second half of the cycle during supply phase the micropump should provide more flow through the inlet port than that through the outlet port when the maximum diaphragm deflection occurred upward.

5.1 Flow rate and rectification efficiency

The net flow rate was calculated as the difference between the outlet and the inlet flow rate through the whole micropump. At low frequency $f \prec 200Hz$ the planar microdiffuser achieved higher net flow rate. At frequency $f \geq 200Hz$ as shown in Fig. 4 the pyramidal microdiffuser generated higher net flow rate. This is because the square cross section achieves better flow-directing effect for the diffuser element than the rectangular cross section (Peter W. Rundstadler et al., 1975). The pyramidal microdiffuser maximum net flow rate was 18.3$\mu L/min$ which was 63.2% higher than that for planar one (6.73$\mu L/min$).

The rectification efficiency at different frequencies reveals that at high frequency $f \geq 200Hz$ the pyramidal microdiffuser rectification efficiency is high comparing with the planar microdiffuser. The maximum rectification efficiency was 0.351$\%$ for the pyramidal microdiffuser and 0.304$\%$ for planar microdiffuser which was 13.4$\%$ less than that for the pyramidal one as depicted in Fig. 5.

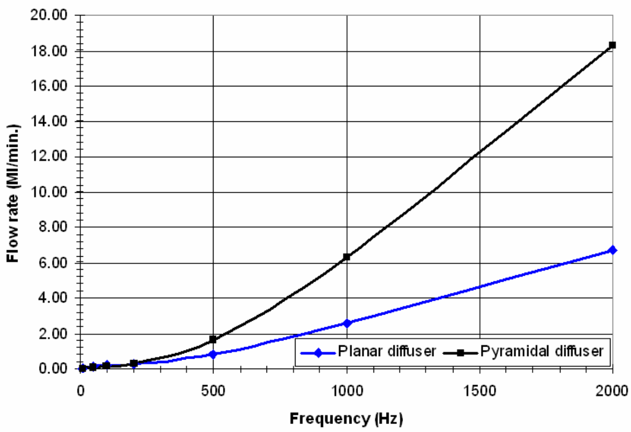

Fig. 4. Net flow rate at different frequencies.

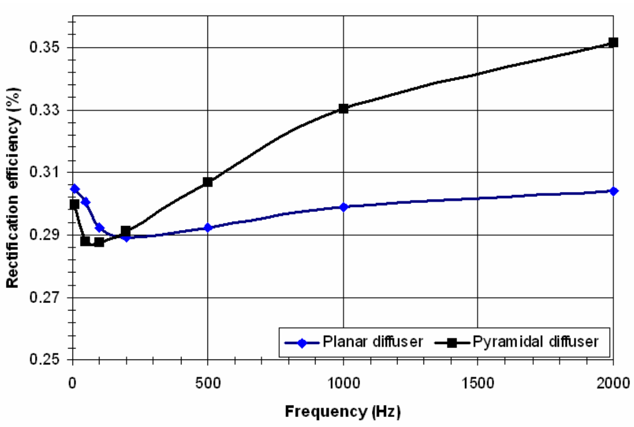

Fig. 5. Micropump rectification efficiency vs. frequency.

6. Conclusions

The performance comparison between the planar and pyramidal microdiffuser has been performed using 3-D CFD simulation. Based on the simulation results for 6μm maximum diaphragm amplitude and different actuation frequencies (8, 50, 100, 200, 500, 1000, and 2000*Hz*), the net flow rate for both types of microdiffuser increased as the actuation frequency increased. The pyramidal micro-diffuser gave better performance for valveless micropump comparing with the planar microdiffuser. At actuation frequency of 2000*Hz* the pyramidal microdiffuser gave 13.4*%* higher rectification efficiency and 63.2*%* higher net flow rate respectively.

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