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Numerical Studies of Curved-walled Micro Nozzle/Diffuser

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***Abstract*—In this study, commercially available software CFD was adopted for analyzing the performance of straight-walled and curved-walled micro nozzle/diffuser. Such nozzle/diffuser was used in valve-less micro-pumps. This model tested different types of nozzle/diffuser and the results showed that the pressure loss coefficient for nozzle/diffuser decreases with the increase of Reynolds number. At the same Reynolds number, the pressure loss coefficient for nozzle is higher than that of the diffuser. At a given volumetric flow rate, the pressure loss coefficient and ratio of pressure loss coefficient for curved-walled nozzle/diffuser are slightly higher than that of the straight-walled nozzle/diffuser. In this study, the numerical data was found good agreement with previous analytic solution and experimental results.**

Keywords-Fluent, Nozzle, Diffuser, Pressure loss coefficient, Reynolds number

I. INTRODUCTION

Computational Fluid Dynamics, Theoretical Fluid Mechanics and Experimental Fluid Mechanics have been the master stream of studying the Fluid Mechanics recently. In 1995, Gerlach and Wurmus[1] presented the performance analysis of nozzle/diffuser, they utilized anisotropic etching to fabricate nozzle/diffuser on silicon wafer and detect nozzle/diffuser have different qualities when the Reynolds is larger than 100. In 1996, Olsson et al.[2] brought up the analysis for pressure loss of micro nozzle/diffuser, they separate the total pressure loss into three sections in chief. And in 1999 [3]and 2000[4] they utilized the lumped-mass model and Finite Element Method to analyze the nozzle/diffuser of valve-less pump and imitated the properties of the fluid passing through the cross-section of diffuser separately. It shows that the efficiency for diffuser increases with the decrease of a cone's angle and the enhancement of the length.

In 2004, Yang et al.[5] obtained the pressure loss coefficient by analysis and experiment, they find that the pressure loss coefficient decreases with the increase of Reynolds number. According to the results, they assumed that the "backflow" will be generated when the open angle is greater than 20° of micro diffuser and this phenomenon let the pressure loss coefficient increase and reduces the performance of the diffuser. In the same year, Wu et al.[6] directly examine and discuss the performance of micro nozzle/diffuser, it shows the nozzle/diffuser with curved-walled($y = ax^{5/3}$) has smaller pressure loss coefficient and higher ratio of pressure loss coefficient.

This paper adopts FLUENT for numerically analysis and collocates the GAMBIT to analyze the properties for different border types of nozzle/diffuser, and discusses the relationship between pressure loss coefficient and ratio of pressure loss coefficient at different Reynolds number. The border types include both the straight-walled and curved-walled. The application need in the fabrication of micro nozzle/diffuser from this study.

II. THEORY

Micro nozzle/diffuser are used to replace the moved-valve in valve-less pump, rely on the different pressure between the nozzle and diffuser to make the flow running, as shows in Figure 1. From Figure 2, when the incompressible flow throws the nozzle/diffuser, the generated pressure can separated into three sections. Region 1 is the inlet, region 2 is the internal part and region 3 is the outlet. Furthermore, the total pressure drop of the nozzle/diffuser is shown in Equations (1) and (2) respectively.

$$\Delta P_{diffuser} = \Delta P_{d,1} + \Delta P_{d,2} + \Delta P_{d,3} \quad (1)$$

$$\Delta P_{nozzle} = \Delta P_{n,1} + \Delta P_{n,2} + \Delta P_{n,3} \quad (2)$$

According to the Bernoulli equation, the relative equation between two different cross-sections of the incompressible flows flowing in the tube can be written as simplification, like as equation (3). ρ is the density, V is the velocity.

$$\frac{P_1}{\rho} + \frac{V_1^2}{2} = \frac{P_2}{\rho} + \frac{V_2^2}{2} \quad (3)$$

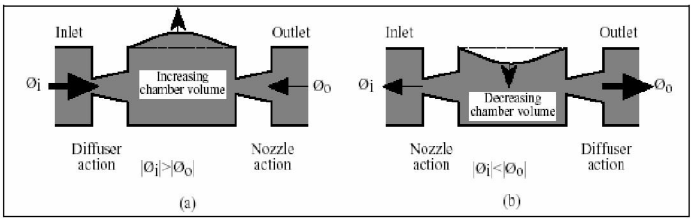

Fig. 1 Operation of the diffuser-based pump: (a) supply mode; (b) pump mode

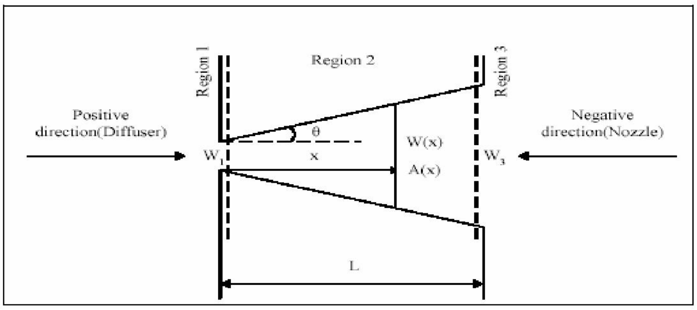

Fig. 2 The schematic of micro nozzle/diffuser element.

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TABLE I. GEOMETRICAL DIMENTION OF MICRO NOZZLE/DIFFUSER

The formula of straight-walled border：$W(x)=W_1+2x\tan(\theta)$				
θ	**5°**	**10°**	**15°**	**20°**
Width of the outlet, W_3 (μm)	824.9	1358	1907.6	2484
Curved-walled(1)：With the same width of inlet(W_1) and outlet(W_3) Width of the midpoint：$W_2=1/2(W_1+W_3)-1/4(W_3-W_1)$				
Types	**5°**	**10°**	**15°**	**20°**
W_2 (μm)	431.2	564.5	701.9	846
Curved-walled(2)：With the same width of inlet(W_1) and the same volume Boundary formula：$W(x)=W_1+2(ax^{5/3})$				
a	**1/1780**	**1/884**	**1/582**	**1/428**
W_3 (μm)	1001.1	1711.8	2444.4	3216
W_1=300 μm，Legth=3000 μm, Depth=135 μm				

In terms of the pressure loss coefficient, the pressure drop can be written as

$$\Delta p = \xi \times \frac{1}{2}\rho \bar{u}^2 \tag{4}$$

ξ is the pressure loss coefficient, Δp is the pressure drop, ρ is the fluid density and $\bar{u}$ is the mean flow velocity throw the narrowest cross-section. The ratio of pressure loss coefficient is shown as equation (5) and it defines the flow directing capability.

$$\eta = \frac{\xi_{nozzle}}{\xi_{diff}} \tag{5}$$

Because the cross-section area of the nozzle/diffuser is not the same, we should consider the change of the cross-section. The effective width of x location is shown as below, W_1 is the width of the inlet,

$$W(x) = W_1 + 2x\tan(\theta) \tag{6}$$

Besides, we also consider the hydraulic diameter(D_h) and velocity($V(x)$) of the x location. We can get the pressure drop of x location at region 2, Δp_x, like as equation (7).

$$\Delta p_x = \int_0^1 2 f_f(x) \frac{1}{D_h(x)} \rho V^2(x) dx \tag{7}$$

$f_f(x)$ is the Fanning friction factor for Cross-section at x location and the friction factor is $4f_f$.

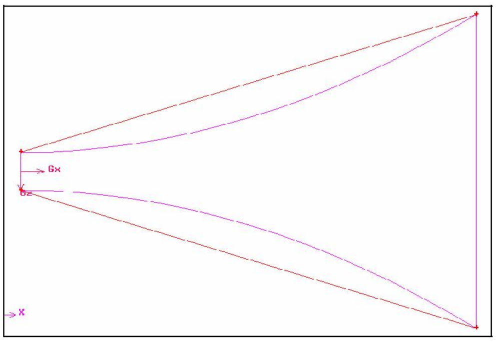

Fig. 3 The diagram of the straight-walled and curved-walled micro nozzle/diffuser with the same width of inlet and outlet.

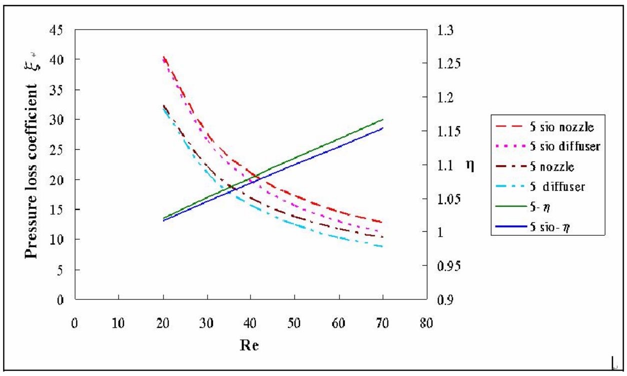

Fig. 4 The relationship between pressure loss coefficient and Reynolds number at the open angle is 5° with the same width of inlet and outlet.

Using the Reynolds number into the pressure loss coefficient; we can get the relationship between the pressure loss coefficient and the Reynolds number.

$$\zeta = \frac{2\Delta P}{\frac{\mu^2}{\rho D_1^2}\mathrm{Re}_1^2(1-\frac{A_1^2}{A_2^2})} \tag{8}$$

Re_1 is the Reynolds number of the inlet, D_1 is the hydraulic diameter of the inlet, A_1 and A_2 is the corss-section area of the inlet and the outlet respectively.

III. SIMULATION

A. Model Building

At first, using the GAMBIT to build the 3-D model of nozzle/diffuser, the geometrical diameter is divided into 3 different types in Table I.

1. Straight-walled.
2. Curved-walled (1): the same width of inlet and outlet as straight-walled.
3. Curved-walled (2): the same width of inlet and the same volume as straight-walled.

B. Boundary setting

Adopting the Segregated Method of FLUNT software to assays the velocity and the difference of pressure. The boundary conditions of the model are set as steady flow, laminar flow and continuum flow. Besides, the pressure, density and viscosity coefficient are 101325 Pa, 1.1496 kg/m^3 and 1.84166e^{-05} kg/m-s respectively. However, we assume 6 different flow rates, 4, 6, 8, 10, 12 and 14 ml/min separately for analyzing.

IV. RESULT AND DISCUSSION

A. With the same width of inlet(W_1) and outlet(W_3)

Figure 3 shows the shapes of the straight-walled and curved-walled micro nozzle/diffuser with the same width of inlet and outlet(Table II). The relationship between the Reynolds number and pressure loss coefficient with the same

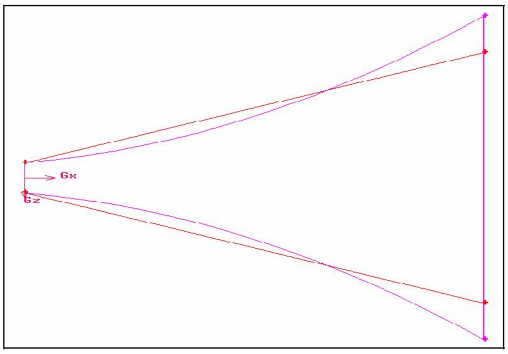

Fig. 5 The diagram of the straight-walled and curved-walled micro nozzle/diffuser with the same width of inlet and the same volume.

width of inlet and outlet is shown in Figure 4, and we can find the pressure loss coefficient of the nozzle/diffuser decrease with the increase of Reynolds number, but the ratio of pressure loss coefficient is quite the contrary. It also shows that the straight-walled micro nozzle/diffuser has smaller pressure loss coefficient and higher ratio of pressure loss coefficient than the curved-walled one.

B. With the same width of inlet(W_1) and the same volume

Figure 5 is the shapes of the straight-walled and curved-walled(2) micro nozzle/diffuser with the same width of inlet and the same volume. The relationship between the Reynolds number, pressure loss coefficient and ratio of pressure loss coefficient with the same width of inlet and the same volume is shown in Figure 2. We can find the pressure loss coefficient of the nozzle/diffuser decreases with the increase of Reynolds number and the ratio of pressure loss coefficient increases with the increase of Reynolds number.

Although the curved-walled one has higher pressure loss coefficient but the ratio of pressure loss coefficient of the curved-walled micro nozzle/diffuser is still higher than straight-walled one in Figure 6. Table II shows the detail data of pressure loss coefficient and ratio of pressure loss coefficient when Reynolds number is 70.

Figure 7~10 show the relationship between pressure loss coefficient and Reynolds number, and we can observe that when the open anger is getting larger, the pressure loss coefficient

TABLE II. RE=70, PRESSURE LOSS COEFFICIENT OF THE MICRO NOZZLE/DIFFUSER

Types / Angle	Straight-walled			
	5°	**10°**	**15°**	**20°**
ξ (diffuser)	8.88	6.15	4.83	3.97
ξ (nozzle)	10.35	7.23	5.84	4.96
η	1.166	1.177	1.210	1.247
Types / Angle	**Curved-walled(1) With the same width of inlet and outlet**			
	5°	**10°**	**15°**	**20°**
ξ (diffuser)	11.12	8.61	7.48	6.71
ξ (nozzle)	12.83	9.98	8.73	7.96
η	1.154	1.159	1.169	1.186
Types / coefficient a	**Curved-walled(2) With the same width of inlet and the same volume**			
	1/1780	**1/884**	**1/582**	**1/428**
ξ (diffuser)	9.04	6.76	5.57	4.76
ξ (nozzle)	10.64	8.04	6.81	6
η	1.177	1.189	1.223	1.260

coefficient is getting smaller and while the Reynolds number is larger than 60, the change of curve for pressure loss coefficient becomes more smooth. Besides, we can also know that the curved-walled(2) micro nozzle/diffuser has higher pressure loss coefficient.

C. Analysis of Theory and Experiment

When Re=70, the experimental, theoretical and analytical result of the pressure loss coefficient at open angle 10° in the diffuser of the curved-walled one are 8.78, 8.62 and 8.61 respectively and in the nozzle are 9.21, 9.12 and 9.98 separately, they are all very close to each other.

D. The effect between pressure loss coefficient and Reynolds number

Figure 11~12 show the relationship between the pressure loss coefficient and Reynolds number of the straight-walled and curved-walled micro nozzle/diffuser with same width of inlet and the same volume.

When it's the straight-walled, the pressure loss coefficient

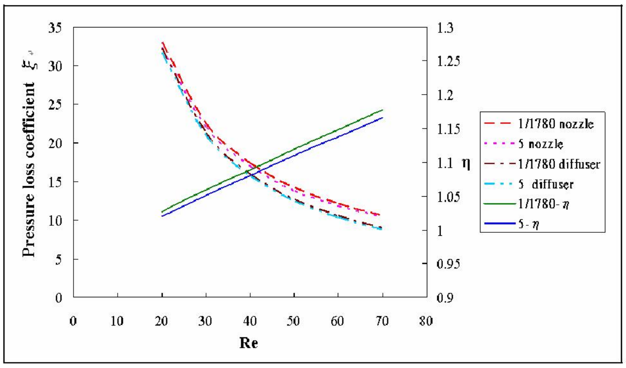

Fig. 6 The relationship between pressure loss coefficient and Reynolds number at the open angle is 5° with the same inlet and the same volume.

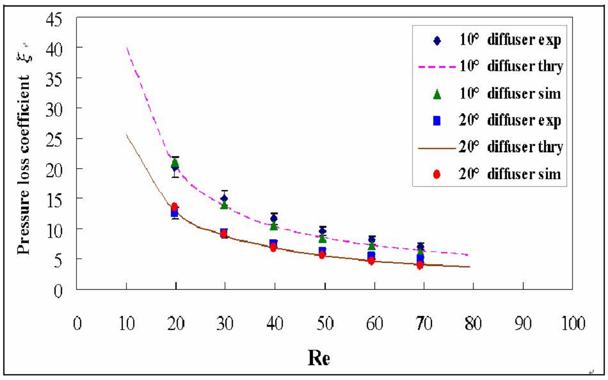

Fig. 7 The relationship between pressure loss coefficient and Reynolds number of the diffuser(straight-walled).

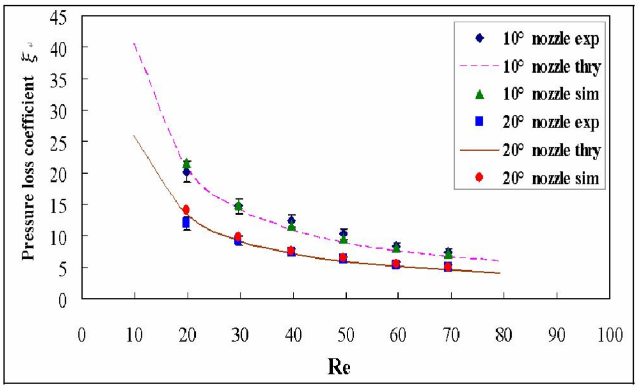

Fig. 8 The relationship between pressure loss coefficient and Reynolds number of the nozzle(straight-walled).

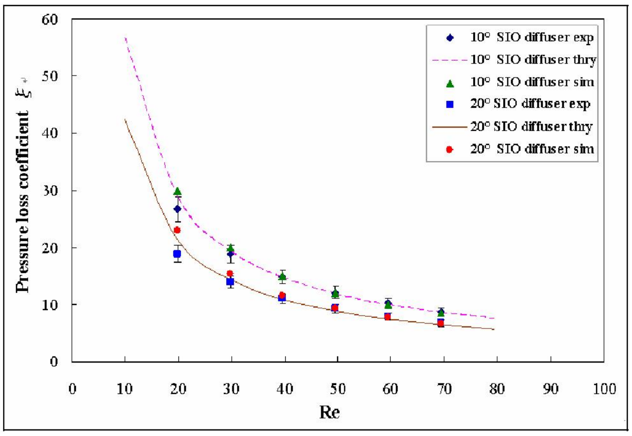

Fig. 9 The relationship between pressure loss coefficient and Reynolds number of the diffuser(curved-walled(1)).

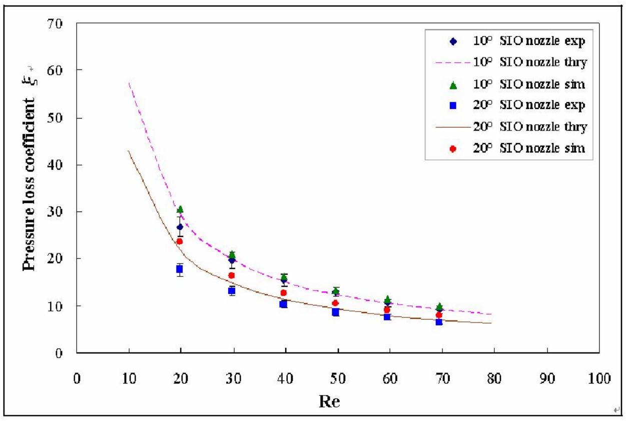

Fig. 10 The relationship between pressure loss coefficient and Reynolds number of the diffuser(curved-walled(1)).

decreases with Reynolds number increase when the Reynolds number is from 300 to 400, however, the pressure loss coefficient increases when Reynolds number is 600 to 1500 as shown in Figure 11. Furthermore, while it is curved-walled micro nozzle/diffuser, the pressure loss coefficient decreases as the Reynolds number is from 300 to 600 and decreases while

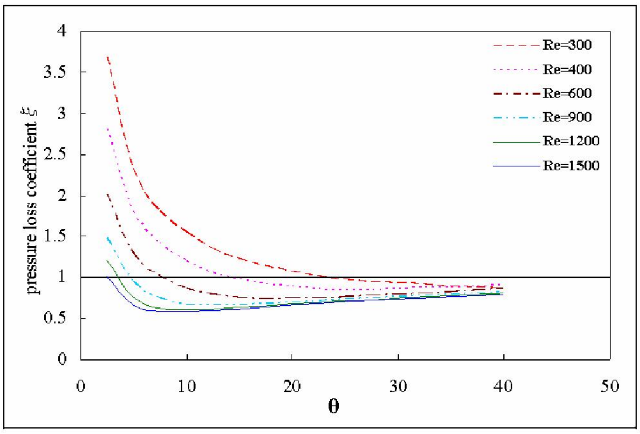

Fig. 11 The relationship between pressure loss coefficient and Reynolds number of the diffuser of the diffuser(straight-walled).

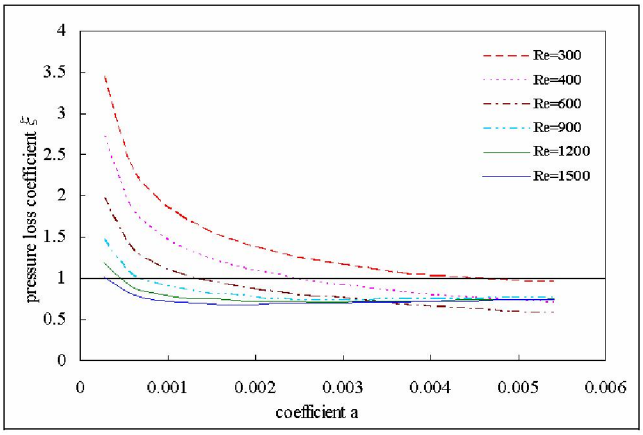

Fig. 12 The relationship between pressure loss coefficient and Reynolds number of the diffuser(curved-walled(2)).

it's from 900 to 1500. This phenomenon is because of the "backflow".

V. Conclution

This study utilizes the FLUENT to calculate pressure loss coefficient for straight-walled and curved-walled micro nozzle/diffuser with the same width of inlet and the same volume. This research also provides the basis design and application for valve-less pump in the future. Our major conclusions are summarized as follows.

1. At the lower Reynolds number, the pressure loss coefficient decreases accompany with the increase of the open angle.
2. The curved-walled micro nozzle/diffuser has the higher pressure loss coefficient and higher ratio of pressure loss coefficient, so it can improve the driving flow rate effectively.
3. At the higher Reynolds number, because of the separation and backflow, the pressure loss coefficient of the straight-walled micro nozzle/diffuser increases with the increase of Reynolds number.

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