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TECHNICAL PAPER

Novel no-moving-part valves for microfluidic devices

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Abstract This study characterizes and analyzes the performances of micro diffusers/nozzles with five types of enhancement structures and one of conventional micro nozzle/diffuser valve. The pressure drops across the designed micro nozzles/diffusers are found to be increased considerably when the obstacle and fin structure are added. Further, the micro nozzle/diffuser having added circular area reveals the lowest pressure drop, owing to the hydraulic diameter is increased by circular area and lower interface friction. The maximum improvement of the loss coefficient ratio is about 16% for an added 3-fin structure operated at a Reynolds number around 70. Upon this situation, the static rectification efficiency improves 4.43 times than the conventional nozzle/diffuser. Experimental results indicate the performance peaks at a Reynolds number around 70, and an appreciable decline is encountered when the Reynolds number is reduced. It is due to the efficiency ratio of conventional micro nozzle/diffuser significant increases with the Reynolds number.

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List of symbols

A	Cross-sectional area (m^2)
C	Perimeter (m)
D_h	Hydraulic diameter (m)
f	Friction factor
H	Depth (m)
L	Length (m)
$\dot{m}$	Mass flowrate (kg/s)
Re	Re number
$\overline{u}$	Mean velocity (m/s)
V	Velocity (m/s)
W	Throat width (m)
x	Position from the neck (m)
θ	Opening angle (°)
α	Aspect ratio
μ	Dynamic viscosity (Ns/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

1 Introduction

The micropumps are key microfluidic devices applicable to chemical process control, drug delivery system, and cooling of tiny electrical elements (Ullmann and Fono 2002). The flow directing elements significantly affect the micropump characteristics, yet some active valves (Zdeblick and Angell 1987) and passive valves (Tiren et al. 1989) are normally implemented for flow directing. However, for reliability concern, valveless design such as nozzle/diffuser element (Van De Pol 1989) has been devised. The nozzle/diffuser micro pump uses two specially designed nozzle/diffuser elements (Stemme and Stemme 1993; Gerlach and Wurmus 1995; Jiang et al. 1998) to avoid the exploitation of active or passive valves accompanying with the conventional one, thereby giving it a simple, reliable, and low cost feature. The operational principle of the valve-less micropump is based on the flow characteristic difference between the nozzle and diffuser shown in Fig. 1. The ejected velocity from nozzle is often very high and is regarded as a free jet flow; leading to a greater pressure loss with a higher loss coefficient. In the meantime, normally the loss coefficient of diffuser is less than that of nozzle, hence more fluid flow rate through the diffuser than the nozzle is expected at the same pressure drop across both elements. However, the published literature about the micro nozzle/diffuser is mainly focused on the manufacturing technology as well as its performance (Yang et al. 2004; Chen et al. 2008) or simulating the performance of micropump with micro nozzle/diffuser valve (Yang et al. 2006, 2008). 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 micropump. Unfortunately, very rate attention is made toward the improved performance using enhanced structure. Therefore it is the purpose of this study to experimentally analyze the performance of the micro diffuser/nozzle with certain enhancement structures.

2 Experimental setup

A total of six types of micro nozzle/diffuser were made and tested. The geometries of the test micro diffuser/nozzle structure and their detailed dimensions are tabulated in Table 1. The test samples were fabricated using the deep reactive ion etching. 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 sample was 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/h to 519 mL/h), 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 2,100 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 1,300–13,000 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°C. In the experiment, the derived typical uncertainty of the pressure loss coefficient is <5%.

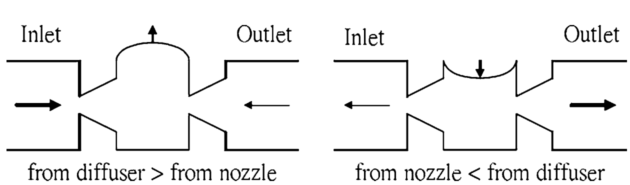


Fig. 1 Operation of the diffuser-based pump: **a** supply mode, **b** pump mode

3 Analysis of the micro nozzle/diffuser

Considering the schematic of the diffuser/nozzle element shown in Fig. 4, the flow inside the diffuser/nozzle is regarded two-dimensional. The pressure drops across the nozzle/diffuser element can be divided into three parts. Namely, the pressure drop at the entrance (region 1), pressure drop within the diffuser/nozzle (region 2), and the expansion loss of the pressure drop at the exit of the nozzle/diffuser (region 3):

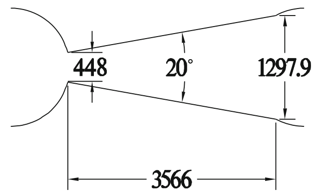
$$\Delta P_{\text{diff}} = \Delta P_{d,1} + \Delta P_{d,2} + \Delta P_{d,3} \quad (1)$$

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

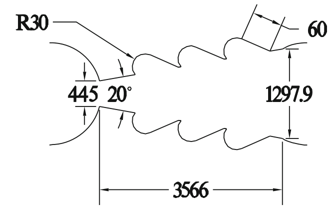
where the subscripts of d and n denote diffuser and nozzle, respectively. For a sharp entrance of the diffuser, ξ is 0.5

Table 1 Detailed geometry of the test micro nozzle/diffuser

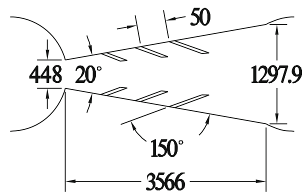
No. 1 Base model



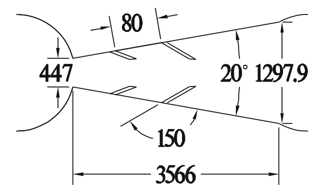
No. 2 Fish-skin



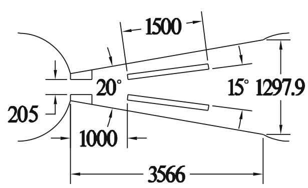
No. 3 3-fin



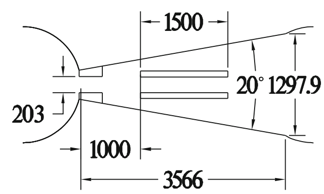
No. 4 2-fin



No. 5 Obstacle I



No. 6 Obstacle II



whereas $\xi = 0.05$ (White 1986) for a smooth round entrance. Similarly, a loss coefficient of 1 (Idelchick 1993) is given at the exit section.

For a rectangular cross section in the diffuser or nozzle, it is essential to consider the influence of the area change. As shown in Fig. 1, the effective width of the diffuser in the x position is

$$W(x) = W_1 + 2x\tan(\theta) \tag{3}$$

where W_1 is the width of the diffuser element at the entrance section. Hence the hydraulic diameter at x is

$$D_h(x) = \frac{4A(x)}{C(x)} = \frac{4W(x)H}{2W(x) + 2H} \tag{4}$$

Note that H is the depth of the diffuser, $A(x)$ and $C(x)$ are the cross-sectional area and the periphery at x location, respectively. The average velocity at x location can be obtained from the continuity equation, i.e.,

$$V(x) = \frac{\dot{m}}{\rho A(x)} = \frac{A_1\bar{u}}{A(x)} \tag{5}$$

where $\dot{m}$ is the mass flowrate, A_1 and V_1 are the cross-sectional area and velocity at the throat position, respectively. Therefore the Reynolds number at x position can be expressed as:

$$Re(x) = \frac{\rho V(x) D_h(x)}{\mu} \tag{6}$$

The pressure drop in the region 2 can be calculated as follows:

$$\Delta P_2 = \int_0^L 2f(x)\frac{1}{D_h(x)}\rho V^2(x)\mathrm{d}x \tag{7}$$

where $f(x)$ is the corresponding Fanning friction factor inside rectangular cross section at x position. Hartnett and Kostic (1989) proposed a simplified polynomial to describe the friction factor for laminar flow through a rectangular channel that is accurate to $\pm 0.05\%$:

$$f = \frac{24\left(1 - 1.3553\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5\right)}{Re} \tag{8}$$

where $\alpha = H/W$ is the aspect ratio of the rectangular section. In the valve-less micropump, the nozzle/diffuser element connected to the fluid cavity volume with an

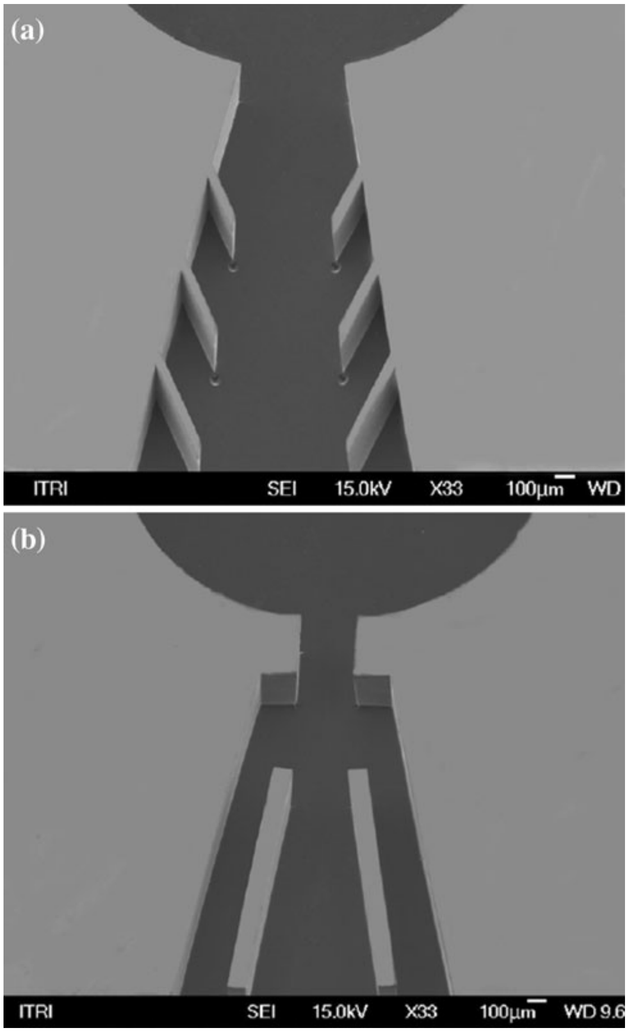


Fig. 2 The SEM photo of **a** No. 3 and **b** No. 5 tested sample

oscillating diaphragm. The total pressure drop ΔP of micro nozzle/diffuser is often presented in terms of the pressure loss coefficient ξ, i.e.,

$$\Delta P = \xi \times \frac{1}{2}\rho\bar{u}^2 \quad (9)$$

The most common modeling and evaluation of micropump performance used efficiency ratio of the nozzle/diffuser element can be expressed as

$$\eta = \frac{\xi_{\text{nozzle}}}{\xi_{\text{diff}}} \quad (10)$$

Another evaluation of micropump performance is termed the static rectification efficiency. It is equivalent to the "pump stroke efficiency" (Gerlach 1998). The static rectification efficiency ε is given as

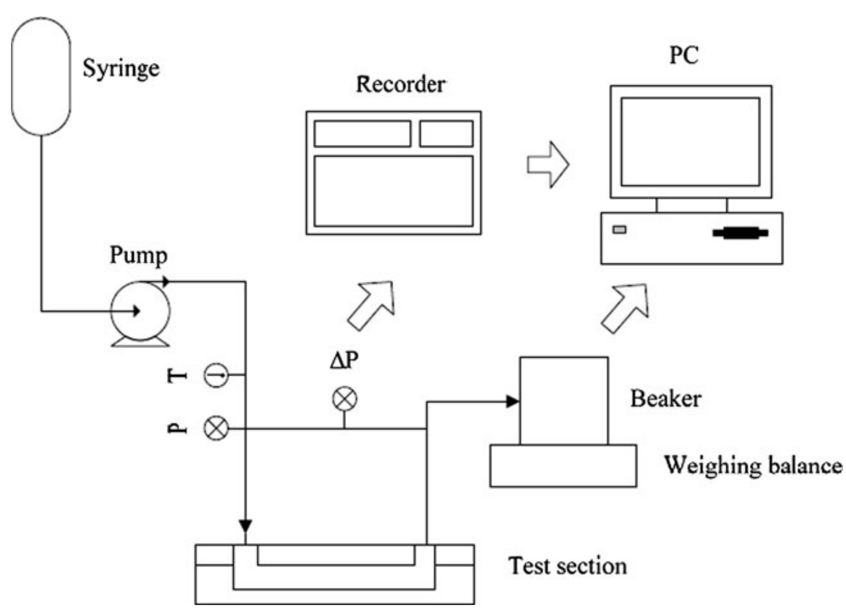
$$\varepsilon(p) = \left.\frac{Q_+ - Q_-}{Q_+ + Q_-}\right|_p = \frac{\eta^{1/2} - 1}{\eta^{1/2} + 1} \quad (11)$$

where Q is the flow rate of the nozzle/diffuser at a pressure P, the flow into the converging diffuser flow is regarded as positive (+) while in the diverging one is negative (−).

4 Results and discussion

Test results of pressure drops versus Reynolds number for all the test samples are plotted in Fig. 5. As expected, the pressure drop increases with the rise of Reynolds number. For the pressure drop among the test samples, it can be found that the pressure drops increase considerably when the obstacle and fin structure are added. However, it should be pointed out that the pressure drops are quite sensitive to the surface structure. For instance, the pressure drops for

Fig. 3 Schematic diagram of the experimental setup



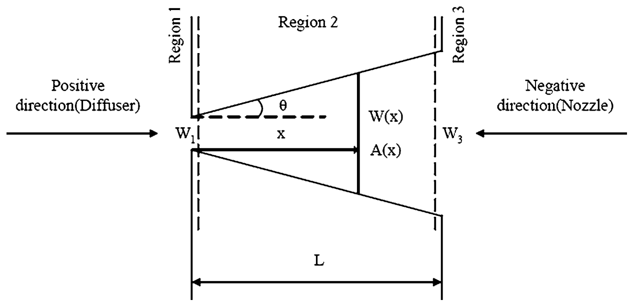


Fig. 4 Definitions of the different regions in the diffuser/nozzle element

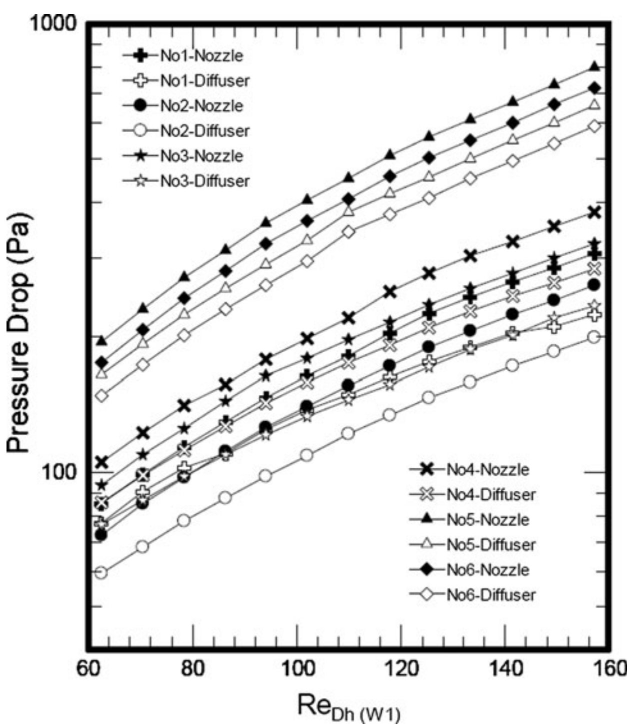


Fig. 5 Pressure drops versus Reynolds number for micro nozzle/diffuser

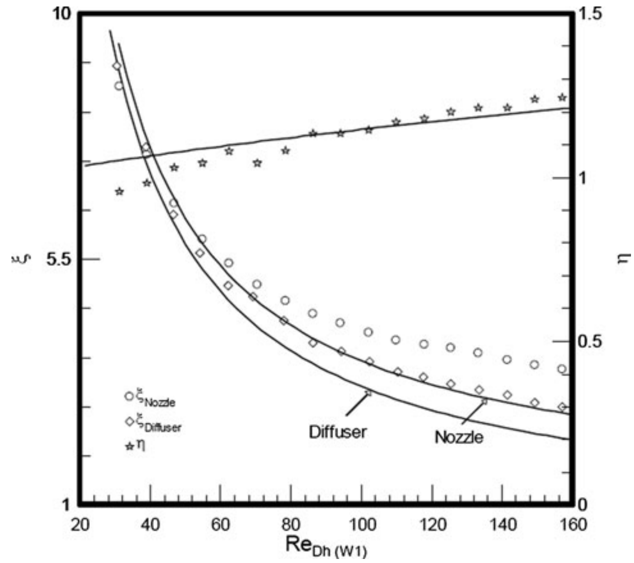


Fig. 6 Pressure loss coefficient and efficiency ratio versus Reynolds number for conventional micro nozzle/diffuser

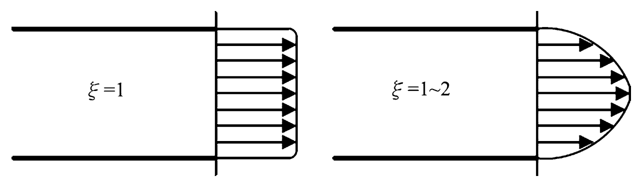


Fig. 7 The resistance coefficient of **a** uniform and **b** parabolic outlet velocity distribution

sample #2, the so called fish-skin surface, reveals a much lower pressure drop than the base model. Apparently, with the fish-skin outward wavy surface, some of the liquid is trapped within this structure, yet it gives rise to lower friction at the interface of this trapped liquid and of the liquid flow in/out of the nozzle/diffuser. Accordingly, one can see a much lower pressure drop of this sample in comparison with other samples. Conversely, the structure employing a fin like design like samples #3 to #6, possesses a higher pressure drop than the base model. This is somehow expected due to the presence of additional fin surface which provides more flow resistance.

As shown in Fig. 6, the pressure drop coefficient and efficiency ratio as a function of Reynolds number are plotted for further comparison against the theoretical analysis and measured data of conventional micro nozzle/diffuser. The results show that the measured pressure loss coefficients are higher than calculated results, the phenomenon is especially pronounced at the higher Reynolds number region. This is due to the theoretical analysis is based on fully developed flow. In practice, in the developing region more pressure drop of the water flow at the higher Reynolds number region is expected. Another possible cause is the loss coefficient that is as high as 1 at the outlet region. As shown in Fig. 7, the loss coefficient is 1 for a uniform velocity distribution at the outlet. However the profile of outlet velocity distribution is actually parabolic that would lead to a higher loss coefficient somewhere between 1 and 2 (Idelchick 1993). In summary of these two effects, one can see the difference amid the measured data and the calculation. Notice that the forgoing effects prevail in both nozzle and diffuser; therefore the efficiency ratio is good agreement between measured data and calculated results as shown in Fig. 6.

For further comparison of the performance for the test samples, the pressure drops are then in terms of dimensionless efficiency ratio versus the Reynolds number. The Reynolds numbers are based on throat width of the test samples without enhancement. Test results are shown in

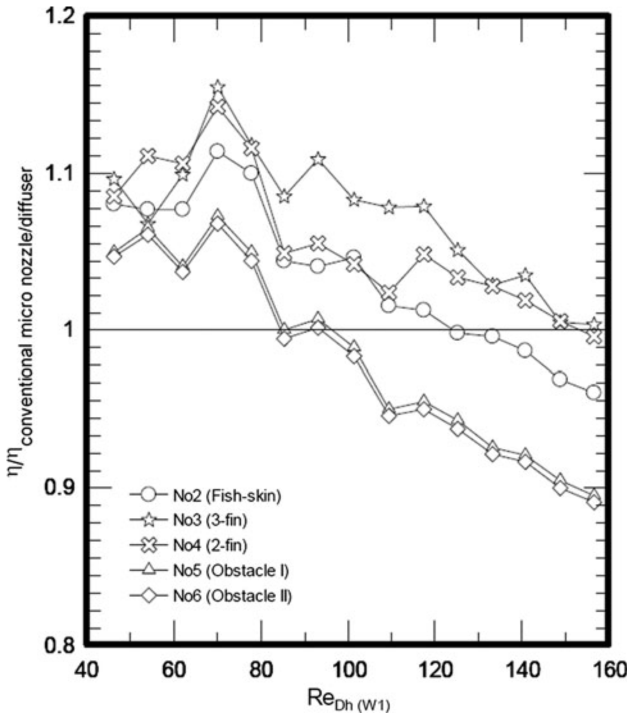


Fig. 8 The efficiency ratio between conventional micro nozzle/diffuser versus Reynolds number

Fig. 8, the ordinate of the figure is $\eta/\eta_{\mathrm{No.\ 1}}$. 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 suggest that the micro nozzle/diffuser with adding fins such as No. 3 and No. 4 shows considerable improvement in performance. The maximum efficiency ratio improvement is about 16% for an added 3-fin operated at low Reynolds number around 70. Upon this situation, the static rectification efficiency of No. 3 is increased over 4.43 times than conventional nozzle/diffuser. For a further decline of the Reynolds number, one can see a detectable decrease of performance when the Reynolds number is lowered than 70. At the first place, the design concept of enhancement is to change the flow direction pertaining to higher flow resistance at the nozzle side while a smaller resistance at the diffuser side. However, in the low Reynolds region, the flow passing through added surface acts like a duct flow (Yang et al. 2007) without appreciable direct interactions amid added structure and main flow. As a consequence, a noticeable decline in performance is encountered at the very low Reynolds number region. On the other hand, the improvement of micro nozzle/diffuser with enhancement decreases with the rise when the Reynolds number above than 70. It is due to the efficiency ratio of conventional micro nozzle/diffuser significantly increases with the Reynolds number. 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 (Yang et al. 2004). Accordingly in higher flow velocity region, the added enhancements reduce the influence of the above-mentioned two factors, thereby resulting in a lower efficiency.

5 Conclusions

In this study, we have fabricated and measured the pressure drop characteristic of micro diffusers/nozzles with five types of enhancement structures and one of conventional micro nozzle/diffuser valve, and its performance is analyzed. The pressure drops across the designed micro nozzles/diffusers are found to be increased considerably when the obstacle and fin structure are added. Further, the micro nozzle/diffuser having circular area gives rise to a lower pressure drop, owing to the hydraulic diameter is increased by circular area and lower interface friction. The tested results show that the measured pressure loss coefficients are higher than the calculated results, the phenomenon is especially pronounced for higher Reynolds number region. The departure of prediction and measurement is because the model is fully developed base yet the velocity distribution of outlet condition provides some additional pressure drop of the water flow at high Reynolds number region.

The maximum improvement of the proposed structures is about 16% for an added 3-fin structure operated at a Reynolds number around 70. Upon this situation, the static rectification efficiency improves over 4.43 times than the conventional nozzle/diffuser. Experimental results indicate that the improvement of micro nozzle/diffuser with enhancement peaks at a Reynolds number of 70, and a detectable decline is encountered when the Reynolds number is further decreased. It is due to the efficiency ratio of conventional micro nozzle/diffuser significant increases with the Reynolds number.

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