Experimental influence of a splitter vane on the flow fields in a wide-angled diffuser

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Abstract. Based on PIV and high-speed photography technology, the lengths and area ratios of flow separation zone under different Reynolds numbers $Re$ in a diffuser with a fixed angle (28°), with and without a splitter vane were obtained. The flow field, vorticity and the flow distribution (hydrogen bubble tracing) at the downstream vicinity of the outlet of the diffuser under three representative conditions ($Re = 1000, 6000$ and $12000$) were given. The experimental results show that with increasing $Re$, the area proportion of the separation zone decreases, but the length proportion of the separation zone increases, because the thickness of the separation zone along the vertical flow direction is reduced. Due to the existence of vane, the area of the corresponding separation zone is always smaller than that without the vane.

1. Introduction

Diffuser is widely used in engineering applications, e.g., in pump-turbines and petrochemical key components [1-4], etc., to convert the kinetic energy (dynamic pressure) into the pressure energy (static pressure), which is crucial to obtain a low energy loss and a high-efficiency flow [5]. In this process, the flow inside the diffuser is decisive to the efficiency of the diffuser.

At present, the research on the flow patterns of the diffuser mainly focus on the experimental and numerical investigations. In the experimental investigations, Kline S. J. [6-8] found that in the absence of vanes, or other means of boundary-layer control, the divergence angle, ratio of throat width to wall length and free-stream turbulence are important in determining the behaviour of the flow. Variations in $Re$ and aspect ratio appear to have little effect on the flow regime for the range of aspect ratios normally encountered and for all $Re$ in excess of a few thousand. On the other hand, Nishi [9, 10] conducted a boundary layer calculation. From a consideration of flow stability, it was found that the onset of separation on a diffuser depends upon the local blockage factor. At the same time, it was proven that the formula deduced in his paper also applies to conical diffusers.

However, there are no more quantitative results in these experimental studies, which is unfavourable for further understanding of the related fluid mechanics. Therefore, through the PIV and high-speed photography technology, this paper presents the flow distribution in the diffuser at a fixed divergence angle (28°), and the evolution diagram of the area and length proportion of the main flow area and the separation area, which is necessary to further reveal the relevant dynamic flow mechanism.

The structure of the present paper is described as follows: first, the diagram of the test bench and the related description is presented. Then, the test process and test conditions are designed. Thirdly, the experimental results and related analyses are given. Finally, the conclusion is obtained.
2. Experimental system

2.1. Experimental setup and facilities

The experimental system mainly includes a water tank, a magnetic flow meter, regulation valves, the splitter vane system, the test diffuser, honeycomb, extension baffle, drainage tank, PIV system, and data acquisition system. The flow rate \((Re)\) and its feedback can be controlled by the magnetic flow meters and regulation valves. The circulation of the system is attributed by gravity (water level in the water tank is higher than it in the test diffuser), the drainage tank and circulating pump. The related experimental system is illustrated in Figure 1.

![Figure 1. Experimental loop.](image)

1. Water tank 2. Magnetic flow meter 3. Regulation Valve 4. Moving splitter vane system 5. Test diffuser 6. Honeycomb 7. Extension baffle 8. Lasers 9. CCD camera 10. Data acquisition system 11. Drainage tank with a circulating pump.

The test section of the diffuser is all made of polymethyl methacrylate (PMMA), and the honeycomb is made of circular tubes with a wall thickness of 0.5 mm. The flexible connectors are adopted at the connection part of the end of the diffuser blade and the extension baffle, as well as at the root cylinder of the diffuser blade to facilitate the adjustment of the divergent angle of the diffuser. In this paper, the divergence angle is fixed at 28°. The width of the diffuser throat \(d = 50 \text{ mm}\). In addition, the thickness of the splitter vane \(d_1\) is 3mm. Considering that the flow at the outlet of the diffuser should not affect the flow pattern inside the diffuser, the diffuser and its downstream length are set as 40\(d\). The free-surface level inside the diffuser is 150 mm. The structure of the diffuser test section is shown in Figure 2. The measurement range of the magnetic flow meter is 0-50 m³/h, and the measurement error within 1%.

![Figure 2. Geometry of diffusers and entrance section (Top view).](image)

2.2. Experimental conditions
PIV measurement and high-speed photographic recording of the flow patterns at Reynolds number $Re = 1000$-$12000$ were carried out in the experiments. The corresponding Reynolds number is defined as follows

$$Re = \frac{U \cdot d}{\nu},$$

where $U$ is the average velocity in the throat of the diffuser, $d$ is the width of the throat and $\nu$ is the dynamic viscosity of the test fluid (water at 20 °C is presented in this paper). In this paper, three cases (case 1: $Re = 1000$; case 2: $Re = 6000$; case 3: $Re = 12000$) are analyzed in detail. The time-averaged experimental results of PIV and the transient test results of hydrogen bubbles are given respectively.

2.3. Experimental procedure

The experiments are carried out as follows:

1. A certain amount of experimental fluid (20 °C water in this experiment) is stored in the water tank, reaching a water level $> 200$ mm, to overcome the loss of the pipeline system, and ensure that the flow velocity at the throat of the diffuser satisfy the highest experimental requirements ($Re = 12000$).

2. The regulation valve is then gradually opened, fill the experimental fluid in the entire experimental loop system. When the water level in the diffuser reaches 150 mm, based on the downstream weir plate overflows, the water begins to flow into the circulating water tank.

3. The circulating pump is then turned on, and the flow rate is adjusted to meet the corresponding case.

4. After running the test bench smoothly and stably for at least 15 minutes, PIV experimental and hydrogen bubble system are turned on. In the present paper, the PIV shooting frequency is 200 fps. In terms of the experimental system error is $< 2\%$. PIV uniformity is $< 5\%$.

3. Results and discussions

In this section, the flow separation length $L_c$ and separation area $A$ against $Re$ is given first, providing detailed understanding on the influence of the splitter vane on the characteristics of the separation zone, and the flow pattern in the diffuser. Then the three selected typical cases are analysed in detail.

3.1. Flow separation in diffuser

The length of the separation zone $L_c$ (based on the definition of the stall period [7], $L_c$ is the distance of the detachment point and the end of the relative diffuser blade) along the flow direction and the area of the separation zone $A$ (the separation zone is enclosed by $L_c$ and the separation boundary (an imaginary line) in the flow fields, on which the most of the velocity vectors’ directions are opposite to the mainstream direction) near one side of the diffuser blade are defined respectively, as shown in Fig. 3 (a) and (b).

![Figure 3. Flow separation factors in the diffuser.](image)

The statistical results of the above separation zone length and separation zone area for various $Re$ are shown in Fig. 4, in which the length percentage of separation area $\eta_L$ is the ratio of $L_c$ to diffuser blade...
length $L_b$, and the area percentage of separation area $\eta_A$ is obtained by dividing the flow area into 1056 equal-area grids, and then the ratio of the occupied grid of separation area to the total grid is statistically obtained. It can be found that for the diffuser without vane, $\eta_L$ (the dotted line) fluctuates slightly with the increasing of Re and the value of $\eta_L$ increasing gradually; for the vaned diffuser, $\eta_L$ is lower. It should be noted that in the first two cases ($Re = 1000$ and 2000), $\eta_L$ varied steadily, and then began to fluctuate violently, which may attribute to the flow transition from laminar to turbulent in the diffuser. When $Re \geq 9000$, the variation trend slows down gradually. On the whole, $\eta_L$ for different $Re$ fluctuates and evolves first, and then increasing with a high level of about 10%.

On the other hand, $\eta_A$ (the solid line) for vaneless cases decreases gradually with $Re$, and the final reduction of the separation area is about 10%. When vaned, $\eta_A$ is lower than the corresponding value in the same cases without vane. For the low $Re$, $\eta_A$ increases smoothly and then fluctuates violently. When $Re \geq 9000$, the fluctuation starts smooth transition, which is similar to $\eta_L$. Overall, when vaned, $\eta_A$ first fluctuates and then decreases, besides, the vane has a significant inhibitory effect on the separation flow in the diffuser.

![Figure 4](image_url) Figure 4. Variation of the length percentage of separation area $\eta_L$ and area $\eta_A$ with $Re$.

### 3.2. Flow patterns for typical cases

#### 3.2.1 Case 1: $Re=1000$

Fig. 5 (a) and (b) are the time-averaged PIV measurement results and hydrogen bubble flow fields in the diffuser without and with splitter vane, respectively. It can be found that the separation area (the red dotted line) is smaller for the vaned case than that for the vaneless case. The separation point is closer to the downstream of the diffuser for the vaned case. Meanwhile, the vorticity (boundary layer near the wall) in the diffuser with a splitter vane is higher than that without it. The results of the hydrogen bubble experiment for case 1 show that when vaneless, the backflow bubbles form on the platinum wire, which locates in downstream of the diffuser channel, and the hydrogen bubbles in the main flow region are along the upper blade. However, the corresponding length ratio of the main flow direction $\eta_m$ and the opposite direction $\eta_o$ is about 9:1 for the vaned case. At the same time, the area of the visible hydrogen bubbles in the main flow region increases obviously.
3.2.2 Case 2: Re=6000

Fig. 6 (a) and (b) are the results of the PIV and hydrogen bubble inside the diffuser when Re= 6000 under the condition of without and with a splitter vane, respectively. For the vaned case, the separation area (the red dotted line area) is smaller. In this case, the separation points are both close to the throat of the diffuser, which may be due to the stronger turbulence. Similarly, the vorticity value in the vaned diffuser is stronger than that in the vaneless one. For the vaneless case at the same Re, the back-flow hydrogen bubble still exists on the platinum wire, and \( \eta_o \approx \eta_A \). In the consistent position, the length of the main flow direction on the platinum wire increases obviously, and \( \eta_A / \eta_o \approx 7:3 \) for the vaned case. Similarly, the area of the visible hydrogen bubbles in the main flow region increases obviously.

(a) Flow field and vorticity distribution in the diffuser for Re=6000.

(b) Distribution of hydrogen bubbles near diffuser outlet for Re=1000.

Vaneless

Vaned

**Figure 5.** Flow patterns for Re=1000.
3.2.3 Case 3: Re=12000

The results of the PIV and hydrogen bubble inside the diffuser when Re= 12000 for the vaned and vaneless cases are illustrated in Fig. 7 (a) and (b), respectively. Similar to cases 1 and 2, the separation area (the red dotted line area) is smaller in the flow field for the vaned case. At the same time, the separation points are both close to the throat of the diffuser. Besides, the vorticity distribution is basically the same for the vaned and vaneless cases, which may be related to the high Re and turbulent flow. Without vane, \( \eta_o \approx \eta_A \). \( \eta_A \) increases obviously for the vaned case, and \( \eta_A / \eta_o \approx 8:2 \). For all three cases, the difference for the length of the flow region on the platinum wire between the PIV results and the hydrogen bubble results may be owing to that the PIV results are time-averaged and the hydrogen bubble results are instantaneous.

4. Conclusion

In the present paper, based on the experimental results, the flow fields in the diffuser with and without a splitter vane was quantitatively analyzed. The evolution of separation length and separation area against Re was given.
The experimental results show that when the $Re=1000$, the separation area is smaller for the vaned case. The separation point is closer to the downstream of the diffuser for the vaned case. Besides, the vorticity in the diffuser is higher than the diffuser without vane. When $Re=6000$, for the vaned case, the separation area became smaller. In this case, the separation points are both close to the throat of the diffuser for vaned and vaneless cases, which may be due to the stronger turbulence. Similarly, the vorticity distribution in the vaned diffuser is stronger than those without one. When $Re=12000$, similar to cases 1 and 2, the separation area is the smallest in all cases. For the constant case, the separation points are both closer to the throat of the diffuser. Besides, the vorticity distribution is basically the same for vaned and vaneless cases, which may be related to the turbulent flow. On the other hand, the length of the main flow direction on the platinum wire increases obviously for vaned cases, and the corresponding length ratio of the main flow direction and the opposite direction, i.e. $\eta_A/\eta_o$ is about 9:1, 7:3 and 8:2, respectively.

5. References

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