Study on the Change of Incident Direction and Incoming Flow Velocity to the Reattachment Point and the Center Position of the Large Vortex

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Abstract. This paper establishes a model with the variation of the standard angle with the height of the step. Numerical simulation is carried out to study the influence of the change of the incident direction and the incoming velocity on the large eddy structure and the length of the recirculation zone in the reattached shear layer under different standard angles. Finding that with the increase of the incident angle β, the length of the recirculation zone tends to increase firstly and then decrease. The large vortex center position Y/H firstly maintains a small range of fluctuations; when the incident angle β reaches a certain value, the large vortex center position suddenly rises sharply to a certain value. The center position of the large vortex decreases again when β continues to increase. When the Reynolds number increases from 150 to 300, the value of Xr/H will suddenly increase sharply and the position of the large vortex will have a significant downward trend. When the Reynolds number is greater than 300, the length of the recirculation zone will remain unchanged from the center of the large vortex. That is the recirculation zone length and the Y/H value of the center position of the large vortex is not affected by the Reynolds number.

1. Introduction
As the simplest and most typical flow in the two-dimensional separation and reattachment movement, the backward step flow has been generally valued.

Roos et al. [1] pointed out through experiments that large-scale vortex structures exist in both laminar and turbulent separations, as the shear turbulence increases, the large-scale structures become more and more irregular. Zhou Huiliang et al. [2] had used flow field display technology to find that the scale near the reattachment point is comparable to the step height.

The study of the large eddy structure in the above literature is carried out in the case where the incident direction is perpendicular to the step, that is, the incident angle is β=0° according to the model presented in Fig 1. H. Iwai et al. [3] studied the influence of fluid gravity on the backward step flow when the tilt angle and roll angle change with time and found that the reattachment point moves forward with the increase of the tilt angle which within a certain range from 0° to 180°. The influence of different inflow velocity on the large eddy structure is analyzed by numerical simulation in this paper. It is found that with the increase of the incident angle β, the length of the recirculation zone shows a trend of increasing firstly and then decreasing and the value Y/H of center of the large vortex firstly keeps fluctuations in a small range; when the incident angle β reaches a certain value, the center position of the large vortex suddenly rises sharply to a certain value and it decreases again when β continues to increase. When the Reynolds number increases from 150 to 300, the value of Xr/H will suddenly increase sharply and the position of the large vortex will have a significant downward trend. The recirculation zone length and the Y/H value of center position of the large vortex is not affected.
by the Reynolds number as it grows greater than 300.

2. Model Establishment and Verification
The backward step flow studied in this paper is shown in Figure 1, where θ represents a standard angle, which is related to the step height H, β is the incident angle and V is the incoming flow velocity.

![Figure 1. Schematic diagram of the flow backward step](image)

In order to check the accuracy of the construction of this model, the calculation parameter is $H=0.049m$ and the height of the flow before the step is 0.052m according to the literature [4]. The standard angle is $\theta=30^\circ$. The calculation grid is $98 \times 490$ under the grid noncorrelation test. Setting the fluid medium to water and the outlet pressure to 0 in Fluent. To study the response of the recirculation zone length with the variation Reynolds number in the case of low Reynolds number. The specific verification method is to determine whether the length of recirculation zone changes with the Reynolds number is consistent with the literature [4] when the standard angle is equal to the incident angle, ie $\beta=\theta=30^\circ$, under the Reynolds number is changed from 100-1500. The results obtained in this experiment and the results obtained in the literature [4] are shown in Figure 2. $Xr/H$ represents the ratio of the length of the recirculation zone to the height of the step in the figure. It is found through analysis that the length of the recirculation zone becomes longer as the Reynolds number increases, however, the length of the recirculation zone is reduced and kept fluctuating up and down within a certain range as the Reynolds number higher than a certain value shows in literature [4]. We obtained through numerical simulation that the length of the recirculation zone increases with the increases of the Reynolds number in the low Reynolds number range, but this trend continues for a short time only and it fluctuates with a small range in the range of the Reynolds number.

In terms of the overall trend, the Reynolds number equals 290 where the length of recirculation zone reached limit in this paper as compared to the Reynolds number at the maximum length of recirculation zone in the literature [4] is 1070. It can be considered that the construction of grid in this paper is more reasonable.

![Figure 2. The relationship between the lengths of recirculation zone to Reynolds number](image)
3. Calculation Results and Analysis

3.1. Influence of Incident Angle on Flow Field Vortex Structure

A backward step model with a standard angle θ of 15, 30, 45 and 60 degrees is constructed successively to study how the influence of the change of the incident angle on the position of the reattachment point and the influence of the position of the large vortex center based on the above-mentioned verified mesh model. In each of the backward step models, the incident angle value is changed and satisfies 0° ≤ β ≤ 60°. The obtained result is processed by the software GetData to obtain the data as shown in Table 1 and the influence of the change of the incident angle on the length of the recirculation zone and the position of the large vortex at different standard angles is respectively extracted by software Origin 8.5, as shown in Figure 3, 4, where the XY coordinates established in the figure are the origin of the coordinates of the bottom of the step.

We found that the length of the recirculation zone is always increased when 15° ≤ θ ≤ 30° by changing the height of the step whatever the β is. However, the length of the recirculation zone has been reduced when 30° ≤ θ ≤ 60° by changing the height of the step, which is most obvious when β = 0°. We found there is a phenomenon of symmetrical change of θ = 30°. The length of the recirculation zone also changes as β changes when θ keeps constant under each model. It can be seen from Fig. 3 that the length of the recirculation zone shows a tendency to increase firstly and then decrease as the β increases. This trend is easy to see from θ = 30°, θ = 60°, while θ = 15°, θ = 45° only shows a tendency to increase the length of the recirculation zone however the downward trend has not yet appeared.

Analysis of Figure 4 shows that the center position of the large vortex is increasing when 15° ≤ θ ≤ 30° by changing the height of the step under the β = 0°. The center position of the large vortex shows a downward trend when 30° ≤ θ ≤ 60°. The Y/H value of center position of the large vortex seems to satisfy a trend that firstly maintains a small range of fluctuations as the incident angle increases in the backward step model structure with different standard angles. The position of the center of the large vortex suddenly rises sharply to a certain value when the incident angle β reaches a certain value. The center position of the large vortex decreases again when β continues to increase. However, the trend is not obvious and the center of the large vortex shows a tendency to rise slowly when the standard angle is 30°.

| Table 1 | The effect of incident angle on reattachment point and the center position of large vortex |
|-----------------|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| θ=15°, Re=150   |                                | β               | X_r/H           | H               | Y/H             |
|                 |                                | 0               | 10              | 15              | 20              | 25              | 30              | 35              | 40              | 45              | 50              | 55              | 60              |
|                 |                                | 0.7             | 0.7             | 0.8             | 0.7             | 0.8             | 0.8             | 0.8             | 0.8             | 0.8             | 0.7             | 0.7             | 0.7             | 1.0             |
| X_r/H            |                                | 0.3             | 0.3             | 0.3             | 0.3             | 0.7             | 0.7             | 0.7             | 0.7             | 0.7             | 0.7             | 0.7             | 0.6             | 0.6             |
| θ=30°, Re=150   |                                | β               | X_r/H           | H               | Y/H             |
|                 |                                | 0               | 10              | 15              | 20              | 25              | 30              | 35              | 40              | 45              | 50              | 55              | 60              |
|                 |                                | 3.2             | 3.3             | 3.4             | 3.3             | 4.4             | 4.4             | 4.3             | 4.3             | 4.3             | 4.3             | 4.3             | 4.3             | 4.3             |
| X_r/H            |                                | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.5             | 0.6             | 0.7             |
| θ=45°, Re=150   |                                | β               | X_r/H           | H               | Y/H             |
|                 |                                | 0               | 10              | 15              | 20              | 25              | 30              | 35              | 40              | 45              | 50              | 55              | 60              |
|                 |                                | 0.7             | 0.7             | 0.8             | 0.9             | 1.0             | 1.0             | 1.1             | 1.1             | 1.2             | 1.3             | 1.4             | 1.4             | 1.5             |
| X_r/H            |                                | 0.3             | 0.4             | 0.3             | 0.4             | 0.4             | 0.4             | 0.4             | 0.4             | 0.7             | 0.7             | 0.7             | 0.7             | 0.7             |
| θ=60°, Re=150   |                                | β               | X_r/H           | H               | Y/H             |
|                 |                                | 0               | 10              | 15              | 20              | 25              | 30              | 35              | 40              | 45              | 50              | 55              | 60              |
|                 |                                | 0.8             | 0.8             | 0.9             | 1.1             | 1.1             | 1.2             | 1.2             | 1.3             | 1.3             | 2.2             | 2.4             | 1.9             | 1.8             |
| X_r/H            |                                | 0.3             | 0.3             | 0.7             | 0.7             | 0.7             | 0.7             | 0.6             | 0.6             | 0.5             | 0.5             | 0.5             | 0.6             | 0.6             |
3.2. **Influence of Reynolds Number on Vortex Structure of Flow Field**

We obtained the Reynolds number $150\leq \text{Re} \leq 5000$ by changing the magnitude of the flow velocity $V$ in this paper to study the influence of the Reynolds number on the reattachment point and the center position of the large vortex when the standard angles are equal to the incident angle and the data as shown in Table 2.

It is found that the change of the length of the recirculation zone is similar under four different standard angles with the increasing Reynolds number. That is said that the value of $X_r/H$ will suddenly increase sharply when the Reynolds number increases from 150 to 300 at a low Reynolds number. Then the length of the recirculation zone can be considered to remain unchanged, that is, not affected by the Reynolds number. However, there will be a small range of fluctuations in the graph because an error in the data acquisition from GetData and the error range is in the range of 0.2-0.4. Considering this small range of fluctuations in the figure 5 can be considered to be consistent. It can also be clearly seen from the figure that the standard angle satisfies $15^\circ \leq \theta \leq 60^\circ$ by changing the height of the step and the value of $X_r/H$ decreases continuously as the standard angle $\theta$ increases.

From the analysis of Fig. 6, it is found that the center position of the large vortex has a significant downward trend when the Reynolds number is $150\leq \text{Re} \leq 300$. The center position of the large vortex remains unchanged when the Reynolds number satisfies $300\leq \text{Re} \leq 5000$, that is, The $Y/H$ value of the
center position of the large vortex center is not affected by the Reynolds number. Moreover, it can be analyzed from the figure that the position of the large vortex center is not affected by the change of the step height, that is, the center position of the large vortex remains unchanged when the standard angle $\theta$ is increased from $15^\circ$ to $60^\circ$.

**Table 2.** The effect of Reynolds number on reattachment point and the center position of large vortex

| $\beta=\theta=15^\circ$ | Re | 150 | 300 | 600 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
|-------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X/H                     |    |     |     |     |     |     |     |     |     |     |     |     |     |
| H                       | 0.8 | 4.7 | 4.3 | 4.2 | 4.4 | 4.4 | 4.4 | 4.6 | 4.5 | 4.6 | 4.6 | 4.6 | 4.6 |
| Y/H                     | 0.3 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

| $\beta=\theta=30^\circ$ | Re | 150 | 300 | 600 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
|-------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X/H                     |    |     |     |     |     |     |     |     |     |     |     |     |     |
| H                       | 3.4 | 3.9 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 | 3.7 |
| Y/H                     | 0.5 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

| $\beta=\theta=45^\circ$ | Re | 150 | 300 | 600 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
|-------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X/H                     |    |     |     |     |     |     |     |     |     |     |     |     |     |
| H                       | 1.3 | 3.2 | 3.0 | 3.0 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.1 | 3.0 |
| Y/H                     | 0.7 | 0.4 | 0.5 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

| $\beta=\theta=60^\circ$ | Re | 150 | 300 | 600 | 1000 | 1500 | 2000 | 2500 | 3000 | 3500 | 4000 | 4500 | 5000 |
|-------------------------|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| X/H                     |    |     |     |     |     |     |     |     |     |     |     |     |     |
| H                       | 1.8 | 3.0 | 2.8 | 2.9 | 3.0 | 2.5 | 2.5 | 2.4 | 2.3 | 2.2 | 2.2 | 2.2 | 2.2 |
| Y/H                     | 0.6 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |

**Figure 5.** The effect of Reynolds number change on the length of the recirculation zone at different standard angles
Conclusions

The length of the recirculation zone $X_r/H$ and the center position of the large vortex $Y/H$ are studied by changing the incident angle $\beta$ and the flow velocity $V$ in this paper through numerical simulation method and the following conclusions are obtained:

Firstly: The length of the recirculation zone exhibits a tendency to increase firstly and then decrease as the incident angle $\beta$ increases. This may have a lot to do with the structure we are studying; the reattachment point achieves the maximum value when the incident angle increases to a certain value, which is also obvious in practice. Similarly, similar results were obtained by changing the pitch angle of the duct in the article by Iwai H et al in literature [3].

Secondly: The value of $X_r/H$ will suddenly increase when the Reynolds number increases from 150 to 300. The length of the recirculation zone can be considered to remain unchanged when the Reynolds number is greater than 300, that is, not affected by the Reynolds number. The conclusions we get here are consistent with the conclusions obtained by Zhou Ning et al. [6], however, our study reached saturation at a Reynolds number of 300 because our study is carried out under the model of the incident angle equal to the standard angle ($\beta = \theta$) as compared to the incident angle of the literature [6] is always zero $\beta=0$.

Thirdly: The center position of large vortex firstly maintains a small range of fluctuation as the incident angle increases; The center position of large vortex suddenly rises sharply to a certain value when the incident angle $\beta$ reaches a certain value and the position of the center of the large vortex is decreasing again with $\beta$ continues to increase. The conclusions of our research here are inconsistent with the conclusion that the scale of the vortex near the reattachment point is comparable to the height of the step proposed in literature [2] in which the incident angle is $\beta=0$. The conclusion of this paper is more realistic since the incident angle is changeable.

Lastly: The center position of the large vortex has a significant downward trend when the Reynolds number $150 \leq Re \leq 300$ and the center position of the large vortex remains unchanged when the Reynolds number satisfies $300 \leq Re \leq 5000$, that is, the $Y/H$ value of the center position of large vortex is not affected by the Reynolds number. It can be clearly seen from Fig. 6 that the center position of the large vortex is maintained at about 0.5 which means that the scale of the large eddy is equivalent to the height of the step, regardless of which model of different standard angle we are studying. This conclusion is consistent with the literature [4].

The shortcoming of this paper is that there will be a human factor error in the range of 0.2-0.4 when taking value of the recirculation zone length $X_r$ and the large vortex center coordinate $Y$. 

Figure 6. The effect of Reynolds number change on the center position of large vortex at different standard angles
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