Research on the Effects of Nonsmooth Surfaces on Backward-facing Step Flow

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Abstract: To achieve the purpose of backward-facing step flow control, a passive control approach, which consists in introducing nonsmooth structures in solid walls, is applied to the upstream of the backward-facing step. Based on STAR CCM+ software, the standard k-ε turbulence model was established to simulate flow characteristics of the right angle step, fillet step and nonsmooth fillet step. The introduction of the nonsmooth surface leads to a significant reduction in recirculation region length (17.5%) and a decrease in downstream wall pressure coefficient. According to the analysis of separation point position and turbulent kinetic energy, the delay of separation point and the enhancement of momentum exchange are the main reasons for the success of flow control. Compared with the right angle step, the delay of flow separation of the fillet step leads to a reduction in step expansion ratio (ER), and the existence of the nonsmooth structure enhances the turbulent kinetic energy at the fluid separation points and the momentum mixing at the downstream of the step, thus reducing the reattachment length and the downstream wall pressure coefficient.

1. Introduction
Flow separation is a classical flow phenomena, exists widely in practical engineering problems, for instance, airfoil flow, automobile tail flow and so on. The occurrence of flow separation will generate additional drag and noise, therefore, effective control on flow separation is of great significance. As a classical separation flow model, the backward-facing step flow has the advantages of simple geometry and fixed separation position and has been widely used to study the separation phenomena.

A number of studies have been made on backward-facing steps by means of physical experiments [1-3] and numerical simulations [4-5]. From the time-averaged point of view, the downstream flow field of the backward-facing step consists of a separated vortex and an angular vortex respectively. Previous study found that the inlet conditions and geometry parameters are the main factors affecting the flow characteristics of the backward-facing step [6]. Ötügen found that with the decrease of the expansion ratio, the turbulence intensity of the downstream shear layer increases, while the length of the separation bubble decreases effectively [7]. Westphal et al. also found that the expansion ratio may affect the velocity and Reynolds stress distribution near the average reattachment position [8]. Ra et al. studied the influence of the pressure gradient, and found that the length of separation bubble increases with the increase of pressure gradient [9].

In order to reduce flow separation, various fluid control methods have been applied to backward-facing step flow. In order to reduce the separation bubble length, Park et al. applied square sheets on the step to enhance the mixing of the fluid flow [10]. Pouryoussefi et al. used plasma actuator to control the flow separation and found that the best control effect could be achieved only by
installing the actuator on the separation point [11]. Sakuraba et al. studied the flow field through uniform suction at the step, and analyzed the influence of suction flow on wall pressure coefficient, pressure loss coefficient and reattachment length [12]. Dejoan et al. analyzed the effects of jet amplitude and frequency on the backward-facing flow field [13].

In this paper, the influence of non-smooth structures on fillet step flow field were studied by using RANS (Reynolds Averaged Navier-Stokes) method. The feasibility of the simulation method and the solution strategy was verified by comparing with the available experimental results [14]. The impact mechanism of the nonsmooth structures on the flow field was also discussed.

![Figure 1. Computational domain of the backward-facing steps.](image)

2. Numerical Simulation Method

2.1. Computational model and domain

In order to verify the simulation reliability, the computational model is the same with the available experiment [14]. The two-dimensional computational domain is shown in figure 1(a). The height of the step is \( h = 0.0381 \text{ m} \), the channel height upstream of the step is \( H = 0.0762 \text{ m} \), the expansion ratio (\( ER \)) is 1.5, the inlet distance away from step is \( L_1 = 0.1905 \text{ m} \), the outlet distance away from step is \( L_2 = 1.143 \text{ m} \), the radius of the fillet step is \( R_1 = 0.01 \text{ m} \) (figure 1(b)), the radius of the nonsmooth fillet step is \( R_2 = 0.01 \text{ m} \) (figure 1(c)), the nonsmooth structure is V-shaped (figure 1(d)) with the height of \( h_3 = 0.0001 \text{ m} \) and the width of \( L_3 = 0.0001 \text{ m} \).

The boundary layer grids were generated by prism layer grids (determined by the thickness of the first layer and the number of prism layer), and the grids near the wall were refined. The first layer thickness near the wall is \( 10^{-6} \text{ m} \), the number of boundary layer is 25, and the total number of two-dimensional flow field grids reaches 350,000. The uniform velocity inlet was adopted at the entrance of the computational domain, and the inlet velocity was set to 18.2 m/s. It is considered that the fluid has reached full development state at the outlet, so the outlet boundary was set as pressure outlet. The wall boundary was set as non-slip, so the slip velocity and wall pressure gradient are 0.

2.2. Governing equation

The standard \( k-\varepsilon \) turbulence model was used to simulate the backward-facing step flow. Since the inlet velocity is much lower than the sound velocity, the fluid is considered as incompressible. There is also no temperature difference under flowing conditions. As a result, the governing equations include the mass conservation equation and momentum conservation equation.

Mass conservation equation is as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\] (1)
Momentum conservation equation is as follows:

\[
\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho uu) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + F_x, \\
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho vv) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{yx}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + F_y,
\]

(2)

where \(u\) and \(v\) are the velocity components in \(X\) and \(Y\) directions respectively, \(\rho\) is fluid density, \(P\) is pressure, \(\mu\) is viscous coefficient.

The \(k\) equation is as follows:

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_x)}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu}{\sigma_f} \right) \frac{\partial k}{\partial x} \right] + P_k - \rho(\varepsilon - \varepsilon_0) + S_k
\]

(3)

The \(\varepsilon\) equation is as follows:

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_x)}{\partial x} = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu}{\sigma_f} \right) \frac{\partial \varepsilon}{\partial x} \right] + \frac{1}{C_l} \frac{1}{T_c} \frac{1}{P_c} - C_{\varepsilon 2} \frac{\varepsilon}{T_c} + S_\varepsilon
\]

(4)

Due to the limitation of the paper length, the specific meaning of the parameters can be found in related literature [15].

2.3. Model validation

In order to verify the reliability of the calculation model, the reattachment point of the right angle step was calculated under the same conditions with available experiments [14]. The simulation results are shown in figure 2. The position of reattachment point predicted by the numerical simulation is 7.24, which shows satisfactory agreement with the available experimental data (7.1) [14]. The error between them is kept at 1.79 %. We may thus conclude that the calculation model and method are reliable.

Figure 2. Wall shear stress of the right angle backward-facing step.

Figure 3. Wall Shear stress on downstream walls with three steps.
3. Results and discussion

3.1. Recirculation region characteristics

The commercial software STAR CCM+ was used to simulate the flow characteristics of the right angle step, fillet step and nonsmooth fillet step. According to the calculation results of the wall shear stress downstream of the steps (figure 3), the reattachment point of right angle step is $X_F = 7.24\, h$, that of fillet step is $X_R = 6.28\, h$, and that of nonsmooth fillet step is $X_N = 5.97\, h$. Compared with right angle step, fillet step and nonsmooth fillet step make the reattachment point move forward, the length of reattachment and the recirculation region decrease, which lead to positive effects on flow fields.
The steady time-averaged flow structures are shown in figure 4. The downstream flow fields of different steps have common characteristics: the stable recirculation regions are formed downstream of the steps, and recirculation vortices are formed in the recirculation regions, the size of the vortex has the same order of magnitude as the height of the step. However, there are also obvious differences among them. The main difference lies in the size of the recirculation vortex. As shown by the red dotted line frame in figure 4, the recirculation vortex of the right angle step is the largest, followed by the fillet step, and the nonsmooth fillet step has the smallest recirculation vortex, which is consistent with the conclusions obtained above.

3.2. Wall pressure distribution

The pressure coefficients on downstream walls are shown in figure 5. In the initial section, pressure coefficient decreases gradually with the increase of the distance along the way, then the coefficient reaches the lowest at the center of the recirculation vortex, and then increases continuously until \( x \) reaches 10 \( h \), finally the pressure coefficient tends to be stable after \( x \) reaches 10 \( h \). As can be seen in figure 5, the wall pressure coefficients of fillet step and nonsmooth fillet step are significantly reduced. When \( x \) is between 3 \( h \) and 8 \( h \), the nonsmooth fillet step has the smallest wall pressure coefficient.

3.3. Separation point location

Figure 6 shows the velocity contours of three steps. The velocity contours also have common characteristics: the fluid velocity is small in the corner region of the step, and the velocity in the downstream channel recovers uniformly after \( x \) reaches 7\( h \). Compared with the right angle step and the fillet step, the velocity at the downstream of the separation point of the nonsmooth fillet step has the strongest change. The main reason is that the existence of non-smooth structures enhance the normal momentum exchange and increase the momentum variation.

Figure 7 shows the separation points of three steps. The separation point of right angle step is always fixed at corner point. The fillet and nonsmooth fillet steps have the same separation delay. The delay of the separation point is equivalent to the reduction of the step height \( (h) \), which makes the expansion ratio \( (ER) \) become smaller. Previous studies show that the smaller the expansion ratio \( (ER) \)
is, the closer the reattachment point is to the separation point [7,16]. Therefore, the change of the expansion ratio is one of the main reasons affecting the flow field.

![Figure 7. Changes in the position of the separation points of the three steps](image)

3.4. Turbulence Kinetic Energy

The turbulent kinetic energy contours are shown in figure 8. The turbulent kinetic energy intensity below the step height is relatively large and uneven, and the turbulent kinetic energy intensity at the center of the recirculation vortex reaches the largest. Compared with the right angle step and the fillet step, the turbulent kinetic energy of the nonsmooth fillet step has significant fluctuation, especially in the area downstream of step separation point. The reason is that the existence of nonsmooth structure enhances the normal energy exchange of fluid at the step, increases the turbulent kinetic energy and the momentum mixing in the downstream area of the step, thus reducing the range of the separation region and the length of the attachment point.

![Figure 8. Turbulent kinetic energy contours of three steps.](image)

4. Conclusions

In this paper, a new passive control approach, which consists in introducing nonsmooth structures in backward-facing step, is proposed. The main conclusions are as follows:

1. According to the simulations on the wall stress and the pressure coefficient, it is concluded that compared with the right angle step, the other two steps can make the reattachment point move forward,
thus effectively reducing the reattachment length and the wall pressure coefficient. The control effects of the nonsmooth fillet step are better than that of smooth fillet step.

2. The fillet step changes the position of fluid separation point and leads to the phenomenon of separation delay. The delay of the separation point reduces the step expansion ratio ($ER$) and thus reducing the reattachment length.

3. The existence of nonsmooth structure enhances the normal energy exchange of fluid at the step, increases the turbulent kinetic energy and momentum mixing in the downstream area of the step, thus reducing the range of the separation region and the length of the attachment point.

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