Large eddy simulation of turbulent flow over a backward-facing step: effect of inflow conditions

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ABSTRACT

In this study, in order to understand the effect of inflow conditions (the thickness of the oncoming boundary layer), the turbulent flow over a backward-facing step was investigated by using the large eddy simulation.

The skin friction coefficient shows some dependence on Re as well as δ/h. At lower Reynolds number (Re=5100), the friction coefficient is somewhat dependent on δ/h. On the other hand, at higher Reynolds number (Re=45000), the friction coefficient does not significantly change in terms of δ/h. Also, the turbulence statistics downstream of the backward-facing step (mean streamwise velocity and streamwise turbulence intensity) significantly depend on both the oncoming boundary layer thickenss and the Reynolds number.

INTRODUCTION

Backward-facing steps are regarded as a simplified configuration of various engineering applications such as diffusers, combustors and so on. The flow over a backward-facing step has received much interest because it contains flow separation, reattachment, and development to turbulent boundary layer. The important features of the turbulent flow over a backward-facing step such as separation and reattachment are closely associated with the characteristics of the oncoming boundary layer (the momentum thickness and turbulence intensity, etc.). There exists some controversy about the most effective frequency resulting in the mixing enhancement (Chun and Sung 1996), which may be related to the inflow conditions.

So, the effect of the inflow conditions on the flow structure over a backward-facing step has been regarded as one of the crucial issues to be resolved (Adams and Johnston 1988a, 1988b, Aider et al. 2007 among them). However, due to some limitations of managing systematically the upstream conditions in experiments, our understanding is not yet complete. Therefore, in the present study, we investigate the effect of inflow conditions on the turbulence structures downstream of a backward-facing step at Re=5100, 24000 and 45000 by using large eddy simulations. We consider three different boundary thicknesses, i. e, δ/h =0.25, 0.5 and 1.2. Here, h is the step height.

COMPUTATIONAL DETAILS

The filtered governing equations of an unsteady incompressible viscous flow for LES are

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i \tilde{u}_j}{\partial x_j} = -\frac{\partial \tilde{p}}{\partial x_i} + \frac{1}{\mathrm{Re}} \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}, \quad (1)$$

$$\frac{\partial \tilde{u}_i}{\partial x_i} = 0, \quad (2)$$

where x_i are the coordinates, $\tilde{u}_i$ are the corresponding filtered velocity components, $\tilde{p}$ is the filtered pressure and Re denotes the Reynolds number. The subgrid-scale (SGS) stress tensor, τ_{ij}, is modelled using the dynamic SGS model by Germano et al. (1991) together with the least-square method suggested by Lilly (1992).

We solve (1) and (2) using a semi-implicit fractional-step method proposed by Akselvoll and Moin (1996). The Crank –Nicolson method is used for the implicit terms and a third-order Runge-Kutta method is used for the explicit terms. Also, the second-order central difference scheme is employed for all the spatial derivative terms. More details of the numerical methods used in this paper are shown in Kang and Choi (2002).

Figure 1 shows the schematic diagram of the computational domain, where (x=0, y=h) is the location of the backward-facing step edge. The computational domain size in each direction is $L_i = 2.5h$, $L_x = 22.5h$, $L_y = 6h$ and $L_z = 4h$, respectively. So, in this study the expansion ratio (ER) is 1.2. To provide a realistic inlet turbulence, a separate LES of turbulent boundary layer flow is performed based on the method of Lund et al. (1998).

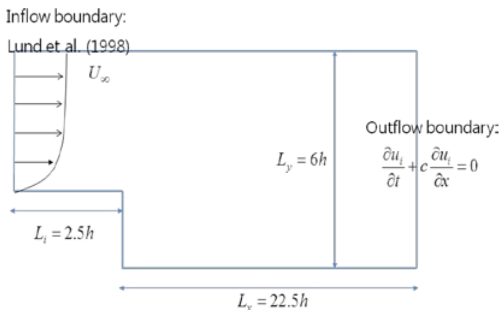
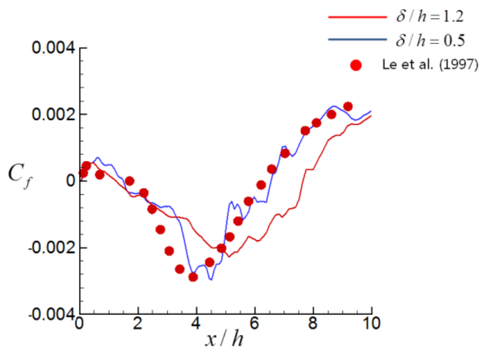
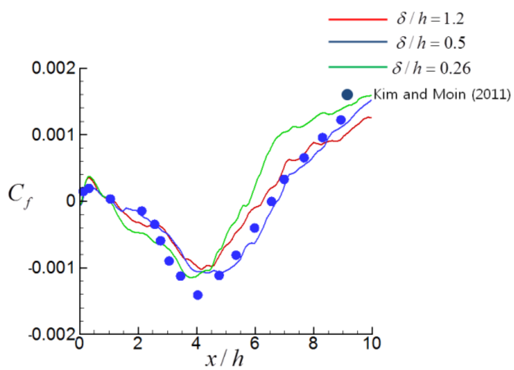


Figure 1. Computational domain.



(a)



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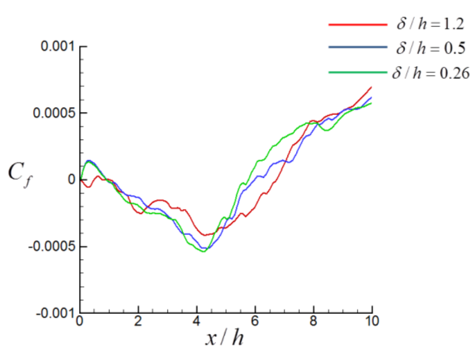
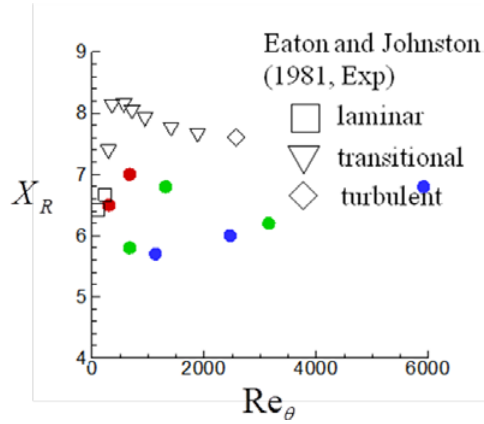
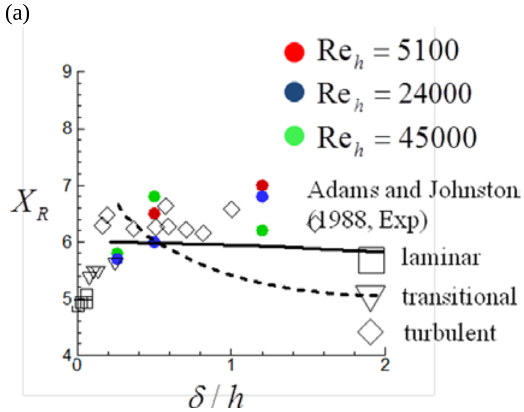


(c)

Figure 2. Skin friction coefficients on the downstream wall: (a) Re=5100; (b) Re=24000; (c) Re=45000.



(a)



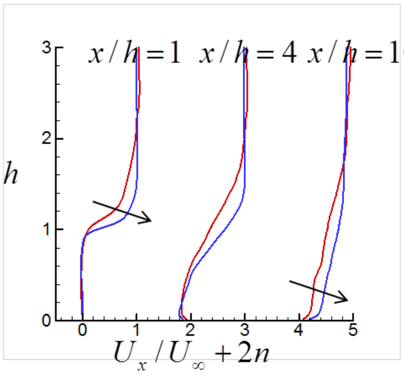
(b)

Figure 3. Reattachment length in terms of (a) Re_θ and (b) δ/h.

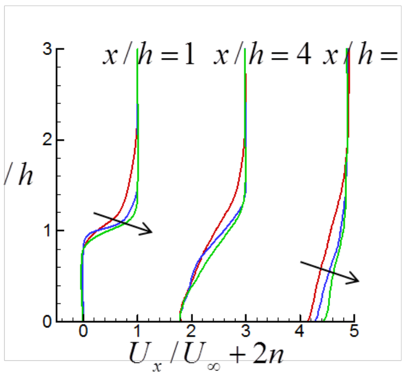
Also, at the exit the convective boundary condition is considered. Among many parameters characterizing the oncoming boundary layer, the effect of the ratio of the boundary layer thickness (δ) and the step height (h) is focused. To do so, as mentioned above three different δ/h's of 0.26, 0.5 and 1.2 are considered. On the other hand, the flow over a backward-facing step should depend on the Reynolds number as well as the boundary layer thickness at the inlet. Therefore, we consider three different Reynolds numbers of Re=5100, 24000, and 45000 which is based on the step height h and inlet free-stream velocity U_∞. The number of grid points used is $151(x) \times 56(y) \times 64(z)$, which is very similar to that used in Kang and Choi (2002). Non-uniform grid distributions are used in both the streamwise and wall-normal directions, and uniform grid distribution in the spanwise direction.

NUMERICAL RESULTS

Figure 2 shows the variation of the skin friction coefficient profiles for different Re and δ/h considered, together with previous results (Le et al. 1997; Kim and Moin 2011). As shown in Fig. 2, the friction coefficients



(a)



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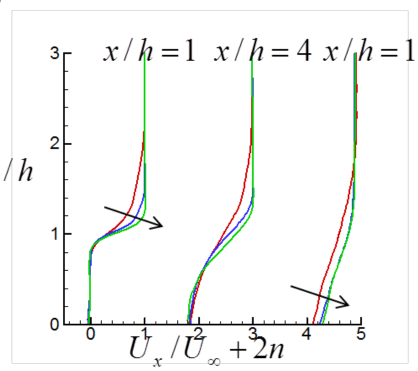
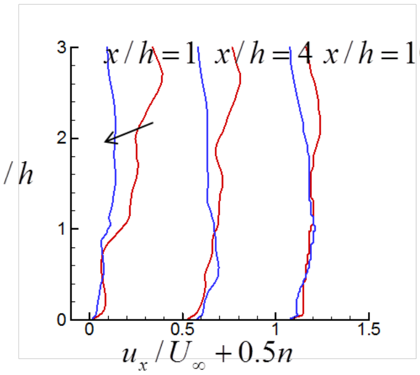


(c)

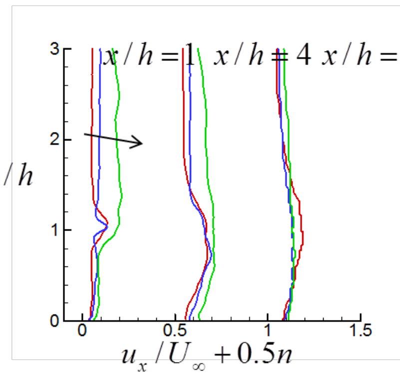
Figure 4. Mean streamwise velocity profiles at some streamwise locations: (a) Re=5100; (b) Re=24000; (c) Re=45000. Red line, δ/h=1.2; blue line, δ/h=0.5; green line, δ/h=0.26.

show a reasonably good agreement with those of the previous studies. At lower Reynolds number (Re=5100), the friction coefficient is somewhat dependent on δ/h. On the other hand, at higher Reynolds number (Re=45000), the friction coefficient does not significantly change in terms of δ/h.

For the turbulent flow over a backward-facing step, mixing increase or decrease is one of the important interests. As a measure of mixing, the reattachment length is usually used. Seeing the change of the reattachment



(a)



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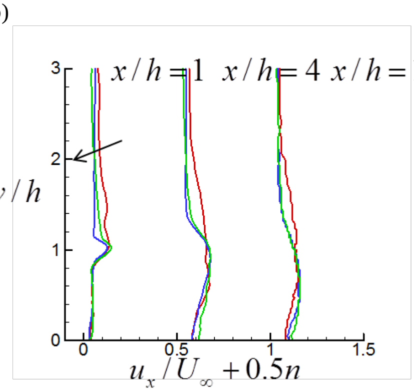

(c)

Figure 5. Streamwise turbulence intensity profiles at some streamwise locations: (a) Re=5100; (b) Re=24000; (c) Re=45000. Red line, δ/h=1.2; blue line, δ/h=0.5; green line, δ/h=0.26.

length with respect to Re and δ/h, δ/h does not significantly affect the reattachment length, like Adams and Johnston (1988b).

To investigate the effect of inflow conditions on the reattachment length in more detail, the reattachment length is presented in terms of Re_θ or δ/h in Fig. 3. For comparison, the experimental data by Eaton and Johnston (1981) and Adams and Johnston (1988b) are included. As shown in Fig. 3, the reattachment length might be determined by δ/h rather than Re_θ, which is in an agreement with the findings by Adams and Johnston

(1988b). However, even for the same δ/h, the reattachment length shows some non-negigible deviation with respect to Re. In the previous studies, the scatter of the reattachment length had been explained by the characteristics of inflow conditions: laminar, transition and turbulence. However, considering the fact that all the inflow conditions in this study are turbulent, the explanation could not be applied to the present results.

Figures 4 and 5 show the variation of the mean streamwise velocity and streamwise turbulence intensity profiles, respectively, for different Re and δ/h. As shown in these figures, the turbulence statistics downstream of the backward-facing step significantly depend on both the oncoming boundary layer thickenss and the Reynolds number. For the mean streamwise velocity, as the oncoming boundary layer thickness decreases, the mean streamwise velocity becomes larger for all the Reynolds numbers considered in this study. On the other hand, the streamwise turbulence intensity profiles show more complicated behavior than the mean streamwise velocity as shown in Fig. 5.

CONCLUSIONS

In this study, in order to understand the effect of inflow conditions (the thickness of the oncoming boundary layer), the turbulent flow over a backward-facing step was investigated by using the large eddy simulation.

The skin friction coefficient shows some dependence on Re as well as δ/h. At lower Reynolds number (Re=5100), the friction coefficient is somewhat dependent on δ/h. On the other hand, at higher Reynolds number (Re=45000), the friction coefficient does not significantly change in terms of δ/h. Also, the turbulence statistics downstream of the backward-facing step (mean streamwise velocity and streamwise turbulence intensity) significantly depend on both the oncoming boundary layer thickenss and the Reynolds number.

In the final presentation, to further understand the effect of the inflow boundary layer thickness on the flow structure over a backward-facing step, the turbulence statistics such as time-averaged velocity, turbulence intensity and Reynolds shear stress profiles from the simulation would be presented, comparing against those in experiments and previous numerical simulations. Finally, this work would help to deepen the insight into the mixing phenomenon associated with the turbulent flow over a backward-facing step.

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