IMPLEMENTATION OF VLES TURBULENCE MODELING IN OPENFOAM FOR SEPARATED FLOW SIMULATION

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1. Introduction

Most of the fluid flows in engineering applications are in the turbulent regime. Turbulence modelling is thus the hot research topics for many years. However, for the complex nature of turbulence, the high-fidelity modelling is still challenging even now. In the past decades, turbulence modelling has developed rapidly with the development of several disciplines.

Turbulence modelling can be generally divided into three main groups, RANS (Reynolds-Averaged Navier-Stokes), LES (Large Eddy Simulation) and DNS (Direct Numerical Simulation). In recent years, LES is becoming more and more popular as it can resolve the large turbulent structures directly. The computation grid is directly related to the resolved turbulence scale in LES. In high Reynolds turbulent flow, the small turbulence scale becomes smaller, and thus it needs very fine mesh to resolve the small turbulence scales, especially in the near-wall region. The high computation cost has become one of the barriers to limit the application of LES for high Re number flow simulation.

In the past two decades, hybrid turbulence modelling, i.e. combing different turbulence approaches, are becoming more and more popular as it uses the advantages of different methods. Hybrid RANS-LES method is supposed to be the main method which can make LES applicable for high Re flow in engineering problems [1]. Among them, various hybrid methods are proposed. The DES (Detached Eddy Simulation) method [2] is one of the most widely used and it has been applied for various turbulent flows. In recent years, several unified turbulence modelling are proposed and they attract intensive interests, such as VLES (Very-Large Eddy Simulation) [3, 4], PANS (Partially-Averaged Navier-Stokes) [5], PITM (Partially-Integrated Transport Method) [6]. The present study focuses on the VLES modeling. The main idea of unified turbulence modelling is that, based on the resolution mesh scale and the local turbulence scales, the turbulence modelling can gradually evolve from RANS to LES, finally to DNS. It means that there is no boundary between different turbulence methods, and the one modelling method can cover the three traditional modelling methods of RANS, LES and DNS in a unified framework. The main advantage is that it can be applied for various turbulent flow simulations, especially for high Re turbulent flow in engineering applications.

The research of separated turbulent flow has attracted extensive interests in both academia and industry for decades. It is encountered in various applications, such as flow around various bluff bodies, internal flows with large pressure gradients, etc. However, the accurate prediction of separated flow is still challenging for turbulence modelling. Thus, the present study aims to investigate the performance of VLES modelling for separated flow based on the open source toolbox, OpenFOAM. The main objectives are two aspects: firstly, to validate the relatively new VLES modelling for separated flow simulation; and secondly, to assess the OpenFOAM toolbox for complex flow simulations.

2. Numerical methods

In the present study, two versions of VLES modelling [3, 4] are applied, i.e. based on the standard k-ε turbulence model and the Wilcox k-ω model (referred to as *VLES_ke* and *VLES_kw*), respectively. In the VLES modelling, the form of the underlying RANS modelling is not changed, and only the turbulent viscosity is modified by scaling with a resolution control function *Fr*. The parameter, *Fr*, is the core of VLES modelling. It has the form as shown in Eq. (1), where L_c, L_i and L_k are the cut-off length scale, integral length scale and Kolmogorov length scale, respectively.

$$Fr = \min\left[1.0, \left(\left(1.0-\exp(-\beta L_c / L_k)\right) / \left(1.0-\exp(-\beta L_i / L_k)\right)\right)^2\right] \tag{1}$$

With the mesh resolution changing, the control function *Fr* has a value between 0 and 1.0, which determines how much of the turbulence is modelled. Thus, with different mesh resolution, it can work in different turbulence modelling modes, ranging from the RANS, LES to DNS. More details can be found elsewhere [3, 4].

On the basis, the *VLES_ke* modelling can be shown as in Eqs. (2) - (4), where the governing equations of turbulent kinetic energy k and its dissipation rate ε is the same as in the standard k-ε turbulence model. The turbulent viscosity is scaled by the resolution control function *Fr*.

$$D\rho k / Dt = P_k - \rho\varepsilon + \partial\left[\left(\mu + \mu_t / \sigma_k\right)\partial k / \partial x_j\right] / \partial x_j \tag{2}$$

$$D\rho\varepsilon / Dt = (\varepsilon / k)(C_{\varepsilon 1} P_k - C_{\varepsilon 2}\rho\varepsilon) + \partial\left[(\mu + \mu_t / \sigma_\varepsilon)\partial\varepsilon / \partial x_j\right] / \partial x_j \quad (3)$$

$$\mu_t = Fr \cdot \rho C_\mu k^2 / \varepsilon \quad (4)$$

Similarly, the *VLES_kw* modelling can be written as in Eqs. (5) - (7), where the control function *Fr* has the same form as in the *VLES_ke* model (refer to Eq. (1)).

$$D\rho k / Dt = P_k - \beta_1^* \rho k\omega + \partial\left[(\mu + \sigma_k^* \mu_t)\partial k / \partial x_j\right] / \partial x_j \quad (5)$$

$$D\rho\omega / Dt = (\gamma\omega P_k / k - \beta_2^* \rho\omega^2) + \partial\left[(\mu + \sigma_\omega^* \mu_t)\partial\omega / \partial x_j\right] / \partial x_j \quad (6)$$

$$\mu_t = Fr \cdot \rho k / \omega \quad (7)$$

The present VLES methods have been implemented in the OpenFOAM toolbox [7]. The unsteady simulations are performed using the modified pimpleFOAM solver. For high-fidelity simulations, the convective terms are discretized using a second-order central differencing scheme coupled with a small fraction of first order upwind scheme in order to minimize the numerical dissipation. A second-order implicit Crank-Nicolson scheme (with a small fraction of first order implicit scheme) is used for the temporal discretization.

Two separated flow test cases are selected, i.e. the flow past a backward facing step flow and the periodic hill flow. Based on the previous studies, there are generally two kinds of flow separation. The first one is triggered by the sharp geometry changes and the separation point is fixed, such as sharp edges. The second one corresponds to smooth flow separation, where the separation point changes in the flow. Thus, the selected backward facing step flow corresponds to the first kind of separation and the periodic hill flow to the second kind.

3. Backward facing step flow case with Re=40000

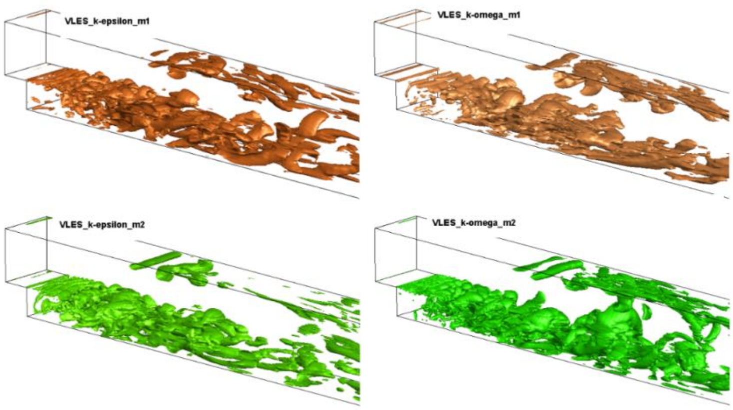
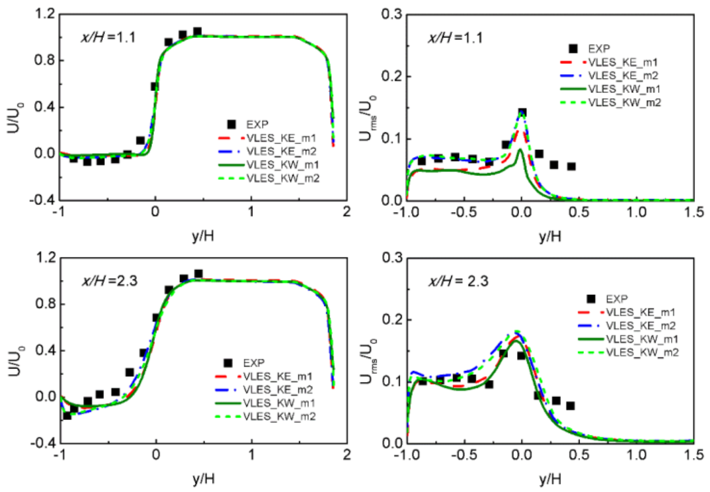


Figure 1: Iso-surface of the second invariant of the velocity gradient (Qh^2/U_0=0.2) for backward facing step flow with different VLES modelling.

The test case deals with a channel flow which separates from a downstream backward-facing step. It is a typical flow separation case and has been widely studied. The Reynolds number is 40000 based on the height of the step (h), i.e. Re = $U_0 h/\nu$ =40000. There is a thick boundary layer at the inlet, which is around 0.37 times of the step height. In the present VLES simulations, two quite coarse meshes are applied, which contains about 0.6 million and 2.0 million cells (denote as m1 and m2), respectively. The simulation results are compared with available experimental data [8].



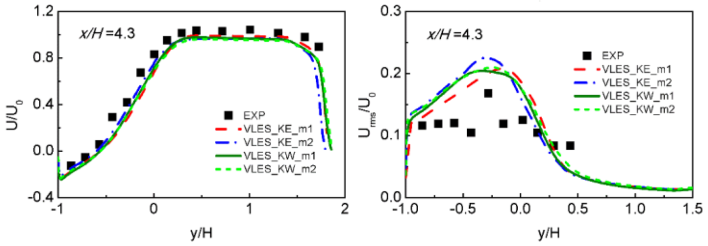


Figure 2: Comparisons of the mean (left) and RMS velocities by the present VLES modelling with experiments [8] in the backward facing step flow, at different downstream locations.

Figure 1 shows the Q criteria of turbulent structures by VLES method for backward step flow. It shows that the two VLES method gives quite close predictions. With increasing the mesh resolution, more turbulent structures can be observed. The mean and RMS velocities at three downstream locations are presented in Fig. 2, accompanying with the experimental data [8]. The comparisons show that the two VLES methods both give satisfactory results and they agree well with experiments. Also, with decreasing the mesh resolution, the predictions just slightly become less good. The test case demonstrates that the present VLES modelling can accurately predict the backward facing step flow on the basis of OpenFOAM toolbox.

4. Periodic hill flow case with Re=10595

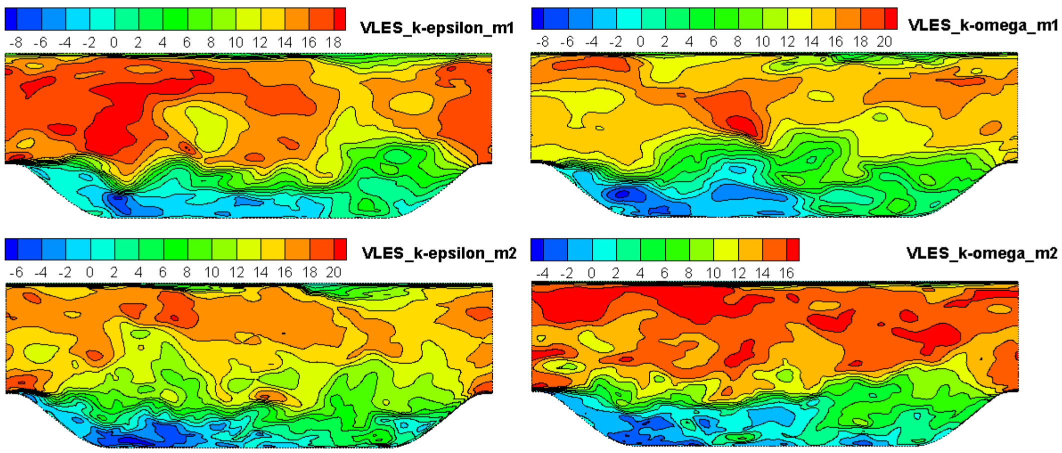


Figure 3: Instantaneous velocity distributions for periodic hill flow with different VLES modelling.

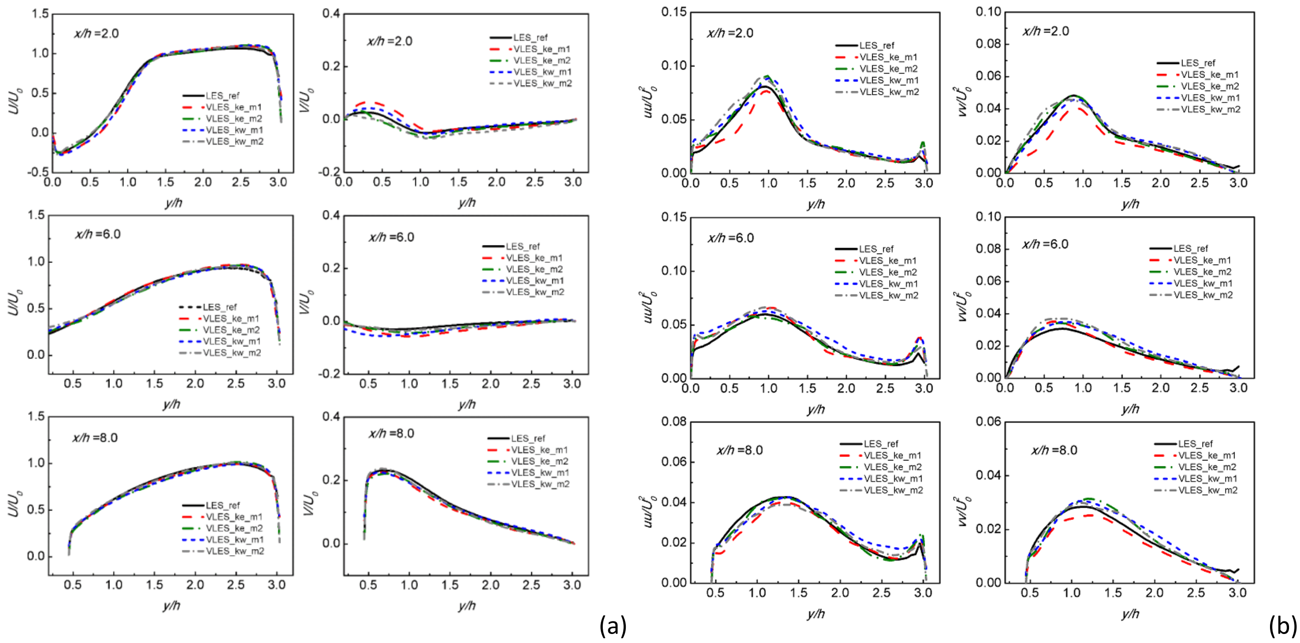


Figure 4: Comparisons of the mean velocities (left) and Reynolds stresses by the present VLES modelling with reference LES results [9] in the periodic hill flow, at different downstream locations.

The periodic hill flow test case represents a flow separation in a channel with periodic smoothly curved hills on the bottom wall. The test case involves complex flow phenomena, such as smooth flow separation, recirculation, vortex movement, reattachment, etc. The Reynolds number is Re_h = 10595, based on the hill height h, and the bulk velocity U_0 above the hill crest. It has been numerically studied using a well-resolved LES [9] and the LES results are used here as the reference data. In the present VLES simulations, two quite coarse meshes are applied, which contains about 0.6 million and 1.8 million cells (denote as m1 and m2), respectively.

Figure 3 shows the instantaneous streamwise velocity predicted by the present VLES. It shows that complex flow revolution can be observed. With increasing the mesh resolution, smaller turbulent structures can be observed. Figure 4 presents the results of the mean velocities and the normal Reynolds stresses by the VLES method. The first observation is that the present VLES modelling gives quite good results compared with reference LES results, for both the mean velocity and Reynolds stress. With increasing the mesh resolution, the results can be improved. However, on the coarser mesh m1, the predictions by VLES method are still satisfactory, considering the computation mesh used (about 0.6 million cells). The results also show that on the coarser m1, the VLES modelling based on the k-ε model gives the worst predictions, compared with other three sets of results. It implies that the VLES modelling based on the k-ω model performs better than the VLES modelling based on the k-ε model for the periodic hill case.

The present results demonstrate that the present VLES modelling based on k-ε model and k-ω model both can give satisfactory results for the complex separated flow simulations, and quite coarse meshes can be used in the simulations. The study also shows that the OpenFOAM software can provide a very good platform for high-fidelity simulation of complex separated flow. The accuracy and reliability are both quite satisfactory.

More simulation results, comparisons and detailed analysis will be given in the full length paper.

Acknowledgements

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