On the Filter Size of DMM for Passive Scalar in Complex Flow

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Abstract. Effect of filter size of dynamic mixed model combined with a box filter on the prediction of passive scalar field has been investigated in complex flow. Unlike in the simple channel flow, the result shows that the model performance depends on the ratio of test to grid filter widths.

1 Introduction

The role of large eddy simulation (LES) in most of engineering applications involving turbulent flows increases everyday. Since direct numerical simulation (DNS) is restricted to a relatively low Reynolds number due to the resolution requirement for the length-scale in dissipation range, it is currently less attractive as an engineering tool and LES becomes more popular as a reasonably accurate and at the same time less expensive methodology.

Even though the significant development has been made to the LES modeling for the prediction of velocity field, relatively much less effort has been done in the calculation of passive scalar transport in spite of its obvious practical importance and this fact is reflected in the difficulty of predicting the passive scalar field with satisfactory accuracy using current LES models. The difficulty of investigating passive scalar transport is possibly due to the fact that errors associated with LES models embedded in a velocity field reduces the accuracy in the prediction of passive scalar in a way not clearly understood. Consequently, more effort should be devoted to the development of LES methodology for more accurate and reliable approach for the design of thermal system.

The present work mainly intended to examine the performance of dynamic mixed model (DMM, Zang et. al. [1]) for passive scalar transport in complex flow (Na [2]). An exhaustive number of LES models has been reported in the literature but DMM was chosen here for the following two reasons: (1) From the perspective of large eddy simulation of engineering flows, computations based on finite difference formulations are certainly of great interest. Thus, DMM with finite difference formulations, which

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most conveniently use filters in physical space, were considered and tested for turbulent channel flows; (2) DMM has been known to produce good results in a wide range of turbulent flows.

The dynamic mixed model extended to passive scalar transport will be briefly explained and its characteristics are discussed in the case of turbulent channel flow with wall injection.

2 Mathematical Formulation

2.1 Dynamic Mixed Model for Passive Scalar

The filtered governing equations for the LES of a passive scalar T for incompressible flows are given as follow:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial \overline{u_i}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_i}\,\overline{u_j}) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}(2\nu \overline{S_{ij}} - \tau_{ij}), \tag{2}$$

$$\frac{\partial \overline{T}}{\partial t} + \frac{\partial}{\partial x_j}(\overline{u_j}\,\overline{T}) = \frac{\partial}{\partial x_j}(\alpha \frac{\partial \overline{T}}{\partial x_j} - q_j). \tag{3}$$

where the grid-filtering operation is denoted by an overbar. The effect of unresolved subgrid scales is represented by the following residual stress tensor τ_{ij} and residual scalar flux vector q_j.

$$\tau_{ij} = \overline{u_i u_j} - \overline{u_i}\,\overline{u_j}, \tag{4}$$

$$q_j = \overline{T u_j} - \overline{T}\,\overline{u_j}. \tag{5}$$

Only two terms τ_{ij} and q_j in equations (1)-(3) should be obtained through the appropriate LES models. Details of how to calculate τ_{ij} and q_j using DMM approach are explained in Lee & Na [3] and will not be repeated here.

In order to discretize the grid-scale and the test-scale filters, a box filter in physical space was employed. After the model coefficients C_S and C_T are computed through the least-squares approach, they are averaged locally in space within the test-filtering volume as suggested by Zang et. al [1].

For the actual computation using DMM, the only adjustable parameter is the ratio of test to grid filter width, $\alpha = \overline{\widetilde{\Delta}} / \overline{\Delta}$. Two commonly used definitions of the effective filter width are (1) $\tilde{\bar{\Delta}} / \bar{\Delta} = (\tilde{\bar{\Delta}}_x \tilde{\bar{\Delta}}_z / \bar{\Delta}_x \bar{\Delta}_z)^{1/3} = 2^{2/3}$ and (2) $\tilde{\bar{\Delta}} / \bar{\Delta}$ = $(\tilde{\bar{\Delta}}_x \tilde{\bar{\Delta}}_z / \bar{\Delta}_x \bar{\Delta}_z)^{1/2} = 2$. The value of α =2 is known to be the optimal choice in the simulation of a turbulent channel flow using a sharp cutoff filter (Germano et al. [4]), but optimal value is likely to depend on the types of grid and test filters used. Thus, the investigation of effect of α on the prediction of passive scalar is the main objective of the present study. The sensitivity of the numerical results to the choice of α was examined for two different values of α (2 and $2^{2/3}$) in a channel with wall injection for Pr=1.

2.2 Computational Domain

In order to test DMM for a passive scalar field, an incompressible flow between two parallel walls driven by the wall injection was considered. Figure 1 shows a schematic diagram of three-dimensional computational domain. The streamwise extent of the domain is L_x=26*h* and the spanwise extent is L_z=6.5*h,* where *h* is the half channel height. In terms of wall units (based on the friction velocity at inlet of the computational domain), the domain size is approximately equivalent to 3850 in the streamwise, 296 in the wall-normal, and 963 in the spanwise directions. The Reynolds number based on inlet bulk velocity and half-channel height was set to 2250.

The turbulent structures originated from the flat channel region are lifted by the action of wall injection applied from the location of *x*=13.4*h* and this induces a strong mixing layer away from wall. In turn, this formation of strong shear layer causes more turbulent structures to grow in space (Figure 2) and thus, the flow experiences very rapid changes in the mean flow direction.

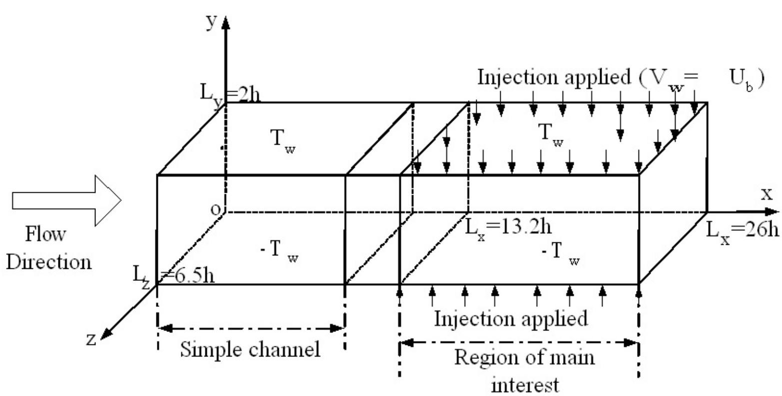

Fig. 1. Flow geometry and computational domain for the test of passive scalar using DMM

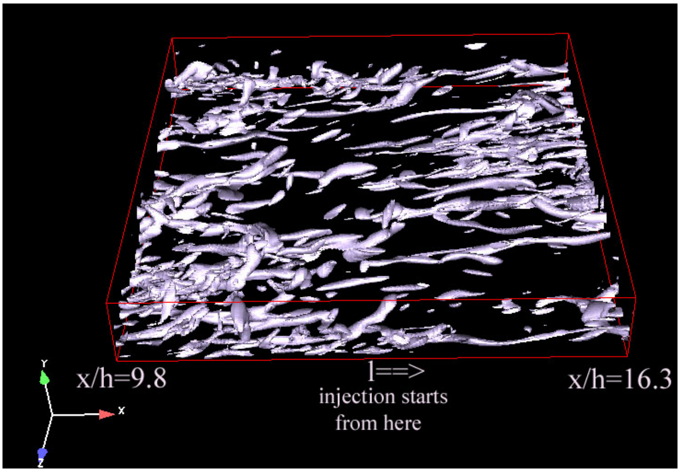

Fig. 2. Turbulent structures generated in a region with a strong injection applied at the wall

2.3 Boundary Condition

No-slip boundary condition was used along the walls except in the region where constant blowing was applied (*x/h*>13.4). The strength of the wall injection, ε, defined by the ratio of injected velocity to the inlet bulk velocity, was set to 0.05, representing a quite strong injection. It remained constant along both upper and lower walls and the spatial variation of ε was not considered. The bottom wall was cooled ($-T_w$) and the top wall was heated (T_w) at the same rate so that both walls were maintained at constant temperature.

The flow was assumed to be homogeneous in the spanwise direction which allows transform method. The adequacy of the computational domain size and the periodic boundary condition in the spanwise direction was assessed Na [2].

3 Results and Discussion

The effect of α on the performance of DMM for passive scalar was investigated in a channel with wall injection. The computation was done with $129 \times 65 \times 65$ grids. The impact of the injected vertical flow on the turbulent boundary layer is accompanied by the lifted shear layer and this adds complexity to flow. Mass conservation leads to a streamwise acceleration or strong inhomogeneity in the middle of the channel. As shown in Figure 2, the flow is characterized by the formation of increasingly stronger streamwise vortices as it moves downstream. This feature of getting more and more turbulent structures in the streamwise direction is thought to be associated with the growing lifted shear layer.

It would be useful to investigate the effect of α in this type of complex flow to investigate the range of model's utility. For the purpose of comparison, DNS with $513 \times 257 \times 257$ grids were also performed and the data were filtered in physical space to get the filtered statistics.

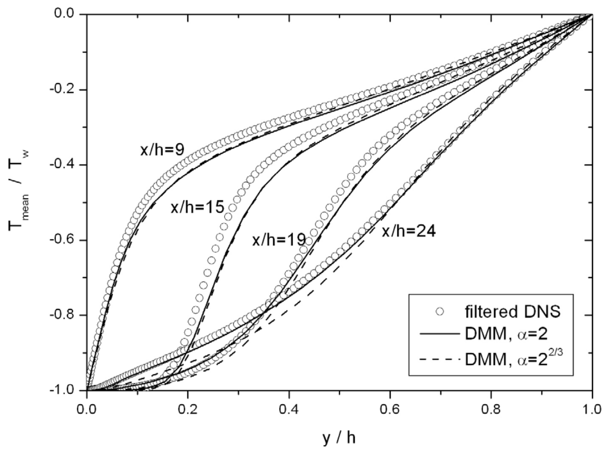

Fig. 3. Time-averaged temperature (passive scalar) profiles at several streamwise locations

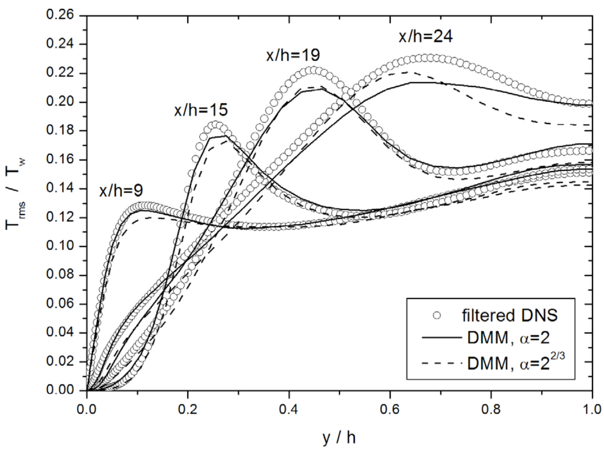

Fig. 4. Root-mean square temperature (passive scalar) profiles at several streamwise locations

Figure 3 shows the comparison of mean temperature profiles at several streamwise locations. Note that the location of x/h=9 is in the simple channel flow. It is clear that the mean temperature is not sensitive to the value of α upstream of wall injection. Even though *a priori* test results suggest the sensitivity of α, this sensitivity does not clearly appear in an actual LES. As the flow moves downstream, however, the choice of $\alpha = 2$ produces much better prediction. Thus, it would be interesting to investigate what feature of DMM generates the difference in the presence of wall injection. A similar behavior can also be found in the rms profiles shown in Figure 4.

As mentioned earlier, the resolution may play an important role in the present flow due to the strong shear layer formed away from wall. As a first step of the research, 65 grids were used in the vertical direction in which explicit filtering is not done. However, in order to generalize the effect of α, a more careful examination on the resolution should be carried out in the future.

4 Summary

The dynamic mixed model extended to the prediction of passive scalar transport was tested in a channel with injection. Since the optimal value of α and its range of utility is likely to depend on the flow, DMM was tested in a strong shear layer generated by the strong wall injection.

A close investigation of the results suggests that the performance of the model showed sensitivity to the size of the effective filter width ratio unlike in a simple channel flow. Overall, the value of $\alpha = 2$ produced a better mean and rms passive scalar statistics for the flow under investigation. However, more work for a variety of complex flows will be required in order to determine the model's range of utility of DMM in its current form.

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