International Journal of Heat and Fluid Flow 72 (2018) 329–336

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Improvement of the SGS model by using a scale-similarity model based on the analysis of SGS force and SGS energy transfer

Hiromichi Kobayashi

Department of Physics & Research and Education Center for Natural Sciences, Hiyoshi Campus, Keio University, 4-1-1 Hiyoshi, Kohoku-ku, Yokohama 223-8521, Japan

ARTICLE INFO

Keywords:
Large-eddy simulation
Subgrid-scale model
Scale-similarity model

ABSTRACT

The subgrid-scale (SGS) model is improved by using a scale-similarity model based on the analysis of the SGS force and SGS energy transfer around an elliptic Burgers vortex. Abe (2013) proposed an anisotropy-resolving SGS model in which the Bardina term of a scale-similarity model is mixed with an eddy viscosity model under a new concept wherein the Bardina term does not affect the SGS energy transfer although it affects the SGS force. By using the concept, we propose a scale-similarity model with the Clark term. The SGS energy transfer is determined by the scale-similarity term and not by the eddy viscosity term while the SGS force is improved by using the SGS kinetic energy (Abe, 2013). It is observed that the Clark term yields higher spatial correlation with the true distributions of the SGS force and SGS energy transfer around the elliptic vortex when compared to the Bardina term. The SGS model based on the Clark term exhibits good performance for turbulent channel flows with respect to $Re_\tau = 180$ and 590 even in extremely coarse grid resolutions. Specifically, the SGS model with the SGS kinetic energy fairly improves the mean streamwise velocity profile.

1. Introduction

Given the advancements in computer power, large-eddy simulation (LES) corresponds to a promising numerical method of turbulent flows. In LES, resolved or grid-scale (GS) eddies are directly computed, and unresolved or subgrid-scale (SGS) ones are modeled. Eddy viscosity models, such as the Smagorinsky model (Smagorinsky, 1963), exhibit adequate energy dissipation. However, the spatial correlation of the SGS energy transfer distribution is not high when compared with the true SGS energy transfer distribution obtained from the filtered direct numerical simulation (DNS) (see, e.g., Clark et al., 1979; Salvetti and Banerjee, 1995). In order to improve the correlation, terms similar to the SGS stress tensor are proposed by Clark et al. (1979) and Bardina (1980), and are termed as the Clark term and Bardina term, respectively. The scale-similarity terms result in low SGS energy dissipation, albeit high spatial correlations of the SGS energy transfer and the SGS stress tensor with the filtered DNS results (see, e.g., Lesieur and Métais, 1996; Meneveau and Katz, 2000).

In order to resolve the aforementioned issues, Bardina (1980) proposed a mixed model in which the Bardina term and the Smagorinsky model are linearly combined. Thus, the mixed model yielded high correlation and adequate SGS energy dissipation. Nevertheless, it is necessary to change the model constant of the Smagorinsky model for grid resolutions and flows such as homogeneous isotropic turbulence or turbulent channel flows. The problem is cured by Germano et al. (1991) in which the model parameter of the Smagorinsky model is dynamically determined by using the resolved or GS velocities as a function of time and space. The model with the dynamic procedure is termed as the dynamic model. The dynamic mixed models in which the scale-similarity model, e.g., the Bardina term, the Clark term or modified Leonard term (Germano, 1986) is combined with the Smagorinsky model were proposed (e.g., Zang et al., 1993; Vreman et al., 1994; Liu et al., 1994; Salvetti and Banerjee, 1995; Vreman et al., 1997; Meneveau and Katz, 2000; Kobayashi and Shimomura, 2001). The performance of the dynamic mixed models exceeded that of the mixed model without the dynamic procedure. Although the dynamic models are useful, averaging in homogeneous directions or clipping of negative model parameters is required to stably determine the model parameters. The stabilizing procedure leads to difficulties in applying the dynamic model to flows with complex geometries. In order to compensate for the aforementioned disadvantages, a local model without the dynamic procedure is proposed for the flows with complex geometries, (e.g., Nicoud and Ducros, 1999; Inagaki et al., 2002; Vreman, 2004; Kobayashi, 2005; Kobayashi et al., 2008; Inagaki, 2011). However, each local model is formulated as an eddy viscosity model, and thus a local model mixed with a scale-similarity term is used to improve the performance of turbulence statistics and spatial correlation.

Recently, Abe (2013) proposed an anisotropy-resolving SGS model in which the Bardina model is combined with an eddy viscosity model. Specifically, the features include the following: (1) determination of the eddy viscosity by an equation for the SGS kinetic energy as proposed by Inagaki (2011) and (2) the Bardina term is mixed in the SGS stress

E-mail addresses: hkobayas@keio.jp, hkobayas@phys-h.keio.ac.jp.

https://doi.org/10.1016/j.ijheatfluidflow.2018.06.012
Received 24 November 2017; Received in revised form 9 May 2018; Accepted 20 June 2018

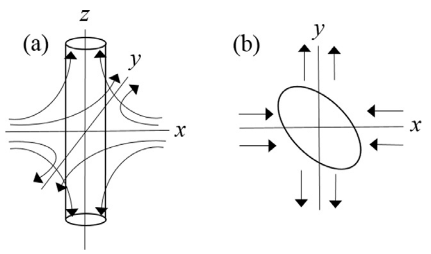

Fig. 1. Sketch of the configuration of (a) the elliptic Burgers vortex with the biaxial background straining flow $U_B = (\alpha x,\ \beta y,\ \gamma z)$ shown by arrows and (b) its cross-section perpendicular to the vortex axis.

Table 1
Numerical conditions and grid resolutions.

Re_τ	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	Δx^+	Δy^+	Δz^+
180	$4\pi\delta \times 2\delta \times \frac{4}{3}\pi\delta$	16 × 64 × 16	141	1.1 ~ 11	47
590	$2\pi\delta \times 2\delta \times \pi\delta$	64 × 64 × 64	58	1.1 ~ 49	29
590	$2\pi\delta \times 2\delta \times \pi\delta$	32 × 64 × 32	116	1.1 ~ 49	58

tensor although it does not affect the SGS energy transfer. Thus, the SGS energy transfer is given only by the eddy viscosity, and the mixed Bardina term affects only the SGS force in the Navier–Stokes equations.

The Abe model perfectly predicts streamwise velocity in turbulent channel flows with $Re_\tau = 395 \sim 2000$ even for extremely coarse grid resolutions.

Real turbulence is considerably complicated, and thus, it is difficult to understand the manner in which modeled terms behave in the complex turbulence. In order to understand this, we initially assess the SGS force and SGS energy transfer around an elliptic Burgers vortex (Moffatt et al., 1994) that is frequently observed in DNS (Kerr, 1985; Vincent and Meneguzzi, 1991; Tanahashi et al., 1994; Das et al., 2006; Wang et al., 2007). The information is used to improve the spatial correlation of the SGS force and SGS energy transfer between the SGS model and filtered DNS results.

In the present study, we improve the SGS model by using the scale-similarity model based on (a) the results of the SGS force and SGS energy transfer around the elliptic Burgers vortex and (b) the concept used in the Abe model, i.e., the scale-similarity term does not contribute to the SGS energy transfer. The proposed SGS models are examined for the turbulence statistics in the turbulent channel flows of $Re_\tau = 180$ and 590.

2. SGS model and numerical methods

2.1. Elliptic Burgers vortex

Several tube-like vortices are observed in DNS, and the vorticity vectors align along the eigenvector of intermediate eigenvalue of the

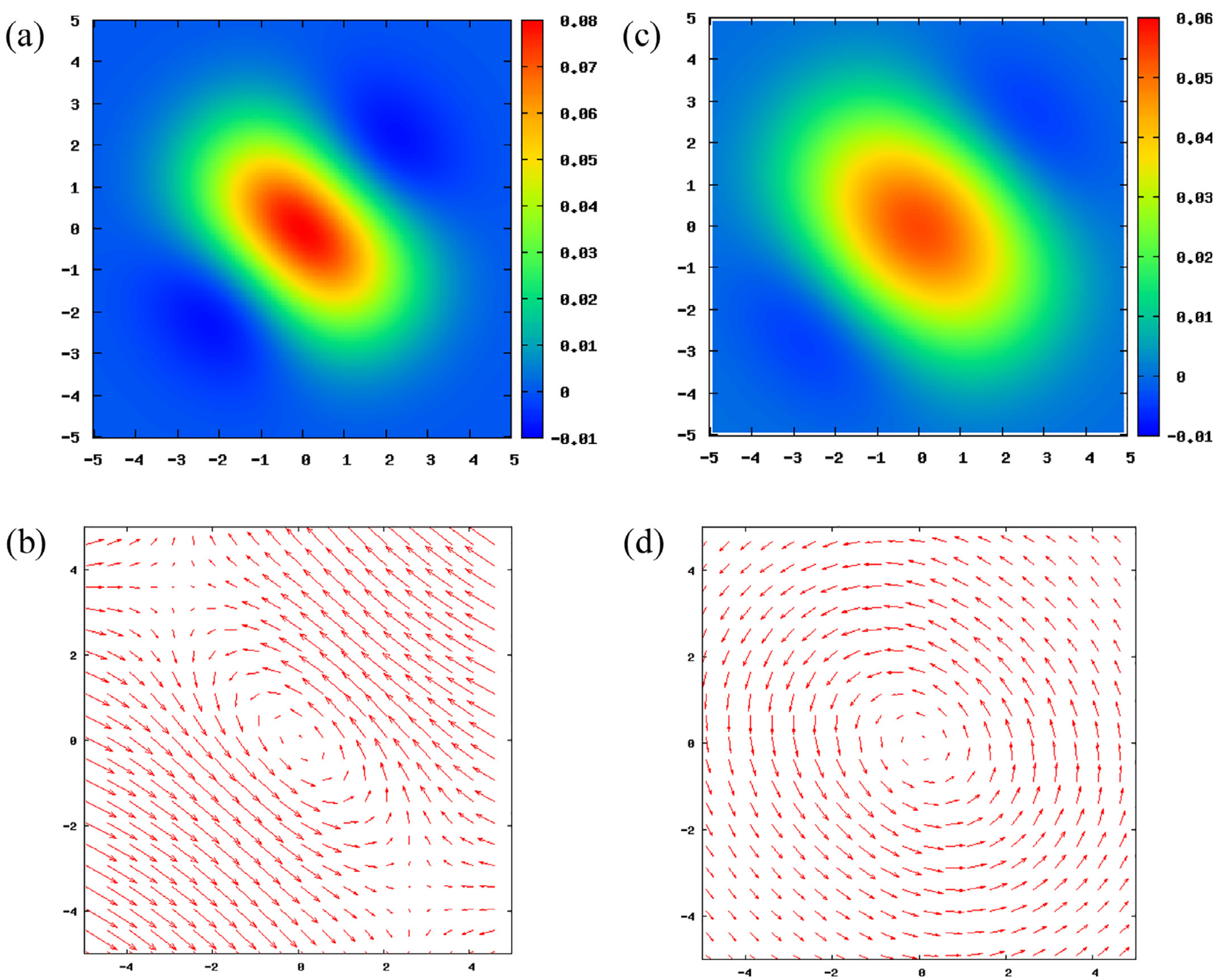

Fig. 2. Exact distributions of (a) vorticity and (b) velocity vector and filtered distributions of (c) vorticity and (d) velocity vector for an elliptic Burgers vortex.