Nuclear Engineering and Design 320 (2017) 309–324

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Wall-resolved spectral cascade-transport turbulence model

C.S. Brown [a,*], D.R. Shaver [b], R.T. Lahey Jr. [c], I.A. Bolotnov [a]

[a] Department of Nuclear Engineering, North Carolina State University, Campus Box 7909, Raleigh, NC 27695-7909, USA
[b] NE Division, Argonne National Laboratory, Argonne, IL 60439, USA
[c] Department of Mechanical, Aerospace and Nuclear Engineering, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

HIGHLIGHTS

- The spectral cascade-transport model (SCTM) is applied to higher Reynolds number channel flow.
- Spectral turbulence models are excellent candidates for multiphase CFD.
- The SCTM provides good predictions of DNS data from channel flow.
- The SCTM has been implemented into the CFD code NPHASE-CMFD.

ARTICLE INFO

Article history:
Received 13 February 2017
Received in revised form 8 May 2017
Accepted 1 June 2017

Keywords:
Spectral-cascade
Spectral turbulence model
Channel flow
DNS
CFD

ABSTRACT

A spectral cascade-transport model has been developed and applied to turbulent channel flows (Re_τ = 550, 950, and 2000 based on friction velocity, u_τ; or Re_δ = 8500; 14,800 and 31,000, based on the mean velocity and channel half-width). This model is an extension of a spectral model previously developed for homogeneous single and two-phase decay of isotropic turbulence and uniform shear flows; and a spectral turbulence model for wall-bounded flows without resolving the boundary layer. Data from direct numerical simulation (DNS) of turbulent channel flow was used to help develop this model and to assess its performance in the 1D direction across the channel width. The resultant spectral model is capable of predicting the mean velocity, turbulent kinetic energy and energy spectrum distributions for single-phase wall-bounded flows all the way to the wall, where the model source terms have been developed to account for the wall influence. The model has been implemented into the 3D multiphase CFD code NPHASE-CMFD and the latest results are within reasonable error of the 1D predictions.

1. Introduction

There are numerous Reynolds-averaged Navier-Stokes (RANS) type turbulence models in the literature but all of them have well known limitations (Wilcox, 2002). However, the continually increasing computational capabilities to perform direct numerical simulation (DNS) (Bolotnov et al., 2008a; Trofimova et al., 2009; del Alamo et al., 2004; del Alamo and Jimenez, 2003; Hoyas and Jimenez, 2006; Fang et al., 2017) provides detailed results that can be used to assess existing turbulence modeling approaches as well as to develop a more physically-based spectral turbulence model. High fidelity computational fluid dynamic (CFD) simulations improve nuclear reactor safety and operation calculations. Moreover, multiphase computational fluid dynamics (M-CFD) remains a challenging problem in engineering and the multiphase flow models in reactor relevant applications must account for complex geometries within the reactor core. More physically based M-CFD simulations of the intricate flow scenarios in nuclear reactor subchannels around spacer grids, mixing vanes, fuel bundles, etc. will deliver better predictions of flow characteristics such as three-dimensional void fraction and velocity distributions. Spectral turbulence models provide more flow statistics than traditional two-equation models (i.e. the turbulent kinetic energy (TKE) spectrum) and are a good choice for M-CFD since bubble source terms can be modeled as contributions to specific turbulence scales.

Some earlier spectral considerations to the modeling of turbulence involved the so-called multiple-time-scale models (Bradbury et al., 1980). The TKE spectrum was split into two or more scales, and each scale was modeled using a separate set of equations (such as k-ε) accounting for the interaction of these scales. Schiestel (1987) used Kovasznay hypothesis (Hinze, 1975) to model the spectral transfer in multiple-time-scale models based

* Corresponding author.
E-mail address: csbrown3@ncsu.edu (C.S. Brown).

http://dx.doi.org/10.1016/j.nucengdes.2017.06.001
0029-5493/

on partial integration of the spectral evolution equations. This spectral term is also used in the presented work.

Kim and Chen (1989) introduced a variable partitioning of the two scales which allowed a constant distribution of energy between the scales in different parts of the spatial domain. Kim (1990) extended the multiple-time-scale model all the way to the wall to obtain the low-Reynolds-number model by using a new wall damping function. Note that these models still used a dissipation rate equation for both scales and had a different set of model coefficients for each scale.

Spectral transport models split the TKE into interacting spectral bins with a separate transport equation solved for each bin. This type of spectral model can be classified as a shell model (Bohr et al., 1998). The idea to use spectral shells in the modeling of turbulent energy cascade was proposed by Desnyanski and Novikov (1974). They reproduced the Kolmogorov spectrum in terms of appropriate ordinary differential equations (ODE) for the averaged velocity field in Fourier space. The so-called GOY model (after Gledzer, 1973; Ohkitani and Yamada, 1989) used a complex variable per shell and featured interactions between nearest and next-nearest neighboring shells, maintaining energy and volume concentration in phase space. Following Desnyanski and Novikov, Lewalle and Tavlarides (1994) developed the cascade-transport (CT) model and performed calibration and testing with homogeneous uniform shear flow experimental data. In their CT model, energy is exchanged between the nearest modes only, the dissipation term is explicit (without the need for an additional dissipation rate transport equation such as in k-ε type models), and the diffusion and production terms match those in the model TKE equation. Lewalle and Tavlarides (1994) used a cumulative spectral eddy viscosity model given by Heisenberg (see Hinze (1975)) to formulate the CT model eddy viscosity with a correction factor used outside of the inertial subrange. The CT model achieved good agreement with the experimental results although the authors note that the solution had considerable sensitivity to the form of the turbulent viscosity correction factor. Lewalle and Tavlarides also note that the added complexity and computation requirements of the CT model are justifiable if multiple length scales are essential to the problem such as in non-equilibrium or two-phase turbulent flows. Note that spectral RANS models provide both spatial and spectral resolution. Therefore, the distribution of turbulent viscosity must be formulated in both spectral and spatial domains to provide the needed closure to the RANS equations.

A spectral approach allows the turbulence dissipation rate transport equation used in k-ε models to be eliminated. Moreover, the detailed TKE scale information can be used to extend this model to dispersed multiphase flows. The latter potential would be impossible using multiple-time-scale models with only two or three scales since the full resolution of the TKE spectrum allows us to recognize the non-linear influence of bubbles from different size groups on the spectrum. A spectral analysis of single and two-phase DNS data in different geometries has been performed (Brown and Bolotnov, 2016) to enhance development of a more physically derived bubble source term for use in spectral cascade models.

The low-Reynolds number (i.e. wall-resolved) spectral cascade-transport model (SCTM) presented in this paper is an extension of the model the authors have developed for single and two-phase flows for the decay of isotropic turbulence (Bolotnov et al., 2008a), uniform shear flow (Bolotnov et al., 2008b), and a high-Reynolds number model for single-phase channel flow (Bolotnov et al., 2009) where wall functions were used to achieve closure near the wall of the conduit. The model presented herein resolves the turbulence in the boundary layer all the way through the laminar sub-layer, thus eliminating the need for wall function boundary conditions in the near wall TKE spectrum. The model formulation utilizes both spectral and spatial damping functions to account for the presence of the wall.

The previous model formulation (Bolotnov et al., 2009) required a boundary condition for the TKE at the smallest resolved y^+ value (typically about 30), as is often the case in the CFD modeling of turbulent flows (Lahey et al., 1993). The previous work (Bolotnov et al., 2009) was only applied to a channel flow for a turbulent Reynolds number based on friction velocity (Re_τ) of 180. A pure inertial subrange was not observed for such a relatively low Reynolds number and the expected $-5/3$ slope in the inertial subrange could not be verified. The presented work expands the model capabilities beyond decay of isotropic turbulence (Bolotnov et al., 2008a), uniform shear flows (Bolotnov et al., 2008b), and channel flow without resolving the near wall behavior (Bolotnov et al., 2009). The model concept and basic formulation can be seen in our previous publications (Bolotnov et al., 2008a,b, 2009) and can be studied to examine these "building blocks" in the SCTM development. In the current work the turbulent boundary layer is fully resolved and therefore the need for *a priori* boundary conditions based on the law of the wall and DNS data is eliminated. The Reynolds number of the modeled flow is considerably increased and the expected $-5/3$ slope in the inertial subrange of the energy spectrum is confirmed. The SCTM has been implemented into the three-dimensional (3D) multiphase CFD code NPHASE-CMFD that was developed by Interphase Dynamics, LLC (2002) and the results from NPHASE-CMFD are also presented here.

The presented model is tested exclusively for channel flow as a precursor to the eventual expansion into more complex geometries (e.g. nuclear reactor sub-channels with mixing vanes and spacer grids). Extending the model to dispersed multiphase flows while maintaining the fully resolved TKE spectrum will greatly enhance multiphase flow analysis capabilities for high void fraction and polydispersed flow applications as demonstrated in Bolotnov et al. (2008a) for decay of isotropic turbulence. Resolving the turbulence all the way to the wall eliminates the need for controversial multiphase law of the wall boundary conditions that would otherwise need to be used in the previous formulation (Bolotnov et al., 2009) when extended to multiphase flows.

DNS data from single-phase turbulent channel flows for various Reynolds numbers (del Alamo et al., 2004; del Alamo and Jimenez, 2003; Hoyas and Jimenez, 2006) has been used for model validation as well as model development and calibration. The spectral results of del Alamo et al. (2004) and Hoyas and Jimenez (2006) are used to provide a direct comparison between the SCTM and DNS. The SCTM was first evaluated using the one-dimensional (1D) partial differential equation solver FlexPDE (PDE Solutions Inc.) (www.pdesolutions.com).

2. Model formulation

The RANS equations are solved using a turbulent viscosity determined by the SCTM equations where the Boussinesq approximation requires that the turbulent viscosity be modeled to obtain closure. In the case of the SCTM the TKE spectrum is modeled by splitting the total TKE into N wave number bins and solving separate, but coupled, transport equations for each wave number bin. Each wave number bin transport equation has similar source terms as used in typical k–ε models (Jones and Launder, 1972); namely, turbulent production, dissipation, and both turbulent and viscous diffusion. A spectral transfer term must be included to account for the energy transfers between the adjacent wave number bins. Following Lewalle and Tavlarides (1994), the general form of the single-phase version of the spectral turbulent cascade transport equation for bin-m is: