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Assessment of the performance of different classes of turbulence models in a wide range of non-equilibrium flows

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ABSTRACT

The performance of thirteen benchmark turbulence models within the RANS framework has been assessed in classical non-equilibrium flows. Linear and non-linear eddy-viscosity schemes, Reynolds stress transport models and single- and two-time-scale approaches have been considered in the investigation. Among the test cases studied are homogeneous shear and normally strained flows, adverse-pressure-gradient, favourable-pressure-gradient and oscillatory boundary layer flows, fully developed oscillatory and ramp up pipe flows and steady and pulsated backward-facing-step flows. The main advantages and drawbacks of the models in each of the test cases are discussed. These discussions provide a reasonably wide understanding of the expected behaviour of the models for future applications in non-equilibrium flows, and also result in suggestions on how the effectiveness of existing models can be further improved.

1. Introduction

Although turbulence modelling approaches such as LES and some hybrid methods are becoming more widely employed, the Reynolds Averaged Navier Stokes (RANS) framework still provides the most widely used approach in industrial computational fluid dynamics (CFD) simulations, where for parametric investigations of complex flows it is often the only viable alternative.

As has been well documented, because of the empirical nature of the RANS approach, numerous models have been proposed over the years and are in use today, both in commercial and research CFD codes. They can be classified into different categories, depending on the way the Reynolds stresses are modelled (linear and non-linear effective-viscosity, and stress transport), on the type of transport equation used for the turbulent length-scale (ε, ω, etc.), on how many scales are used to model the dissipation rate of turbulence (single-scale and multi-scale) and also on whether they only apply to regions where the flow is fully turbulent, or whether they can be extended to regions where even the largest turbulent eddies present are small enough to be affected by viscosity (high-Reynolds- and low-Reynolds-number models).

The most widely used models tend to be effective-viscosity-based models, such as the k–ε and the k–ω, because of the numerical robustness of the effective-viscosity formulation. The values of the model constants involved are determined with reference to some benchmark flows. These typically include equilibrium shear flows such as fully developed boundary layers, and homogeneous decaying turbulence flows. Consequently, while most models can reliably reproduce such benchmark flows used in their development, it is not always known how reliably they can predict a wider range of flows, such as non-equilibrium homogeneous shear flows, boundary layer flows subjected to either favourable of adverse pressure gradients and the other test flows involved in this study.

The simplest turbulence models are, as mentioned above, the linear eddy-viscosity schemes, which evaluate the Reynolds stresses algebraically through Boussinesq's hypothesis, drawing an analogy between the turbulent Reynolds stresses and the law of viscosity. The Reynolds stresses are thus linearly related to the mean strain rates and the modelling challenge is transferred from the Reynolds stresses to the eddy-viscosity, which is usually expressed as a function of a velocity and a length scale characteristic of the local turbulence. The linear eddy-viscosity models are thus generally classified into three main classes: zero-, one- and two-equation models, the number of equations referring to the number of transport equations solved for the turbulence quantities used to calculate the eddy viscosity.

Zero- and one-equation models, where at least one turbulence quantity is estimated through empirical correlations, typically perform satisfactorily for simple 2D shear flows, such as jets, mixing

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Nomenclature

Roman symbols

a_{ij}	dimensionless Reynolds stress anisotropy tensor, $a_{ij} = \frac{\overline{u_i u_j}}{k} - \frac{2}{3}\delta_{ij}$
f	frequency of oscillation
H	step height in backward facing step flows
k	total turbulent kinetic energy
k_P	turbulent kinetic energy stored by the large scales of motion
k_T	turbulent kinetic energy stored by the small scales of motion
K	acceleration parameter in FPGBL cases, $K = \frac{\nu}{U_\infty^2}\frac{dU_\infty}{dx}$
P	mean pressure
P_k	turbulent kinetic energy production rate, $P_k = -\overline{u_i u_j}\frac{\partial U_i}{\partial x_j}$
P_{ij}	Reynolds stresses production rate, $P_{ij} = -\left(\overline{u_i u_k}\frac{\partial U_j}{\partial x_k} + \overline{u_j u_k}\frac{\partial U_i}{\partial x_k}\right)$
r	radial distance
R	radius
Re	Reynolds number
Re_a	Reynolds number used for oscillatory boundary layer, $Re = U_{om}^2/(\omega\nu)$
Re_t	turbulent Reynolds number, $Re_t = \frac{k^2}{\nu\varepsilon}$
Re_θ	Reynolds number based on the momentum thickness, $Re_\theta = \frac{\theta U_\infty}{\nu}$
S_{ij}	mean strain rate tensor, $S_{ij} = \frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}$
St	Strouhal number, $St = \frac{f\ell}{U_b}$
t	time
T	period, $T = \frac{1}{f}$
U, V, W	mean velocity components
u, v, w	fluctuating velocity components
u', v', w'	rms of the fluctuating velocity, $u' = \sqrt{\overline{u^2}}$; in periodic flows: $u' = \sqrt{\langle u^2\rangle}$
$\overline{u_i u_j}$	Reynolds stress tensor
W_{ij}	vorticity tensor, $W_{ij} = \frac{\partial U_i}{\partial x_j} - \frac{\partial U_j}{\partial x_i}$
x, y, w	coordinate directions
X_R	time-averaged reattachment point in backward facing step flows

Greek symbols

δ_{ij}	Kronecker delta
ε	turbulent kinetic energy dissipation rate
$\tilde{\varepsilon}$	isotropic eddy dissipation rate of the turbulent kinetic energy
ε_{ij}	viscous dissipation term in the Reynolds stress transport equation
ε_P	energy transfer rate between the large and small scales of motion
ε_T	energy transfer rate between the small scales of motion and the dissipation zone
ϕ	phase shift in oscillatory flows
ϕ_{ij}	pressure–strain correlation term in Reynolds stress transport equation
μ	molecular viscosity
μ_t	eddy viscosity
ρ	density
ν	kinematic viscosity
ν_t	kinematic eddy viscosity
θ	momentum thickness
σ	turbulent Prandtl number
ω	specific eddy dissipation rate in the SST and WTS models; angular frequency elsewhere, $\omega = 2\pi f$
ω^+	dimensionless forcing frequency in oscillatory pipe flows, $\omega^+ = \frac{\omega\nu}{u_\tau^2}$

Superscripts

+	non-dimensionalized with inner velocity $U_\tau = \sqrt{\frac{\tau_w}{\rho}}$

Acronyms

APGBL	adverse pressure gradient boundary layer
BFS	backward facing step
CG	Chen and Guo's LEV MTS model
EVM	eddy-viscosity model
FPGBL	favourable pressure gradient boundary layer
GL	Gibson and Launder's RST model
HJ	Hanjalić et al.'s LRN RST model
HLS	Hanjalić et al.'s LEV MTS model
HRN	high-Reynolds-number
KC	Kim and Chen's LEV MTS model
LEV	linear eddy-viscosity
LEVM	linear eddy-viscosity model
LRN	low-Reynolds-number
LS	Launder and Sharma's LRN $k - \tilde{\varepsilon}$ model
MTS	multiple time scale
NKS	Nagano et al.'s LRN LEV MTS model
NLEV	non-linear eddy-viscosity
RANS	Reynolds Averaged Navier Stokes
RST	Reynolds stress transport
SSG	Speziale et al.'s SSG RST model
SST	Menter's SST model
STS	single time scale
TCL	Craft's two component limit LRN RST model
WTS	Wilcox's LRN RST MTS model

layers and zero pressure gradient boundary layers. They tend to fail, however, in flows where the turbulence quantities are not proportional to the mean length scale (Rodi, 1993; Versteeg and Malalasekera, 1995).

Two-equation models are thus considered the minimum physically acceptable level of closure (Speziale, 1995), where the most well known and widely used turbulence model, the k–ε model, proposed by Jones and Launder (1972b), usually used with the constants defined by Launder and Spalding (1974), solves equations for the turbulent kinetic energy, k, and its dissipation rate, ε. There are, however, several two-equation models available in the literature, including those proposed by Launder and Sharma (1974), Wilcox (1988a), Menter (1994), Goldberg and Apsley (1997) and Cheng and Yang (2008). They differ mainly in the variables chosen to solve the transport equations for, and in the modelled coefficients' constants and/or expressions, including the addition of low-Reynolds-number terms for near wall treatment. Even though they avoid the use of some highly constraining assumptions, which the simpler zero- and one-equation models have to rely on, and often perform reasonably well in 2-D shear dominated flows where the normal stresses do not play an important role, two-equation models do not always capture more complex flows quite so well. Nevertheless, they constitute the most widely used class of turbulence models in industry and academia.

In an attempt to maintain the simplicity of calculating the Reynolds stress tensor algebraically, but at the same time to reproduce its anisotropy, a feature not well captured in the linear eddy viscosity formulation, the non-linear eddy-viscosity models were