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Analysis of different RANS models applied to turbulent forced convection

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Abstract

The aim of this work is to study the adequacy of different RANS models in terms of accuracy and numerical performance in the description of turbulent internal forced convection flows. Within RANS modelizations, linear and non-linear eddy-viscosity models and explicit algebraic models are explored. A comparison of the suitability of different two-equation platforms such as k–ϵ and k–ω is also carried out. Three different internal forced convection flows are studied: turbulent plane channel, backward facing step, and confined impinging slot jet. The results are compared with DNS or experimental data available in the literature, reviewing mean and fluctuating velocities, turbulent stresses and global parameters like Nusselt number, skin friction coefficient or reattachment point. Governing partial differential equations are transformed to algebraic ones by a general fully implicit finite-volume method over structured and staggered grids. A segregated SIMPLE-like algorithm is used to solve pressure-velocity fields coupling. A verification procedure based on the generalised Richardson extrapolation is applied to ensure the credibility of the numerical solutions.

Keywords: RANS; Two-equation; Non-linear; Channel flow; Backward facing step; Impinging slot jet

1. Introduction

Turbulence plays an important role in engineering applications as most flows in industrial equipment and surroundings are in turbulent regime. Direct Numerical Simulation (DNS) of these flows using full 3D and time dependent Navier–Stokes (NS) equations is generally restricted to simple geometries and low Reynolds number flows due to the large, if not prohibitive, computational resources required to resolve all the scales of motion. Therefore, the use of turbulence modelling employing statistical techniques for high Reynolds numbers or complex geometries is still necessary. In general, this modelization can be based on volume filtering (Large Eddy Simulation, LES) or time averaging (Reynolds-Averaged Navier–Stokes Simulations, RANS) of the NS-equations. LES models are still too expensive for routine calculation because, even though the smallest eddies are modelled, the larger ones have to be solved in detail (3D and unsteady). Otherwise, RANS models can be appropriate to describe most of the main characteristics of the fluid motions [1].

In the past decades RANS-technique has received great interest because of its wide range of applicability and reasonable computational cost. This technique solves the governing equations by modelling both the large and the small eddies, taking a time-average of variables. As consequence of the average new unknowns, so-called Reynolds stresses arise. Different approaches to evaluate them are: (i) Differentially Reynolds Stress Models (DRSM), (ii) Algebraic Reynolds Stress Models (ARSM), and (iii) Eddy Viscosity Models (EVM) [1].

Although EVM models assuming a linear relation between the turbulent stresses and the mean rate of strain

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Nomenclature

B	nozzle width
$C_{\epsilon 1}, C_{\epsilon 2}, C_\mu$	turbulent model constants/function
C_f	skin friction coefficient
c_p	specific heat
D_h	hydraulic diameter
D, E	turbulent model extra terms
f_1, f_2, f_μ	damping functions
H	step height, height of jet discharge above plate
I	turbulence intensity
k	turbulent kinetic energy
l_e	characteristic length scale
Nu	Nusselt number
P_k	production of k due to shear stress
Pr	Prandtl number
Re_τ	friction Reynolds number
Re_θ	Reynolds number based on momentum thickness
Re_H	Reynolds number based on step height
$\overline{S_{ij}}$	mean rate of strain tensor
St	Stanton number
$\overline{T}$	mean temperature
t	time
$\bar{u}_i$	mean velocity
$\overline{u_i'u_j'}, \overline{u'u'}, \overline{v'v'}, \overline{w'w'}, \overline{u'v'}$	Reynolds stresses
$\overline{u_i'T'}$	turbulent heat flux
$\bar{p}$	mean pressure
$\overline{W_{ij}}$	mean vorticity tensor
Y_c	Yap correction
y^+	dimensionless distance to the nearest wall

Greek symbols

$\alpha^*, \beta, \beta^*, \beta_k, \gamma_k$	turbulent model constants
δ_{ij}	Kronecker delta
ϵ	dissipation rate of k
$\tilde{\epsilon}$	isotropic dissipation rate of k
κ	von Karman's constant $= 0.41$
λ	thermal conductivity
μ	dynamic viscosity
μ_t	eddy or turbulent viscosity
ρ	density
$\sigma_k, \sigma_\epsilon, \sigma_\omega$	turbulent model constants
τ	time scale
ω	specific dissipation rate of k
x_i	Cartesian coordinate in the i-direction

Subscripts

i	i-direction
in	inlet
out	outlet

tensor are extensively used, they present limitations such as isotropy, no-prediction of secondary motions in non-circular ducts, boundary-layer separation, erroneous predictions of the production of turbulence in strong strain fields, etc. In the last few years, with the even-increasing computational capacity, new proposals to overcome many of these deficiencies have started to find their way. Thus, algebraic or non-linear relations can be used to determinate the Reynolds (turbulent) stress tensor without introducing any additional differential equation. Most of these models are or will be incorporated into computational tools and there is no sufficient clarity about which model behaves better even in basic situations with different flow structure. Therefore, systematic studies to establish their properties, numerical performance and spatial requirement in basics and widely studied flows are required.

The main goal of this work is to contribute in an effort to provide conclusions about accuracy, convergence, predictive realism, advantages and shortcomings in the use of explicit algebraic Reynolds stress and linear/non-linear eddy-viscosity models. Furthermore, the effect of using ϵ or ω as length scale variable in the simulated configurations is also studied.

Three basic and intensively investigated configurations, which present different flow structure, are numerically studied. The first case tested is one of the best studied situations: a fully developed turbulent flow in a plane channel [2]. The second case is the flow in a backward facing step, that has a more complex flow structure due to separation and recirculation phenomena [3]. The third case is the flow in an impinging slot jet, which presents a very complex structure despite its relatively simple geometry, involving stagnation, recirculation and adverse pressure zones [4]. The first case serves as a baseline test, and the second and third cases are representative of situations where non-linear and explicit algebraic relations should improve the results due to their characteristics.

Conclusions are extracted after the application of two processes to the studied flows. Firstly, a verification procedure based both on the generalised Richardson extrapolation and the Grid Convergence Index (GCI) is applied to the numerical solutions obtained [5]. Once credibility of the numerical results is assured, the mathematical models are validated by comparison with experimental data and/or DNS results from the literature.

2. Mathematical formulation

2.1. Governing equations

The time-averaged governing equations (continuity, momentum and energy) for incompressible Newtonian fluids, assuming negligible body forces, heat friction, and radiative effects; may be written as follows: