Contents lists available at ScienceDirect

Computers and Mathematics with Applications

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

An improved k–ω–φ–α turbulence model applied to near-wall, separated and impinging jet flows and heat transfer

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ARTICLE INFO

Article history:
Received 16 December 2017
Received in revised form 13 April 2018
Accepted 15 April 2018
Available online xxxx

Keywords:
Turbulence model
Elliptic blending
Near-wall flow
Separated flow
Impinging jet flow
Convective heat transfer

ABSTRACT

A turbulence model based on elliptic blending concept, referred to as improved k–ω–φ–α model compared against the original k–ω–φ–α model developed previously, is developed and verified. This model consists of four governing equations. Among them the k and ω equations are based on the Wilcox's k–ω model with some modifications and improvements according to the original k–ω–φ–α model, and the φ and α equations are extracted from the original k–ω–φ–α model directly without any change. The improved k–ω–φ–α model is applied to near-wall, separated and impinging jet flows and convective heat transfer, i.e. the 2D fully developed channel flow, the 2D backward-facing step flow, the 2D impinging jet flow, and the convective heat transfer in the 2D fully developed channel flow and the 2D impinging jet flow. The computational results are compared with available DNS and experimental data and also to those computed using the original k–ω–φ–α model and the popular Menter's SST k–ω model. It is shown that the improved k–ω–φ–α model has better numerical stability, higher computational efficiency and more concise form than the original k–ω–φ–α model. In addition, compared with the original k–ω–φ–α model, the improved k–ω–φ–α model can yield similar velocity profiles in the fully developed channel flow and step flow and friction and pressure coefficients in the step flow and very close temperature profiles in the fully developed channel flow. Moreover, it shows significant improvements on the predictions for the fluid flow and heat transfer in the impinging jet flow. As a whole, the improved k–ω–φ–α model predicts better results than both of the original k–ω–φ–α model and the SST k–ω model.

1. Introduction

Accurately predicting turbulent information is of importance from practical and theoretical points of view because turbulent flows are commonly encountered in engineering applications. It is well known that the Direct Numerical Simulation (DNS) can solve directly the Navier–Stokes (N–S) equations, which are able to describe the details of turbulent motions, without any simplification. However, its huge computing capacity prevents it from being applied in real engineering problems. Alternatively, the Reynolds-Averaged N–S equations (corresponding to RANS methods) and the filtered N–S equations (corresponding to Large Eddy Simulation method, LES) are primarily utilized in practices. Although LES shows more powerful ability than RANS for turbulence simulation, especially for unsteady turbulent flows, its application range is

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https://doi.org/10.1016/j.camwa.2018.04.020
0898-1221/

Please cite this article in press as: X.L. Yang, Y. Liu, An improved k–ω–φ–α turbulence model applied to near-wall, separated and impinging jet flows and heat transfer, Computers and Mathematics with Applications (2018), https://doi.org/10.1016/j.camwa.2018.04.020.

Nomenclature

Greek letters

α	Elliptic variable
$\beta, \gamma, \beta^*, \beta_0$	Turbulence model coefficients
δ	Half width of the channel
$\varepsilon, \varepsilon_h$	Dissipation rate and homogeneous dissipation rate
ω, ω_h	Specific dissipation rate and homogeneous specific dissipation rate
κ	Von Karman constant
μ, ν	Molecular dynamic and kinematic viscosity
μ_t, ν_t	Turbulent dynamic and kinematic viscosity
Ω_{ij}	Vorticity rate tensor
φ	Wall-normal turbulent anisotropy, $\varphi = \overline{v^2}/k$
ρ	Density of fluid
$\sigma_d, \sigma_{d0}, \sigma_{d1}$	Turbulence model constants
$\sigma_k, \sigma_\omega, \sigma_\varepsilon, \sigma_\varphi$	Turbulent Prandtl numbers
τ, τ_w	Shear stress and wall shear stress
θ	Mean temperature of the fluid
θ_w	Wall temperature
θ_{in}	Fluid temperature at inlet
θ^+	The normalized temperature
ζ	Turbulence model constant

Latin letters

B	Width of the inlet of the jet
C_f	Skin-friction coefficient
C_p	Pressure coefficient
c_p	Specific heat of the fluid
$C_{\varepsilon1}, C^*_{\varepsilon1}, C_{\varepsilon2}, C^*_{\varepsilon2}, C_{\varepsilon3}, C_{\varepsilon4}, C_{\varepsilon5}, C_\mu, C_L, C_T, C_\eta, C_1, C_2$	Turbulence model parameters
C_D	Cross-diffusion term
D_k, D^t_k	Turbulent diffusion of k
E	The 'E' term
f	Elliptic relaxation function
f_k, f_ω, f_μ	Damping functions
f_β	Additional function
F_b	Blending function
G_k	Production of turbulent kinetic energy
H	Step height
I	Turbulent intensity
k	Turbulent kinetic energy or thermal conductivity of the fluid
L	Turbulence length scale
n	Turbulence model constant
Nu	Nusselt number
p	Pressure or turbulence model constant
Pr	Molecular Prandtl number
Pr_t	Turbulent Prandtl number
q	Heat flux
Re_H	Reynolds number based on H
Re_t	Turbulent Reynolds number
Re_τ	Friction velocity based Reynolds number
S	Magnitude of strain rate
S_{ij}	Strain rate tensor
t	Physical time
T	Turbulence time scale
$T_{\lim}$	Upper bound of the turbulence time scale
u_i	Instantaneous velocity vector
u, v, w	Velocities along x, y and z directions
U_b	Mean velocity of the bulk flow