International Journal of Heat and Fluid Flow 51 (2015) 268–284

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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

Progress in the extension of a second-moment closure for turbulent environmental flows ☆

Y. Kuwata, K. Suga *

Department of Mechanical Engineering, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan

ARTICLE INFO

Article history:
Available online 11 November 2014

Keywords:
Turbulence modelling
Second-moment closure
Porous media
Vegetated flow

ABSTRACT

An advanced second-moment closure for the double-averaged turbulence equations of porous medium and vegetation flows is proposed. It treats three kinds of second moments which appear in the double-averaged momentum equation. They are the dispersive covariance, the volume averaged (total) Reynolds stress and the micro-scale Reynolds stress. The two-component-limit pressure–strain correlation model is applied to model the total Reynolds stress equation whilst a novel scale-similarity non-linear k–ε two-equation eddy viscosity model is employed for the micro-scale turbulence. For the dispersive covariance, an algebraic relation is applied. Model validation in several fully developed homogeneous porous medium flows, porous channel flows and aquatic vegetation canopy flows is performed with satisfactory agreement with the data.

© 2014 Elsevier Inc. All rights reserved.

1. Introduction

Due to the recent spread of high-performance low-price digital computers, it is generally true that large eddy simulations (LESs) are replacing the methods by the Reynolds-averaged Navier–Stokes (RANS) equations for predicting turbulent flows. However, for mechanical, process and civil/environmental engineers, LESs are likely over the capability of their computers since their routine issues are very large in scale and simultaneously include much smaller-scale geometries. For example, simulations around/over whole-scale motor vehicles and land-scale vegetated canopies require huge computational domains and treating tiny sub-components. Performing LESs for those issues is certainly over the capability of the ordinal computers of the engineers in hand. It will be true for another few decades as Hanjalić (2005) reviewed. Therefore, RANS models will be still useful for those issues and there is no doubt that second-moment closures (or Reynolds stress models) are better routes to model turbulence in engineering and the environment as presented by Hanjalić and Launder (2011).

Although the original idea of the second-moment closure goes back to Chou (1945) and Rotta (1951), its pragmatic forms were developed by the people of Imperial College (Hanjalić and Launder, 1972, 1976; Launder et al., 1975; Gibson and Launder, 1978) in 1970s. Indeed, the model of Launder et al. (1975) has been referred to as the standard second-moment closure and implemented in many versions of commercial software. It is well known that the key issue of the second-moment closure is modelling the pressure–strain correlation term appearing in the Reynolds stress transport equation. (The turbulent energy transport equation does not keep the pressure–strain correlation due to its traceless nature.) The pressure–strain term is split into two parts: the *slow* and *rapid* terms, with correction for wall reflection when body force effects are absence. Although the detailed and complete model information can be seen in Hanjalić and Launder (2011), some related comments to the present study may need summarising briefly.

The slow term expresses the process of anisotropic turbulence to become isotropic. It occurs slowly due to the anisotropy of turbulence. For the slow term, Rotta (1951) proposed the liner return-to-isotropy model consisting of a liner term (in terms of the anisotropic Reynolds stress tensor). It was followed by many other models (e.g., Hanjalić and Launder, 1972, 1976; Launder et al., 1975; Gibson and Launder, 1978). However, by Caley–Hamilton's theorem, the quadratic form is enough and does not require any higher order terms for the general expression. Such non-linear forms were adopted by later models (e.g., Lumley, 1978; Speziale et al., 1991; Craft and Launder, 1996).

Modelling the rapid term requires more complexity. Since the rapid term consists of a fourth rank tensor multiplied by mean velocity gradients, rapid deformation of the flow is reflected to this term immediately. The simple linear quasi-isotropic (QI) model was developed considering three basic conditions: symmetry,

☆ Authors' names are listed alphabetically.
* Corresponding author.
E-mail address: suga@me.osakafu-u.ac.jp (K. Suga).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.10.011
0142-727X/© 2014 Elsevier Inc. All rights reserved.

Nomenclature

a^A_{ij}	anisotropic stress: $R^A_{ij}/k^A - 2\big/3\delta_{ij}$
$\mathcal{A}$	Lumley's stress flatness parameter: $1-\frac{9}{8}(\mathcal{A}_2-\mathcal{A}_3)$
$\mathcal{A}_2$	$a^A_{ij}a^A_{ij}$
$\mathcal{A}_3$	$a^A_{ij}a^A_{jk}a^A_{ki}$
c_F	Forchheimer coefficient
C^F_{ij}	Forchheimer tensor
C^{F*}_{ij}	modified Forchheimer tensor
C^{Fl}_{ij}	molecular part of Forchheimer tensor
C^{Fs}_{ij}	structural part of Forchheimer tensor
C^{Ft}_{ij}	turbulent part of Forchheimer tensor
D_p	mean pore diameter
$\mathcal{E}$	dissipation rate of $\mathcal{K}$
$\mathcal{E}_{ij}$	dissipation rate of $\mathcal{T}_{ij}$
f_i	drag force term
$\mathcal{F}_{ij}$	drag force term of $\mathcal{T}_{ij}$
H	cross-streamwise pitch of rod array or channel height
k^A	total turbulent kinetic energy: $R^A_{kk}\big/2$
k_m	micro-scale turbulent kinetic energy: $r_{kk}/2$
k_M	macro-scale turbulent kinetic energy: $R_{kk}/2$
K	permeability
K_{ij}	permeability tensor
K^*_{ij}	modified permeability tensor
K^{ij}	inverse matrix of permeability tensor
$\mathcal{K}$	dispersive kinetic energy: $\mathcal{T}_{kk}/2$
ℓ	turbulent length scale: $(k^A)^{3/2}/\varepsilon^A$
ℓ_s	porous structural length scale
p	pressure
r_{ij}	micro-scale Reynolds stress: $\overline{\langle \tilde{u}'_i\tilde{u}'_j\rangle^f}$
R^A_{ij}	total Reynolds stress (volume averaged Reynolds stress): $\overline{\langle u'_iu'_j\rangle^f}$
Re_K	permeability Reynolds number: $u_\tau\sqrt{K}/\nu$
R_{ij}	macro-scale Reynolds stress: $\overline{\langle u'_i\rangle^f\langle u'_j\rangle^f}$
R^A_t	turbulent Reynolds number: $(k^A)^2/(\nu\tilde{\varepsilon}^A)$
R^M_t	macro-scale turbulent Reynolds number: $k^2_M\big/(\nu\tilde{\varepsilon}_M)$
R^m_t	micro-scale turbulent Reynolds number: $k^2_m\big/(\nu\tilde{\varepsilon}_m)$
S_{ij}	strain tensor: $\frac{\partial\overline{\langle u_i\rangle^f}}{\partial x_j}+\frac{\partial\overline{\langle u_j\rangle^f}}{\partial x_i}$
t	time
$\mathcal{T}_{ij}$	dispersive covariance: $\langle\bar{\tilde{u}}_i\bar{\tilde{u}}_j\rangle^f$
u_i	velocity
$\hat{u}_i$	relative velocity
u_τ	friction velocity
U_b	bulk mean velocity
U_d	Darcy velocity
x	streamwise coordinate
y	wall normal coordinate
y'	normal distance from the porous surface
δ_{ij}	Kronecker delta
Ω_{ij}	vorticity tensor: $\frac{\partial\overline{\langle u_i\rangle^f}}{\partial x_j}-\frac{\partial\overline{\langle u_j\rangle^f}}{\partial x_i}$
ε^A	dissipation rate of total turbulent energy k^A
ε_m	dissipation rate of micro-scale turbulent energy k_m
ε_M	dissipation rate of macro-scale turbulent energy k_M
ε^A_{ij}	dissipation rate of total Reynolds stress R^A_{ij}
$\tilde{\varepsilon}^A$	isotropic part of ε^A
$\tilde{\varepsilon}_m$	isotropic part of ε_m
$\tilde{\varepsilon}_M$	isotropic part of ε_M
ϕ	variable
φ	porosity
ν	kinematic viscosity
ν^A_t	eddy viscosity
ν^m_t	micro-scale eddy viscosity
ρ	fluid density
τ^A	turbulent time scale: $k^A/\tilde{\varepsilon}^A$
τ_m	micro-scale turbulent time scale: $k_m/\tilde{\varepsilon}_m$
τ_M	macro-scale turbulent time scale: $k_M/\tilde{\varepsilon}_M$
$\overline{\phi}$	Reynolds averaged value of ϕ
ϕ'	fluctuation of $\phi : \phi-\overline{\phi}$
$\langle\phi\rangle$	superficial averaged value of ϕ
$\langle\phi\rangle^f$	intrinsic (fluid phase) averaged value of ϕ
$\tilde{\phi}$	dispersion of $\phi : \phi-\langle\phi\rangle^f$

continuity and normalisation, by Hanjalić and Launder (1972), Launder et al. (1975). Later validation studies suggested that a truncated form of the linear model called the isotropization-of-production (IP) model (Launder et al., 1975) worked better. A more complicated model for the rapid term called the quasi-liner model was derived by Hanjalić and Launder (1972). Later, Speziale et al. (1991) derived a similar form by a more rigorous tensor analysis. This model was proven to be another successful model (Jakirlić and Hanjalić, 2013). The more general cubic model (Fu, 1988; Craft and Launder, 1996) was developed considering the two-component-limit (TCL) turbulence condition as well as the aforementioned three basic conditions. Hence, such a model (e.g., Craft and Launder, 1996; Craft, 1998; Batten et al., 1999) is called the TCL model. (Due to the analysis using Caley–Hamilton's theorem by Johansson and Hällback (1994), it was suggested that fourth order terms were necessary for the most general form.)

As for the low-Reynolds-number (LRN) modelling, Hanjalić and Launder (1976) firstly proposed an LRN second-moment closure whilst Launder and Shima (1989) developed an LRN model based on the model of Gibson and Launder (1978) introducing the effects of stress anisotropy invariants (Lumley, 1978). Hanjalić and Jakirlć (1998) applied the dissipation tensor invariants of Hanjalić and Jakirlć (1993) to calculate the LRN effects in separating flows. The more recent LRN model of Craft and Launder (1996) adopted the stress anisotropy invariants and devised the inhomogeneity correction terms which replaced the wall-reflection terms. Their model employed the quadratic and cubic forms for the slow and rapid terms, respectively.

Although the major issues in the development of the second-moment closures might have been solved in the last century, some further discussions are still going on. Jakirlić and Hanjalić (2002) proposed a new model for the dissipation tensor consistent with the near wall limits. The University of Manchester group are now focusing on the extension of the TCL model to unsteady flows (Al-Sharif et al., 2010; Heynes et al., 2013; Craft et al., 2014). Based on the framework of the TCL model, the present authors (Kuwata and Suga, 2013a) developed a second-moment closure for porous medium flows.

It is readily understood that precisely describing the shape of every pore element of porous media requires despairing efforts for simulating porous medium flows. Vegetation canopies (Finnigan, 2000) are also kinds of porous media whose solid matrices (: plants) are not totally rigid. Thus, applying the volume averaging theory (VAT) (Whitaker, 1986, 1996) to the flow equations is therefore the common approach in engineering computational fluid dynamics (CFD) for porous medium and vegetated

Download English Version:

https://daneshyari.com/en/article/655218

Download Persian Version:

https://daneshyari.com/article/655218

Daneshyari.com