International Journal of Heat and Mass Transfer 72 (2014) 98–113

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Turbulent heat transfer in a counterflow moving porous bed using a two-energy equation model

Marcelo J.S. de Lemos *, Ana C. Pivem

Departamento de Energia – IEME, Instituto Tecnológico de Aeronáutica – ITA, 12228-900 São José dos Campos, SP, Brazil

ARTICLE INFO

Article history:
Received 25 September 2013
Received in revised form 18 December 2013
Accepted 18 December 2013
Available online 25 January 2014

Keywords:
Counterflow
Moving bed
Turbulence
Heat transfer
Porous media

ABSTRACT

This work investigates the influence of physical properties on heat transfer in a turbulent counterflow in a moving bed using the High and Low Reynolds number turbulence models, in which the working fluid flows in opposite direction to that of the steady movement of the permeable rigid medium. Transport equations for flow and heat transfer in a moving bed equipment are applied and discretized using the control-volume method. The system of algebraic equations obtained is relaxed via the SIMPLE algorithm. The effects of Reynolds number, solid-to-fluid velocity ratio, permeability, porosity, ratio of solid-to-fluid thermal capacity and ratio of solid-to-fluid thermal conductivity on heat transport are investigated. Results indicate that motion of solid material, contrary to the direction of the fluid, enhances heat transfer between phases. The same effect was observed for smaller Darcy number and porosity, as well as for higher solid-to-fluid thermal capacity and thermal conductivity ratios. When the intrinsic fluid velocity increases there is a greater conversion of mechanical kinetic energy into turbulence, increasing the final levels of the turbulent kinetic energy for both High and Low Reynolds number models.

1. Introduction

Many applications in industry are concerned with turbulent flow through permeable beds. Among them one can mention moving bed technology in counterflow configuration. Examples about such technology are found in equipment for chemical compound separation, recuperation of petrochemical processes, drying of grains and seeds, removal of organic matter in affluents and in certain types of heat exchangers, just to mention a few applications. Within this context, Yang (2009) [1] showed numerical simulation of turbulent flow and heat transfer in heat exchangers fitted with porous media, where a permeable material was inserted in a heat exchanger to improve its process performance. There, the k–ε model was applied to treat turbulence. Littman et al. (1995) [2], Mansoori et al. (2002) [3] and Zhang and Reese (2001) [4] presented studies about turbulent gas–solid transport, where [2] showed the effect of particle diameter, particle density and loading ratio on the effective drag coefficient in steady transport, [3] presented the thermo-mechanical modeling of turbulence heat transfer in gas–solid flows including particle collisions and [4] studied particle-gas turbulence interactions using a kinetic theory approach applied to granular flows. Turbulent flows in composite domains, involving both a finite porous medium and a clear region, have been also investigated in the literature [5,6].

Several studies on laminar and turbulent flow though permeable media in a number of configurations were conducted and compiled in a book [7]. In those studies, when analyzing heat transport through the phases composing the medium, both the local thermal equilibrium model (LTE) as well as thermal non-equilibrium approach (LTNE) where tackle [8]. For cases when the solid phase also moves, computations for a moving porous beds in parallel [9] and counterflow configurations, have been presented [10]. However, studies in [9,10] were restricted to the laminar flow regime.

The purpose of this contribution is to extend the work in [10], which was limited to laminar flow, to the turbulent regime. One should point out that when going from simulating a simpler laminar flow to accurately predicting turbulent flow regime within acceptable accuracy, not only a proper mathematical model has to be employed, but also the use of an adequate numerical scheme and stable solution algorithm have to be employed. And yet, it is the behavior of the turbulence kinetic energy associated with the flow that is an important result to be observed. Such quantity, evidently, cann ot be obtained with simpler laminar models.

The study herein includes investigation on heat transfer between phases when several flow and material parameters as varied, including the effect Reynolds number, slip ratio, permeability, as well as

---

* Corresponding author. Tel.: +55 12 3947 5860; fax: +55 12 3947 5842.
E-mail address: delemos@ita.br (M.J.S. de Lemos).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.12.051

Nomenclature

A_i	interfacial area [m^2]
a_i	interfacial area per unit volume, $a_i = A_i/\Delta V$ [m^{-1}]
c_F	Forchheimer coefficient
c_k	non-dimensional turbulence model constant
c's	model constants
D	particle diameter [m]
$\mathbf{D}$	deformation rate tensor, $\mathbf{D} = [\nabla\mathbf{u} + (\nabla\mathbf{u})^T]/2$[s^{-1}]
f_2	damping function
f_μ	damping function
G^i	production rate of $\langle k\rangle^i$ due to the porous matrix
H	distance between channel walls [m]
k	turbulent kinetic energy per unit mass [m^2/s^2]
$\langle k\rangle^i$	intrinsic (fluid) average of k
$\langle k\rangle^v$	volume (fluid + solid) average of k
K	permeability [m^2]
L	channel length [m]
p	thermodynamic pressure [N/m^2]
$\langle p\rangle^i$	intrinsic (fluid) average of pressure p [N/m^2]
Re	Reynolds number based on $\bar{\mathbf{u}}_D$
Re_D	Reynolds number based on $\bar{\mathbf{u}}_{rel}$
$\bar{\mathbf{u}}$	microscopic time-averaged velocity vector [m/s]
$\langle\bar{\mathbf{u}}\rangle^i$	intrinsic (fluid) average of $\bar{\mathbf{u}}$ [m/s]
$\bar{\mathbf{u}}_D$	Darcy velocity vector, $\bar{\mathbf{u}}_D = \phi\langle\bar{\mathbf{u}}\rangle^i$ [m/s]
$\bar{\mathbf{u}}_{rel}$	relative velocity based on total volume, $\bar{\mathbf{u}}_{rel} = \bar{\mathbf{u}}_D - \mathbf{u}_S$ [m/s]
u_τ	friction velocity [m/s]
X	dimensionless coordinate
y_+	dimensionless distance among wall and first node, $y^+ = \frac{y_w u_\tau}{\nu}$

Greek

ε	dissipation rate of k, $\varepsilon = \mu\overline{\nabla\mathbf{u}' : (\nabla\mathbf{u}')^T}/\rho$ [m^2/s^3]
$\langle\varepsilon\rangle^i$	intrinsic (fluid) average of ε
ϕ	porosity
μ	fluid dynamic viscosity [kg/(m s)]
μ_t	turbulent viscosity [kg/(m s)]
μ_{t_ϕ}	macroscopic turbulent viscosity [kg/(m s)]
ν	kinematic viscosity [m^2/s]
ρ	density [kg/m^3]
$\sigma_k, \sigma_\epsilon$	non-dimensional constants

Subscript

s,f	s = solid, f = fluid

thermal capacity and thermal conductivity ratios between the moving solid phase and the permeating fluid. With that, a wider range of engineering systems can be analyses with the model detailed in [7].

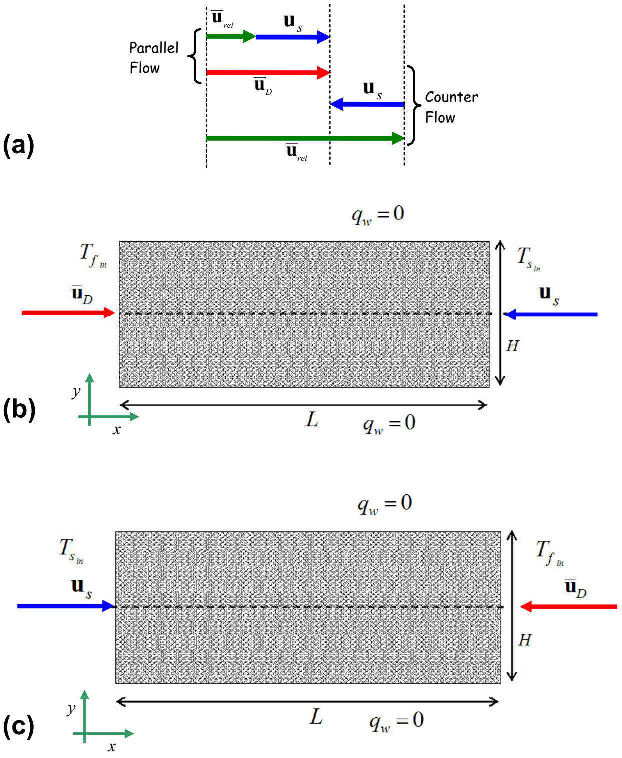

Fig. 1. Porous bed reactor with a moving solid matrix: (*a*) Flow configurations, (*b*) Counterflow with fluid moving west to east, (*c*) Counterflow with fluid moving east to west.

1.1. Macroscopic governing equations

The equations to follow are fully available in the open literature and for that their derivation are not repeated here [7]. Two possible

Table 1
Damping functions and constants for turbulence models.

	High Reynolds number turbulence model proposed by Launder and Spalding (1974) [13]	Low Reynolds number turbulence model proposed by Abe et al. (1992) [14]
f_μ	1.0	$\left\{1 - \exp\left[-\frac{(\nu\varepsilon)^{0.25}y}{14\nu}\right]\right\}^2\left\{1 + \frac{5}{(k^2/\nu\varepsilon)^{0.75}}\exp\left[-\left(\frac{(k^2/\nu\varepsilon)}{200}\right)^2\right]\right\}$
f_2	1.0	$\left\{1 - \exp\left[-\frac{(\nu\varepsilon)^{0.25}y}{3.1\nu}\right]\right\}^2\left\{1 - 0.3\exp\left[-\left(\frac{(k^2/\nu\varepsilon)}{6.5}\right)^2\right]\right\}$
σ_k	1.0	1.4
σ_ε	1.33	1.3
c_1	1.44	1.5
c_2	1.92	1.9

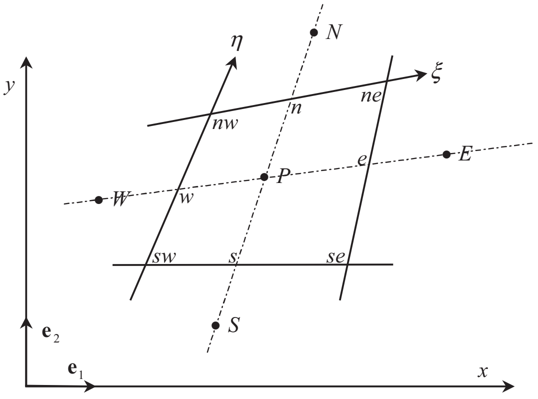

Fig. 2. Control volume and notation.