International Journal of Heat and Mass Transfer 101 (2016) 1003–1015

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Closure of a macroscopic turbulence and non-equilibrium turbulent heat and mass transfer model for a porous media comprised of randomly packed spheres

Furqan Ahmad Khan, Anthony Gerald Straatman *

Department of Mechanical & Materials Engineering, Western University, London, Ontario N6A 5B9, Canada

ARTICLE INFO

Article history:
Received 17 February 2016
Received in revised form 24 May 2016
Accepted 24 May 2016

Keywords:
Computational fluid dynamics (CFD)
Heat transfer
Mass transfer
Turbulence modeling
Porous media
Bed of spheres

ABSTRACT

Turbulent heat and mass transfer in packed beds of spheres is widely encountered in industrial and food storage applications and, as such, modeling of such cases is of interest in design and development. Herein, we propose a closure of the volume- and time-averaged (macroscopic) turbulence, and non-equilibrium turbulent heat and mass transfer equations for randomly packed spheres, based on computational results of flow and heat transfer for a unique geometric model. In this respect, the closure results are derived from pore-level (microscopic) information obtained from numerical simulations of turbulent heat and fluid flow. Turbulence is incorporated at both levels using the k–ε model, and the dispersive effects of turbulence are also considered. For the momentum equation, the closure is sought for the Darcy and Forchheimer terms. For the non-equilibrium heat and mass transport equations, we obtain closures for the dispersion, turbulent flux, turbulent dispersion, and interfacial heat and mass transfer terms. The closure results are found to be dependent upon the porosity and Reynolds number. However, the mean sphere diameter and its local variation inside the representative elemental volumes only weakly affect the results. The closure results are presented as power law-based correlations, such that they can be easily implemented in a volume-time-averaged framework.

1. Introduction

Packed beds of spheres are widely encountered in engineering applications related to the chemical processing industry, and the food storage and processing industries. The convective drying of produce stacks using warm airflow is one example of such problems. In many such applications, the sphere size is significant and heat and mass transfer are turbulent. Furthermore, it is often necessary to couple the solid and fluid phases of the process, which requires consideration of non-equilibrium heat and mass exchanges. The complex nature of such problems makes numerical modeling an attractive approach for gaining insight into the underlying physical phenomena. In this respect, turbulence modeling inside beds of packed spheres becomes critical.

Two approaches are commonly used to model the aforementioned problems. In one approach, the bed of spheres is modeled at the microscopic scale, which is characterized by the length scale of spheres. At this scale, the transport equations are used in their usual forms. However, extensive computational resources are required to model the problem. The second approach is to model the packed bed as porous continuum. By this approach, the bed of spheres is up-scaled to the macroscopic level, and the domain is considered to be comprised of solid and fluid phases with parameters like porosity and permeability describing the resistance to flow through the domain. The benefit of the macroscopic approach is that it eliminates the necessity of modeling the problem at the scale of spheres, which significantly reduces the required computational effort. However, to use this approach, the detailed information about the pore-level flow field and the energy and mass exchanges have to be determined and provided via constitutive models characterizing the porous region. The up-scaling of the mathematical formulation is carried out by volume-averaging the transport equations for mass, momentum, energy and turbulence.

The macroscopic, or volume-averaged, approach for modeling turbulent heat and mass transfer inside packed beds of spheres has been widely used for applications related to food storage and refrigeration. For example, Tapsoba et al. [1] and Moureh et al. [2,3] modeled turbulent airflow inside and around slotted-enclosures filled with spheres to understand the airflow distribution of the problem. In another study, Delele et al. [4] simulated a cold

* Corresponding author.
E-mail address: astraatman@eng.uwo.ca (A.G. Straatman).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.106
0017-9310/

Nomenclature

a_{fs}	interfacial surface area of porous media, m^2
A_{fs}	specific interfacial surface area of porous media, m^{-1}
c_E	inertial coefficient of porous media
c_p	specific heat at constant pressure in fluid region, J/(kg.K)
c_{ps}	specific heat in solid region, J/(kg.K)
$C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ	turbulence model constants
D	mass diffusivity coefficient, m^2/s
D	deformation tensor
d_s	mean sphere diameter, cm
f	body force per unit mass, m/s^2
h	specific enthalpy, J/kg
h_{fg}	latent heat of evaporation at 0 °C in fluid region, J/kg
h_{fs}	interfacial heat transfer coefficient in porous media, $W/(m^2.K)$
h_{fsm}	interfacial mass transfer coefficient in porous media, m/s
I	unit tensor
k	turbulent kinetic energy per unit mass, m^2/s^2
K	Darcy permeability of porous media, m^2
L	REV length, m
$\dot{m}$	mass flow rate, kg/s
n	unit vector normal to the surface
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
R	gas constant, J/(kg.K)
Re	Reynolds number
S	source in a transport equation
Sc	Schmidt number
T	temperature, °C
t	time, s
U	extrinsic velocity, m/s
v	fluid velocity vector [=(u, v, w)], m/s
Y	mass fraction
ε	dissipation rate of turbulent kinetic energy, m^2/s^3
μ_f	dynamic viscosity, $N.s/m^2$
μ_t	turbulent eddy viscosity, $N.s/m^2$
ν_f	kinematic viscosity, m^2/s
ν_t	turbulent kinematic viscosity, m^2/s
σ_T	turbulent Prandtl number for energy equation
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε
ρ_s	density of solid, kg/m^3
ρ_f	density of fluid mixture, kg/m^3
λ_x	thermal conductivity of x-constituent of porous media, W/(m.K)
ϕ	porosity
φ	a quantity
$\bar{\varphi}$	time-average of φ
$\langle\varphi\rangle$	extrinsic volume-average of φ
$\langle\varphi^x\rangle$	intrinsic volume-average of φ (x is fluid or solid-constituent of porous media)
$\langle\bar{\varphi}\rangle$	volume-time-average ofφ

Subscripts and superscripts

a	air
$disp$	dispersive
eff	effective property in porous media
f	fluid
fs	interfacial
t	turbulent
v	vapor
w	water

storage room containing boxes loaded with spheres to predict airflow, temperature and humidity distribution. Similarly, the distribution of a gas used to control fruit ripening inside cold storage rooms was numerically predicted by Ambaw et al. [5]. In addition, the cooling process of packed food stacks was simulated by Alvarez and Flick [6]. All of these studies considered porous media at the macroscopic scale and modeled turbulence using eddy viscosity based models or Reynolds stress models (RSM).

To better understand the difference between the modeling approaches and the information required for the volume-averaged approach, we shift our discussion briefly to turbulence modeling using the eddy-diffusivity concept at the macroscopic scale of porous media. At the macroscopic scale, the modeling of turbulence generally involves volume- and time-averaging of the transport equations. In the volume-averaging operation, a transport equation is integrated over a Representative Elemental Volume (REV) of porous material. The volume-averaged value of a quantity φ, as described by Whitaker [7], is defined as

$$\langle\varphi\rangle = \frac{1}{V}\int_{V_f} \varphi dV \tag{1}$$

where, V refers to the volume over which the averaging process is carried out, V_f is the fluid volume inside V, and $\langle\varphi\rangle$ is defined as the extrinsic-average of φ. Using a similar approach, an intrinsic-averaged quantity $\langle\varphi\rangle^f$ is expressed as

$$\langle\varphi\rangle^f = \frac{1}{V_f}\int_{V_f} \varphi dV \tag{2}$$

The ratio $\langle\varphi\rangle/\langle\varphi\rangle^f$ then defines the porosity ϕ of porous media. Moreover, $\langle\varphi\rangle$ can be split into φ^f and its spatial deviation $\tilde{\varphi}$ as [7]

$$\varphi = \langle\varphi\rangle^f + \tilde{\varphi} \tag{3}$$

Time-averaging can also be utilized in the porous region to characterize the fluctuations of a quantity in time, similar to that done in pure fluid regions. The time-averaging of a quantity φ is give as [8]

$$\bar{\varphi} = \frac{1}{\Delta t}\int_t^{t+\Delta t} \varphi dt \tag{4}$$

Then, similar to that done for spatial deviations in Eq. (3), φ can be split into $\bar{\varphi}$ and its temporal deviation φ' as

$$\varphi = \bar{\varphi} + \varphi' \tag{5}$$

To model a quantity fluctuating in time at the macroscopic scale of porous media, both volume- and time-averaging operations are required. In this respect, Pedras and de Lemos (PDL) [8] introduced the concept of double decomposition, which involves volume-averaging followed by time-averaging or vice versa. The group showed that the order of averaging does not change the solution, i.e. $\langle\bar{\varphi}\rangle^f = \langle\bar{\varphi}\rangle^f$.

Existing literature on the macroscopic modeling of turbulence inside porous regions mainly utilizes the k–ε model, by which turbulence is characterized by the energy (k) of an average energy-containing eddy and its dissipation rate (ε). The basic derivation of the k–ε model is beyond the scope of this article, and the interested reader is directed to Wilcox [9] for a full mathematical treatment. In general, existing k–ε models can be classified based on the manner they define turbulent kinetic energy k. In this respect, early attempts made by Lee and Howell [10], Wang and Takle [11], and Antohe and Lage [12] defined the macroscopic turbulent kinetic energy k_m as [13]