International Communications in Heat and Mass Transfer 36 (2009) 996–1001

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical simulation of turbulent combustion in porous materials ☆

Marcelo J.S. de Lemos

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

ARTICLE INFO

Available online 6 August 2009

Keywords:
Porous burner
Combustion
Radiation
Ceramic foam
Turbulence modeling

ABSTRACT

This paper presents one-dimensional simulations of combustion of an air/methane mixture in porous materials using a model that explicitly considers the intra-pore levels of turbulent kinetic energy. Transport equations are written in their time-and-volume-averaged form and a volume-based statistical turbulence model is applied to simulate turbulence generation due to the porous matrix. Four different thermo-mechanical models are compared, namely Laminar, Laminar with Radiation Transport, Turbulent, Turbulent with Radiation Transport. Combustion is modeled via a unique simple closure. Preliminary testing results indicate that a substantially different temperature distribution is obtained depending on the model used. In addition, for high excess air peak gas temperature is reduced and the flame front moves towards the exit of the burner. Also, increasing the inlet flow rate for stoichiometric mixture pushes the flame out of the porous material.

1. Introduction

Combustion in inert porous media has been extensively investigated due to the many engineering applications and demand for developing high-efficiency power production devices. The growing use of efficient radiant burners can be encountered in the power and process industries and, as such, proper mathematical models of flow, heat and mass transfer in porous media under combustion can benefit the development of such engineering equipment.

Accordingly, the advantages of having a combustion process inside an inert porous matrix are today well documented in the literature [1–8], including a recent review on lean-combustion porous burners [9]. Hsu et al. [10] points out some of its benefits including higher burning speed and volumetric energy release rates, higher combustion stability and the ability to burn gases of a low energy content. Driven by this motivation, the effects on porous ceramics inserts have been investigated in Peard et al. [11], among others.

Turbulence modeling of combustion within inert porous media has been conducted by Lim and Matthews [12] on the basis of an extension of the standard k–ε model of Jones and Launder [13]. Work on direct simulation of laminar in premixed flames, for the case when the porous dimension is of the order of the flame thickness, has also been reported in Sahraoui and Kaviany [14].

Further, non-reactive turbulence flow in porous media has been the subject of several studies [15–17], including many applications such as flow though porous baffles [18], channels with porous inserts [19] and buoyant flows [20]. In such line of work, intra-pore turbulence is accounted for in all transport equations, but only non-reactive flow has been previously investigated in [15–20].

Motivated by the foregoing, this paper extends the previous work on turbulence modeling in porous media to include simulation of reactive flows. Computations are carried out for inert porous material considering one-dimensional turbulent flow and a two-energy equation model.

In addition, four different thermo-mechanical models are here compared, namely Laminar Flow, Laminar Flow with Radiation Transport, Turbulent Flow and Turbulent Flow with Radiation Transport, being the last two models derived from the work in [15–20]. As such, this contribution compares the effects of radiation and turbulence in smoothing temperature distributions within porous burners.

2. Mathematical model

As mentioned, two of the thermo-mechanical models here employed, involving turbulent flow with and without radiation transport, are based on the "double-decomposition" concept [15,16], which has been also described in detail in a book [17]. In that work, transport equations are volume-averaged according to the Volume Averaging Theorem [21–23] in addition to using time decomposition of flow variables followed by standard time-averaging procedure for treating turbulence.

As the entire equation set is already fully available in the open literature, these equations will be just reproduced here and details about their derivations can be obtained in the aforementioned references. Essentially, in all the above-mentioned work the flow variables are decomposed in a volume mean and a deviation (classical porous media analysis) in addition of being also decomposed in a time-mean and a fluctuation (classical turbulent flow treatment).

☆ Communicated by W.J. Minkowycz.
E-mail address: delemos@ita.br.

0735-1933/$ – see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.icheatmasstransfer.2009.07.006

Nomenclature

Latin characters

A	Pre-exponential factor
c_F	Forchheimer coefficient
c_p	Specific heat
$D = [\nabla \mathbf{u} + (\nabla \mathbf{u})^T]/2$	Deformation rate tensor
D_ℓ	Diffusion coefficient of species ℓ
D_{diff}	Macroscopic diffusion coefficient
D_{disp}	Dispersion tensor due to dispersion
$D_{disp,t}$	Dispersion tensor due to turbulene
f_2	Damping function
f_μ	Damping function
D_{eff}	Effective dispersion
K	Permeability
k_f	Fluid thermal conductivity
k_s	Solid thermal conductivity
$\mathbf{K}_{eff}$	Effective Conductivity tensor
m_ℓ	Mass fraction of species ℓ
Pr	Prandtl number
S_{fu}	Rate of fuel consumption
T	Temperature
$\mathbf{u}$	Microscopic velocity
$\mathbf{u}_D$	Darcy or superficial velocity (volume average of $\mathbf{u}$)

Greek characters

α	Thermal diffusivity
β_r	Extinction coefficient
ΔV	Representative elementary volume
ΔV_f	Fluid volume inside ΔV
ΔH	Heat of combustion
μ	Dynamic viscosity
ν	Kinematic viscosity
ρ	Density
ϕ	$\phi = {}^{\Delta V_f}/_{\Delta V}$, Porosity
Ψ	Excess air-to-fuel ratio

Special characters

φ	General variable
$\langle\varphi\rangle^i$	Intrinsic average
$\langle\varphi\rangle^v$	Volume average
$^i\varphi$	Spatial deviation
$\overline{\varphi}$	Time average
$\lvert\varphi\rvert$	Absolute value (Abs)
$\boldsymbol{\varphi}$	Vetorial general variable
$(\ )_{s,f}$	solid/fluid
$(\ )_{eff}$	Effective value, $\phi\varphi_f + (1-\phi)\varphi_s$
$(\ )_\phi$	Macroscopic value

Because mathematical details and proofs of such concept are available in a number of papers in the literature, they are not repeated here, as already noted. These final equations in their steady-state form are the following.

2.1. Macroscopic continuity equation

$$\nabla\cdot\rho\overline{\mathbf{u}}_D = 0 \tag{1}$$

where, $\overline{\mathbf{u}}_D$ is the average surface velocity (also known as seepage, superficial, filter or Darcy velocity) and ρ is the fluid density. Eq. (1) represents the macroscopic continuity equation for the gas.

2.2. Macroscopic momentum equation

$$\rho\nabla\cdot\left(\frac{\overline{\mathbf{u}}_D\overline{\mathbf{u}}_D}{\phi}\right) = -\nabla(\phi\langle\overline{p}\rangle^i) + \mu\nabla^2\overline{\mathbf{u}}_D + \nabla\cdot(-\rho\phi\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i) + \phi\rho\mathbf{g} - \left[\frac{\mu\phi}{K}\overline{\mathbf{u}}_D + \frac{c_F\phi\rho|\overline{\mathbf{u}}_D|\overline{\mathbf{u}}_D}{\sqrt{K}}\right] \tag{2}$$

where the last two terms in Eq. (2), represent the Darcy and Forchheimer contributions. The symbol K is the porous medium permeability, $c_F = 0.55$ is the form drag coefficient, $\langle p\rangle^i$ is the intrinsic (fluid phase averaged) pressure of the fluid, μ represents the fluid viscosity and ϕ is the porosity of the porous medium.

Turbulence is handled via a macroscopic k–ε model given by,

$$\rho\nabla\cdot(\overline{\mathbf{u}}_D\langle k\rangle^i) = \nabla\cdot\left[\left(\mu + \frac{\mu_{t_\phi}}{\sigma_k}\right)\nabla(\phi\langle k\rangle^i)\right] - \rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i : \nabla\overline{\mathbf{u}}_D + c_k\rho\frac{\phi\langle k\rangle^i|\overline{\mathbf{u}}_D|}{\sqrt{K}} - \rho\phi\langle\varepsilon\rangle^i \tag{3}$$

$$\rho\nabla\cdot(\overline{\mathbf{u}}_D\langle\varepsilon\rangle^i) = \nabla\cdot\left[\left(\mu + \frac{\mu_{t_\phi}}{\sigma_\varepsilon}\right)\nabla(\phi\langle\varepsilon\rangle^i)\right] + c_1(-\rho\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i : \nabla\overline{\mathbf{u}}_D)\frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i} + c_2c_k\rho\frac{\phi\langle\varepsilon\rangle^i|\overline{\mathbf{u}}_D|}{\sqrt{K}} - c_2\rho\phi\frac{\langle\varepsilon\rangle^i 2}{\langle k\rangle^i} \tag{4}$$

where

$$-\rho\phi\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i = \mu_{t_\phi}2\langle\overline{\mathbf{D}}\rangle^v - \frac{2}{3}\phi\rho\langle k\rangle^i\mathbf{I} \tag{5}$$

and

$$\mu_{t_\phi} = \rho c_\mu\frac{\langle k\rangle^{i2}}{\langle\varepsilon\rangle^i} \tag{6}$$

Details on the derivation of the above equations can be found in [17].

2.3. Macroscopic energy equations

Macroscopic energy equations are obtained for both fluid and solid phases by also applying time and volume average operators to the instantaneous local equations [24]. As in the flow case, volume integration is performed over a Representative Elementary Volume (REV). After including the heat released due to the combustion reaction, one gets for both phases:

$$Gas: (\rho c_p)_f\nabla\cdot(\mathbf{u}_D\langle\overline{T}_f\rangle^i) = \nabla\cdot\{\mathbf{K}_{eff,f}\cdot\nabla\langle\overline{T}_f\rangle^i\} + h_ia_i(\langle\overline{T}_s\rangle^i - \langle\overline{T}_f\rangle^i) + \phi\Delta HS_{fu}, \tag{7}$$

$$Solid: 0 = \nabla\cdot\{\mathbf{K}_{eff,s}\cdot\nabla\langle\overline{T}_s\rangle^i\} - h_ia_i(\langle\overline{T}_s\rangle^i - \langle\overline{T}_f\rangle^i), \tag{8}$$

where, $a_i = A_i/\Delta V$ is the interfacial area per unit volume, h_i is the film coefficient for interfacial transport, $\mathbf{K}_{eff,f}$ and $\mathbf{K}_{eff,s}$ are the effective conductivity tensors for fluid and solid, respectively, given by,

$$\mathbf{K}_{eff,f} = \left\{\overbrace{\phi k_f}^{\text{conduction}}\right\}\mathbf{I} + \underbrace{\mathbf{K}_{f,s}}_{\text{local conduction}} + \underbrace{\mathbf{K}_{disp}}_{\text{dispersion}} + \underbrace{\mathbf{K}_t + \mathbf{K}_{disp,t}}_{\text{turbulence}} \tag{9}$$