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Turbulent flow with combustion in a moving bed ☆

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ABSTRACT

This paper presents a mathematical model for treating turbulent combusting flows in a moving porous bed, which might be useful to design and analysis of modern and advanced biomass gasification systems. Here, one explicitly considers the intra-pore levels of turbulent kinetic energy and the movement of the rigid solid matrix is considered to occur at a steady speed. 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. The rate of fuel consumption is described by an Arrhenius expression involving the product of the fuel and oxidant mass fractions. Results indicate that fixing the gas speed and increasing the speed of the solid matrix pushes the flame front towards the end of the reactor. Also, since the rate of production of turbulence is dependent on the relative velocity between phases, as the solid velocity approaches that of the gas stream, the level of turbulence in the flow is reduced.

1. Introduction

Energy production based on biomass combustion has called the attention of the world for its potential substitution of non-renewable fossil fuels. Biomass pelletization and preparation for energy production systems may involve a moving porous bed [1–3] in which an exothermic reaction occurs. Examples of studies on such systems are given by Ryu et al. [4], Boman et al. [5] and Shimizu et al. [6] who presented mathematical models for gasification and combustion of renewable fuels. Kayal and Chakravarty [7], Rogel et al. [8] and Nussbaumer et al. [9] investigated technologies to cope with the problem of pollutant emission during combustion and co-combustion of biomass. Related investigations concerning studies on reactive flows in permeable media [10–15], including recent reviews on combustion of gases [16] and liquids [17] in the so-called porous burners, have also contributed to the modeling of flows with combustion through a permeable medium. Recent developments on free flame modeling [18, 19] will further benefit the analyses of the heterogeneous systems just reviewed. Accordingly, the ability to more realistic model such devices is of great advantage to the analysis and optimization of a number of energy, food and materials production processes.

Motivated by the foregoing, in a series of papers a general mathematical model for turbulent flow in porous media, including flows with macroscopic interfaces [20], buoyant flows [21] and impinging jets, with [22, 23] and without [24] thermal non-equilibrium, was developed and documented in a book [25]. Such model was further extended to include movement of the solid phase for non-reacting flows [26] with heat transfer [27]. Subsequently, combustion of gases within a fixed porous medium was also considered [28, 29].

The objective of this contribution is then to combine the previous separated analyses of movement of a porous bed along with an inert flow [26, 27] with that of combustion of a gaseous fuel through a fixed medium [28, 29]. By that, a more complete and more general model is investigated as solutions of a broader range of problems are sought, which aim at simulate, in a more realistic fashion, modern equipment for energy production using renewable fuels.

2. Macroscopic flow model

As mentioned, the thermo-mechanical model here employed is based on concepts already fully described in the literature [25]. In that work, transport equations are volume averaged over a Representative Elementary Volume (REV) according to the Volume Averaging Theorem [30–32]. In addition, the use of time decomposition of flow variables, followed by standard time-averaging procedure, was applied to model turbulence. As the entire equation set is already fully available in the open literature, these equations will be 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 to being also decomposed in a time-mean and fluctuating values (classical turbulent flow treatment). As said, because mathematical details and proofs of such "double-decomposition" concept are available in a number of papers in the literature, they are not repeated here. Only final equations in their steady-state form are presented below.

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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
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
$\overline{\phi}$	Time average
ϕ'	Time fluctuation
$\|\boldsymbol{\varphi}\|$	Absolute value (Abs)
$\boldsymbol{\varphi}$	Vectorial general variable
$(\ )_{s,f}$	solid/fluid
$(\ )_{eff}$	Effective value, $\phi\varphi_f+(1-\phi)\varphi_s$
$(\ )_\phi$	Macroscopic value
$(\ )_{fu}$	Fuel
$(\ )_{ox}$	Oxygen

2.1. Macroscopic slip velocity

In order to analyze the effect of the motion of the permeable structure, one needs first to define velocities and their averages relative to a fixed representative elementary control-volume. One should point out, however, that here only cases where the solid phase velocity is kept constant will be considered.

A moving bed crosses a fixed reactor in addition to a flowing fluid, which is not necessarily moving with a velocity aligned with the solid phase velocity (Fig. 1). The steps below show first some basic definitions prior to presenting a proposal for a set of transport equations for analyzing such systems.

A general form for a volume-average of any property φ, distributed within a phase γ that occupy volume ΔV_γ, can be written as [32],

$$\langle\varphi\rangle^\gamma = \frac{1}{\Delta V_\gamma}\int_{\Delta V_\gamma}\varphi\, dV_\gamma. \tag{1}$$

In the general case, the volume ratio occupied by phase γ will be $\phi^\gamma = \Delta V_\gamma/\Delta V$.

If there are two phases, a solid ($\gamma=s$) and a fluid phase ($\gamma=f$), volume average can be established on both regions. Also,

$$\phi^s = \Delta V_s/\Delta V = 1-\Delta V_f/\Delta V = 1-\phi^f \tag{2}$$

and, for simplicity of notation, one can drop the superscript "f" to get $\phi^s = 1-\phi$. For permeable media, phi is known as porosity.

As such, calling the instantaneous local velocities for the solid and fluid phases, $\mathbf{u}_s$ and $\mathbf{u}$, respectively, one can obtain the average for the solid velocity, within the solid phase, as follows,

$$\langle\mathbf{u}\rangle^s = \frac{1}{\Delta V_s}\int_{\Delta V_s}\mathbf{u}_s\, dV_s \tag{3}$$

which, in turn, can be related to the average velocity referent to the entire REV as,

$$\mathbf{u}_S = \overbrace{\frac{\Delta V_s}{\Delta V}}^{(1-\phi)}\underbrace{\frac{1}{\Delta V_s}\int_{\Delta V_s}\mathbf{u}_s\, dV_s}_{\langle\mathbf{u}\rangle^s}. \tag{4}$$

A further approximation herein is that the porous bed is rigid and moves with a steady average velocity $\mathbf{u}_S$. Note that the condition of steadiness for the solid phase gives $\mathbf{u}_S = \bar{\mathbf{u}}_S = const$ where the overbar denotes, as usual in the literature, time-averaging.

For the fluid phase, the intrinsic (fluid) volume average gives, after using the subscript "i" also for consistency with the literature,

$$\langle\bar{\mathbf{u}}\rangle^i = \frac{1}{\Delta V_f}\int_{\Delta V_f}\bar{\mathbf{u}}\, dV_f. \tag{5}$$

On a total-volume basis, both velocities can then be written as,

$$\bar{\mathbf{u}}_D = \phi\langle\bar{\mathbf{u}}\rangle^i, \mathbf{u}_S = (1-\phi)\langle\mathbf{u}\rangle^s = const. \tag{6}$$

where, $\bar{\mathbf{u}}_D$ is the average surface velocity (also known as seepage, superficial, filter or Darcy velocity).

In the general case, $\bar{\mathbf{u}}_D$ and $\mathbf{u}_S$ need not to be aligned with each other as in the drawing of Fig. 1. For a general three-dimensional flow they are written in Cartesian coordinates as,

$$\bar{\mathbf{u}}_D = \bar{u}_D\,\hat{i} + \bar{v}_D\,\hat{j} + \bar{w}_D\,\hat{k}\,;\ \mathbf{u}_S = u_S\,\hat{i} + v_S\,\hat{j} + w_S\,\hat{k} \tag{7}$$

where u, v, and w are the Cartesian components.

A total-volume based relative velocity is defined as,

$$\bar{\mathbf{u}}_{rel} = \bar{\mathbf{u}}_D - \mathbf{u}_S. \tag{8}$$

Further,

$$\bar{\mathbf{u}}_{rel} = \phi\langle\bar{\mathbf{u}}\rangle^i - (1-\phi)\langle\mathbf{u}\rangle^s;\ \ \bar{\mathbf{u}}_{rel} = \phi\left(\langle\bar{\mathbf{u}}\rangle^i + \langle\mathbf{u}\rangle^s\right) - \langle\mathbf{u}\rangle^s. \tag{9}$$