SIMULATION OF TURBULENT COMBUSTION IN POROUS RADIANT BURNERS

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Abstract. *The objective of this paper is to present numerical simulations of combustion of an air/methane mixture in porous materials using a model that 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 are reduced.*

Keywords*: Filtration Combustion, Radiation, Ceramic Foam, Turbulence*

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 [Howell et al (1996)], [Oliveira and Kaviany (2001), [Henneke and Ellzey (1999), [Bouma and De Goey (1999)], [Babkin (1993)], [Leonardi et al (2003)], [Lammers and De Goey (2003)], [Mohamed et al (1994)] including a recent review on lean-combustion porous burners including a recent review on lean-combustion porous burners [Wood and Harries (2008)]. [Hsu et al (1993)] 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(1993)], among others.

Turbulence modeling of combustion within inert porous media has been conducted by [Lim and Matthews (1993)] on the basis of an extension of the standard k-ε model of [Jones and Launder (1972)]. Work on direct simulation of laminar 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 (1995)]. Further, non-reactive turbulence flow in porous media has been the subject of several studies [De Lemos (2005)], [Pedras and De Lemos (2003)], [Pedras (2006)], including many applications such as flow though porous baffles [Santos and De Lemos (2006)], channels with porous inserts [Assato et al (2005)] and buoyant flows [Braga and De Lemos (2004)]. In such line of work, intra-pore turbulence is accounted for in all transport equations.

Motivated by the foregoing, this paper extends 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. Four different thermo-mechanical models are here compared, namely Laminar Flow, Laminar Flow with Radiation Transport, Turbulent Flow and Turbulent Flow with Radiation Transport. As such, this contribution compares the effects of radiation and turbulence in smoothing temperature distributions within porous burners.

2. MATHEMATICAL MODEL

As mentioned, the thermo-mechanical model here employed is based on the "double-decomposition" concept [Pedras and De Lemos (2003)] and [De Lemos (2005)], which has been also described in detail in a book [De Lemos, (2006)]. In that work, transport equations are volume averaged according to the Volume Averaging Theorem [Slattery 1967], [Whitaker (1969)], [Gray and Lee(1977)] 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 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 of being also decomposed in a time-mean and a

fluctuation (classical turbulent flow treatment). Because mathematical details and proofs of such concept are available in a number of worldwide available papers in the literature, they are not repeated here. These final equation in their steady-state form are the following:

2.1. Macroscopic continuity equation:

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

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

2.2. Macroscopic momentum equation:

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

where μ is the dynamic viscosity, ϕ is the porosity given by ratio of volume of fluid inside the elementary representative volume ΔV_f by the elementary representative volume ΔV given by: $\phi = {\Delta V_f}/{\Delta V}$, where the last two terms in equation (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, ρ is the fluid density, μ represents the fluid viscosity and ϕ is the porosity of the porous medium.

Turbulence is handled via a macroscopic $k-\varepsilon$ model given by,

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

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

where:

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

and:

$$\mu_{t_\phi}=\rho c_\mu\frac{\langle k\rangle^{i^2}}{\langle\varepsilon\rangle^i} \tag{6}$$

Details on the derivation of the above equations can be found in [De Lemos, (2006)] and in a number of papers in the open literature. For such reason, there is no reason to repeat here all derivations therein.

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 [Saito and De Lemos (2006)]. 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:

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

$$\text{Solid: } 0=\nabla\cdot\left\{\mathbf{K}_{eff,s}\cdot\nabla\langle\overline{T_s}\rangle^i\right\}-h_ia_i\left(\langle\overline{T_s}\rangle^i-\langle\overline{T_f}\rangle^i\right) \tag{8}$$

where c_p is the specific heat, S_{fu} is the rate of fuel consumption, $\mathbf{u}_D$ is the Darcy or superficial velocity (volume average of $\mathbf{u}$), $\mathbf{u}$ is the microscopic velocity, T_f is the fluid temperature and T_s the solid temperature, $a_i = A_i/\Delta V$ 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,

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

$$\mathbf{K}_{eff,s} = \left\{ \overbrace{(1-\phi)[k_s}^{conduction} + \frac{\overbrace{16\sigma(\langle \overline{T} \rangle^i)^3}^{radiation}}{3\beta_r}] \right\} \mathbf{I} + \underbrace{\mathbf{K}_{s,f}}_{local\ conduction} \tag{10}$$

In Equations (7)-(10), $\mathbf{I}$ is the unit tensor, ΔH is the heat of combustion [5x10^7 J/kg] , β_r is the extinction coefficient [1000m^{-1}], σ is the Stephan-Boltzman constant [5.66961x10^{-8} W/m^{2}K^4], k_f is the fluid thermal conductivity, k_s is the solid thermal conductivity and S_{fu} is the rate of fuel consumption, to be commented below. All mechanisms contributing to heat transfer within the medium, together with turbulence and radiation, are included in order to compare their effect on temperature distribution. Further, such distinct contributions of various mechanisms are the outcome of the application of gradient type diffusion models, in the form (see [Saito and De Lemos (2006)] for details).

Turbulent heat flux: $$-(\rho c_p)_f \left(\phi \, \overline{\langle \mathbf{u}' \rangle^i \langle T_f' \rangle^i} \right) = \mathbf{K}_t \cdot \nabla \langle \overline{T}_f \rangle^i \tag{11}$$

Thermal dispersion: $$-(\rho c_p)_f \left(\phi \, \langle {}^i\overline{\mathbf{u}}^{\,i} \overline{T_f} \rangle^i \right) = \mathbf{K}_{disp} \cdot \nabla \langle \overline{T}_f \rangle^i \tag{12}$$

Turbulent thermal dispersion: $$-(\rho c_p)_f \left(\phi \, \overline{\langle {}^i\mathbf{u}' \, {}^iT_f' \rangle^i} \right) = \mathbf{K}_{disp,t} \cdot \nabla \langle \overline{T}_f \rangle^i \tag{13}$$

Local conduction: $$\nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n}_i \, k_f \, \overline{T_f} \, dA \right] = \mathbf{K}_{f,s} \cdot \nabla \langle \overline{T}_s \rangle^i \tag{14}$$

$$\nabla \cdot \left[\frac{1}{\Delta V} \int_{A_i} \mathbf{n}_i \, k_s \, \overline{T_s} \, dA \right] = \mathbf{K}_{s,f} \cdot \nabla \langle \overline{T}_f \rangle^i$$

In eqs. (7) and (8) the heat transferred between the two phases was modeled by means of a film coefficient h_i . A numerical correlation for the interfacial convective heat transfer coefficient was proposed by [Kuwahara et al (2001)]. For laminar flow as:

$$\frac{h_i D}{k_f} = \left(1 + \frac{4(1-\phi)}{\phi} \right) + \frac{1}{2}(1-\phi)^{1/2} \, \mathrm{Re}_D \, \mathrm{Pr}^{1/3} \quad \text{, valid for } 0.2 < \phi < 0.9 \text{ ,} \tag{15}$$

For turbulent flow, the following expression was proposed in (Saito and De Lemos, 2006):

$$\frac{h_i D}{k_f} = 0.08 \left(\frac{Re_D}{\phi} \right)^{0.8} Pr^{1/3} \text{; for } 1.0x10^4 < \frac{Re_D}{\phi} < 2.0x10^7 \text{ , valid for } 0.2 < \phi < 0.9 \text{ ,} \tag{16}$$

where Pr is the Prandtl number.

2.3. Macroscopic Mass Transport

Transport equation for the fuel reads,

$$\nabla \cdot (\overline{\mathbf{u}}_D \langle \overline{m}_{fu} \rangle^i) = \nabla \cdot \mathbf{D}_{eff} \cdot \nabla (\phi \langle \overline{m}_{fu} \rangle^i) - S_{fu} \tag{17}$$

where $\langle \overline{m}_{fu} \rangle^i$ is the mass fraction for the fuel. The effective mass transport tensor, $\mathbf{D}_{eff}$, is defined as:

$$\mathbf{D}_{eff} = \underbrace{\mathbf{D}_{disp}}_{dispersion} + \overbrace{\mathbf{D}_{diff}}^{diffusion} + \underbrace{\mathbf{D}_t + \mathbf{D}_{disp,t}}_{turbulence} = \mathbf{D}_{disp} + \frac{1}{\rho} \left(\frac{\mu_\phi}{Sc_\ell} + \frac{\mu_{t_\phi}}{Sc_{\ell,t}} \right) \mathbf{I} = \mathbf{D}_{disp} + \frac{1}{\rho} \left(\frac{\mu_{\phi,ef}}{Sc_{\ell,ef}} \right) \mathbf{I} \tag{18}$$

where Sc_ℓ and $Sc_{\ell,t}$ are the laminar and turbulent Schmidt numbers for species ℓ , respectively, and "*eff*" denotes an effective value. The dispersion tensor is defined such that,

$$-\rho \langle {}^i\overline{\mathbf{u}} \, {}^i\overline{m}_{fu} \rangle^i = \rho \mathbf{D}_{disp} \nabla . \langle \overline{m}_{fu} \rangle^i \tag{19}$$

2.4. Simple Combustion Model

In this work, for simplicity, the chemical exothermic reaction is assumed to be instantaneous and to occur in a single step, which is given by the chemical reaction,

$$CH_4 + 2(1+\Psi)(O_2 + 3.76\,N_2) \rightarrow CO_2 + 2\,H_2O + 2\,\Psi O_2 + 7.52(1+\Psi)\,N_2 \tag{20}$$

where ψ is the excess air in the reactant stream at the inlet of the porous foam. For the stoichiometric ratio, ψ=0. The rate of fuel consumption over the total volume (gas plus solid) was determined by a one step Arrhenious reaction [Kwo (1986)] given by:

$$S_{fu} = \rho^2 A \langle \overline{m}_{fu} \rangle^i \langle \overline{m}_{ox} \rangle^i \exp[-E / R \langle \overline{T} \rangle^i] \tag{21}$$

where $\langle \overline{m}_{fu} \rangle^i$ and $\langle \overline{m}_{ox} \rangle^i$ are the volume-time averaged mass fractions for the fuel and oxidant, respectively, A is the pre-exponential factor [1x10^{10} m^3/(kg.s)] and E is the activation energy [1.4 x 10^8 J/kmol], where all values used are the ones commonly used in the literature for combustion of methane.

Density ρ in the above equations is determined from the perfect gas equation for a mixture of perfect gases:

$$\rho = \frac{P_o}{RT_f \sum_1^{\ell} \frac{m_\ell}{M_\ell}} \tag{22}$$

where P_o is the absolute pressure, R is the universal gas constant [8.134 J/(mol.K)] and M_ℓ is the molecular weight of species ℓ.

2.5. Boundary Conditions and Numerical Details

The set of equations above where solved, for one-dimensional cases, with given temperatures (solid and gas) and fuel mass fraction at inlet, $x = 0$. At exit, $x = 12\,cm$, a zero diffusion condition $\partial(\ )/\partial x = 0$ for the fuel mass fraction and gas temperature was used. For the solid temperature, a balance between the energy conducted to the exit and the radiation leaving to the environment was applied. Further, an initial length of 2 cm was considered to be made of a material that prevents flash back of the flame, which is commonly referred to in the literature as "flame trap" [Trimis and Durst (1996)]. Ignition, is existing, was them calculated for $x > 2\,cm$

3. RESULTS AND DISCUSSION

The computational grid was generated with a concentration of points close to the beginning of the combustion section ($x = 2\,cm$), where steep temperature and species gradients were expected to appear. Figure 1 shows the effect of excess air Ψ on the gas temperature, T_f, and solid temperature, T_p.

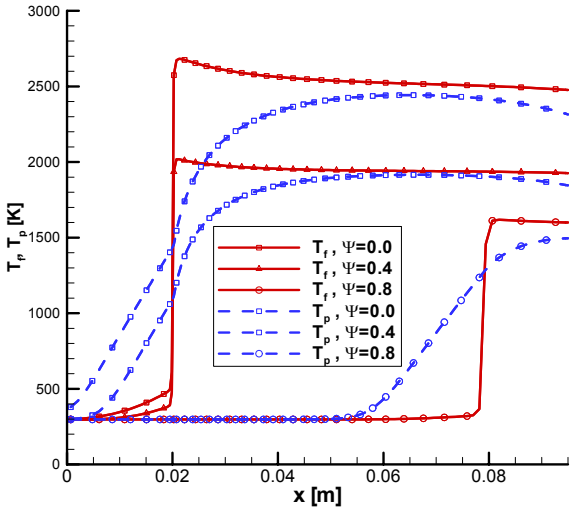

Figure 1 - Effect of excess air Ψ for u_{in}= 0.1 m/s on temperature field.

Temperature levels for the stechiometric case and for $\Psi = 0.8$ gave numerical values close to those from [Zhou and Pereira (1998)]. These results are the outcome of the single step reaction (20) that links the consumption and production rates of individual constituents of the mixture. Reduction of peak temperature with exceess air is a feature well-known in free premixed flames, but the figure indicates that also for filtered combustion a similar behavior is computed.

Four different thermo-mechanical models are now compared, namely Laminar, Laminar with Radiation Transport, Turbulent, Turbulent with Radiation Transport. Radiation model is included by considering the radiation transport term in the T_p equation (10). Turbulence modeling is handled by resolving the $k-\varepsilon$ model (eqs. (3)-(4)) in addition to solving for the macroscopic turbulent eddy viscosity μ_{t_ϕ}, eq. (6). In all models, combustion is simulated via a unique simple closure, which is presented by equations (20) and (21).

Numerical simulations obtained with different models are presented in Figure 2 for two values of U_{in}. First, it is interesting to point out that the four models above were used when calculating both inlet velocity values. Therefore, turbulent transport was also considered for low speed flows and that was done in order to verify the correctness and stability of the developed code. In low speed flows, levels of turbulent kinetic energy, if initially input at inlet, will decay and remain low even if a turbulence model is applied. That was the case for U_{in} = 0.1 m/s when the pore Reynolds number is of the order of 35. On the order hand, for U_{in} = 1.0 m/s, the pore Reynolds number is ten times greater, entering a range where intra-pore turbulence is usually assumed to be significant ([De Lemos, (2006)]). With this matter clarified, results can now be presented.

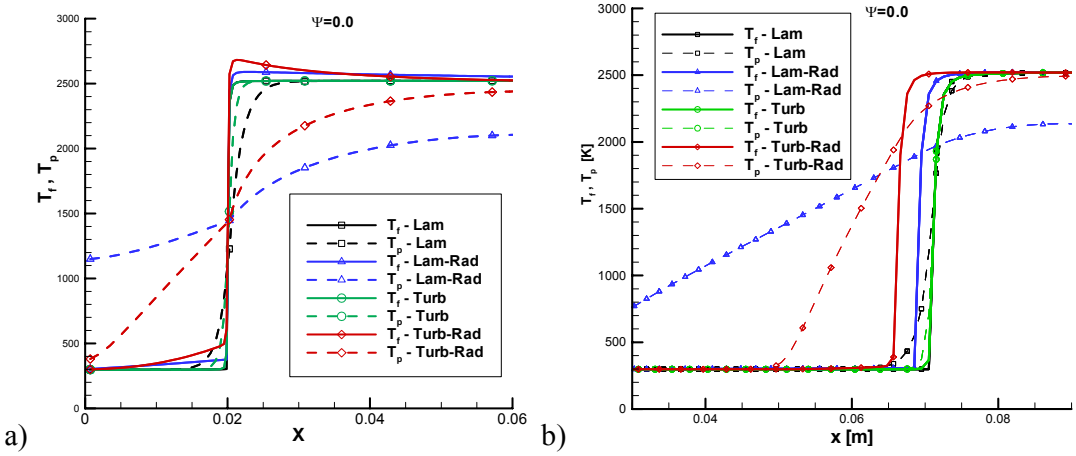

Figure 2 - Comparison of different model solutions: a) U_{in} = 0.1 m/s, b) U_{in} = 1.0 m/s.

Figure 2a shows that for low values of U_{in}, the flame (solid lines) stabilizes close to the beginning of the burning section ($x = 2\,cm$), independently of the mathematical model applied. Solid temperature are influenced by radiation transport, which tends to smooth out temperature differences within the solid matrix, enhancing, as such, the regenerative advantage of porous burners (dashed lines). Regeneration is achieved by preheating the gas prior to the combustion zone. In fact, the use of a turbulence model in conjunction with radiation transport gives the higher temperature peak of the gas temperature at the flame position. Increasing the inlet mass flow rate (Figure2b), the flame is pushed towards the burner exit, regardless of the model used. In Figure 2b, no detectable differences in the gas temperature is found when turbulence is the sole mechanism added and compared with the simple laminar model, a result that could be associated with the simple geometry and one-dimensional flow here computed. For multidimensional cases and complex geometries, turbulent transport might play a more significant role. Here also radiation transport substantially affects the solid temperature distribution, but definitive conclusions on the appropriateness of each model can only be reached after careful comparison with experimental measurements. This shall be the subject of the present ongoing research effort.

4. CONCLUSIONS

This paper presented one-dimensional simulations for a mixture of air and methane burning in a porous material. Four different thermo-mechanical models were compared along with a unique simple closure for combustion. Results indicate that a substantially different temperature distribution pattern is obtained depending on the model used. Results

herein motivates further research work on the subject of reactive turbulent flow in porous burners and should be seen as a preliminary step towards reliable simulation of real porous combustors.

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