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Numerical simulation of turbulent reacting flow in porous media using two macroscopic turbulence models

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ABSTRACT

This paper presents two dimensional simulations of air/methane combustion in cylindrical porous burner using models that explicitly consider the intra-pore levels of turbulent kinetic energy. Two most used turbulence models in porous media, proposed by Pedras and de Lemos (P–dL) and Nakayama and Kuwahara (N–K), have been used in the present study. Results of two macroscopic turbulence models are presented and compared for different Reynolds numbers and several flame locations. The values of turbulent kinetic energy and eddy viscosity calculated by two models are quite different due to the difference between the terms proposed for internal generation in turbulent kinetic energy and dissipation rate equations. It is found that P–dL model more accurately predicts the characteristics of reacting flow in porous media such as turbulent kinetic energy and eddy viscosity. Also, it is shown that the effects of turbulence in porous media are more significant when the flame stabilizes at the downstream of burner. Due to enhancement of heat and species diffusion, the preheating of reactants increases and the flame moves closer to the burner entrance when turbulence models are applied.

1. Introduction

Combustion in porous media improves combustion performance and reduces pollutant emissions by transferring combustion heat upstream via conduction and radiation to preheat reactants. Higher power densities, enhanced efficiencies, high compactness, higher dynamic power ranges and controlled pollutant emissions are of the characteristics of porous burners, which have made them preferable to conventional free-flame burners. The literature already covers a wide range of studies on combustion in porous media [1–4], including recent reviews on burning of gases [5–8] and liquids [9] in such burners and also on numerical modeling of them [10].

Notably, all of the studies cited above considered laminar flow regime inside the porous media whereas the investigations showed that the porous media flows turn to turbulence regime at relatively low Reynolds (Re) numbers in comparison to the clear flow [11]. Obviously, flame thickness, gas and solid temperatures, species concentration distribution and burning speed are all affected by turbulence within the porous burner [12,13]. Lim and Mathews [14] showed that considering turbulence effects in porous media combustion leads to better agreement between numerical predictions and experimental data. Their work has been conducted on the basis of an extension of the standard k–ε model proposed by Jones and Launder [15] with discarding the ε equation using an appropriate length scale. However, their k–ε model suffers from the lack of generality and physical consistency because the numerical results were fitted to the experimental data, at the downstream of porous burner exit, by adjusting many constants of the model.

In the recent years, due to essential influence of turbulence on porous media processes, the study of turbulence characteristics in porous media has received extensive attention in the porous media community [16–20]. To treat the turbulent flows through porous media mathematically, most researchers follow a traditional macroscopical approach for low Re number flows in the porous media, in which the governing equations are obtained by volume averaging over a Representative Elementary Volume (REV). A universal modeling approach is to apply the time averaging for handling turbulence and the space averaging for handling the morphology to the microscopic equations. Almost all of the models derived to simulate turbulence in porous media are based on the clear fluid k–ε model being modified to consider the effect of solid matrix. The accuracy of k–ε model in internal flow configuration is known to be unreliable. Therefore, Kuwahara et al. [21] conducted a Large Eddy Simulation (LES) study of flow through porous media modeled as periodic array of square cylinders. The results were compared against those obtained using conventional k–ε model. They concluded that the k–ε model gives a reasonable level

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of macroscopic turbulent kinetic energy and may well be used to estimate the macroscopic field of turbulent flow in porous media. Diversity of the macroscopic turbulence models in porous media is not only due to the averaging order, but also to the different definitions of the macroscopic turbulence quantities, such as the Turbulent Kinetic Energy (TKE) and the dissipation rate [20]. Furthermore, these models have been employed extensively for non-reacting flows, such as studies of Refs. [22–25], and only few researches have been dedicated to the reacting turbulent flow in porous media. De Lemos [26] has presented one-dimensional simulation of turbulent combustion of an air/methane mixture in porous burner using the turbulence model proposed by Pedras and de Lemos [19]. Recently, Yarahmadi et al. [27] numerically simulated the porous burner, experimentally studied by Trimis and Durst [28], using the turbulence model proposed by Pedras and de Lemos [19]. Their results showed that the turbulence simulation predicts gas and solid temperatures closer to the experimental data.

The comparison of macroscopic turbulence models in porous media has been followed by few researchers from different viewpoints in the literature. Lage et al. [29] reviewed and discussed four methodologies for developing macroscopic turbulence models for incompressible single-phase flow in rigid, fully saturated porous media. They concluded that the method proposed by Pedras and de Lemos (P–dL) [19], based on double decomposition, is probably the most consistent method. However, Guo et al. [30] compared the results of three different models in non-reacting turbulent flow in packed bed. They showed that the model proposed by Nakayama and Kuwahara (N–K) predicts the eddy viscosity more accurate than that of P–dL model. Meanwhile, it should be mentioned that both of P–dL and N–K models suffer from two shortcomings: (a) these models are not validated against experimental data, and (b) the constants of the models have been adopted from the studies of clear flow. Despite of the shortcomings mentioned above, the N–K and P–dL models have been used in many applications such as porous burner in their current form.

Motivated by the foregoing, the results of N–K and P–dL models are presented and compared in the present study in order to inspect the accuracy of these models in predicting the characteristics of reacting flow through porous media. Following the discussion made above, the results of present comparison between N–K and P–dL models should be used carefully because these two models are yet incomplete and should be validated against experimental data and their constants should be determined. In order to inspect the accuracy of two macroscopic turbulence models, turbulent reacting flow inside a cylindrical porous burner is considered. Computations are carried out for inert porous material considering two-dimensional axisymmetric turbulent flow and two-energy equation (LTNE) model. A single step global mechanism is used for the combustion of air/methane mixture. The effects of Re number, flame location and effective conductivity of the porous media have been investigated on the distribution of TKE, eddy viscosity and gas and solid temperatures.

2. Governing equations

The flow under consideration and the coordinate system are schematically shown in Fig. 1 where a single layer cylindrical porous burner is assumed with inert homogeneous porous material and negligible catalytic effects. The porous medium has been considered undeformable in the present study, therefore, the porosity and pore size are constant. The burner length and diameter are L and D, respectively. Due to axisymmetric geometry, only a half of the geometry of the porous burner has been considered as a computational domain. Although it is widely known that an axisymmetric geometry does not necessarily yield an axisymmetric turbulent flow, the assumption of axisymmetric turbulent flow in

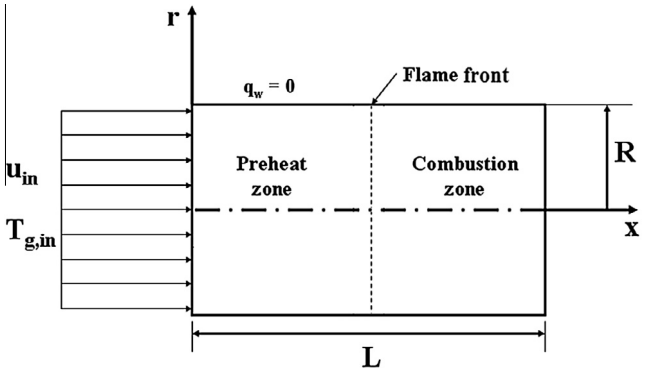

Fig. 1. Schematic of the porous burner geometry.

cylindrical geometry of porous media is adapted here because the microscopic turbulent quantities would be smoothed out after averaging within a representative elementary volume [13]. Therefore, the resulting flow field would be axisymmetric in the porous media geometry considered in the present study. Gaseous radiation has been neglected in comparison to the solid radiation, thus radiation has been considered only between the particles of porous media. All thermophysical properties of the solid material are assumed constant unlike the gas phase for which the properties vary with temperature. Hazen–Dupuit–Darcy equation has been used in the steady general momentum equation to account for the effective viscous and form drags exerted on fluid phase by solid matrix. The air/methane mixture is treated as incompressible ideal gas and density of mixture is determined from the perfect gas equation.

2.1. Macroscopic continuity and momentum equations

Under axisymmetric geometry, Newtonian fluid, steady and turbulence flow assumptions, the continuity and momentum equations are as follows [31]:

$$\nabla \cdot (\rho_f \bar{\mathbf{u}}_D) = 0 \tag{1}$$

where the Dupuit–Forchheimer relationship, $\bar{\mathbf{u}}_D = \phi \langle \bar{\mathbf{u}} \rangle^i$, has been used and $\langle \bar{\mathbf{u}} \rangle^i$ identifies the intrinsic average of the local time – averaged velocity vector $\bar{\mathbf{u}}$ [31].

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

where μ is the fluid dynamic viscosity, K is the permeability, c_F is the non-linear Forchheimer coefficient and $-\rho_f \phi \overline{\langle \mathbf{u}' \mathbf{u}' \rangle}^i$ is the Macroscopic Reynolds Stress Tensor (MRST) modeled as:

$$-\rho_f \overline{\langle \mathbf{u}' \mathbf{u}' \rangle}^i = \rho_f \nu_{t\phi} 2 \langle \overline{\mathbf{D}} \rangle^v - \frac{2}{3} \phi \rho_f \langle k \rangle^i \mathbf{I} \tag{3}$$

where

$$\langle \overline{\mathbf{D}} \rangle^v = \frac{1}{2} \left[\nabla(\phi \langle \bar{\mathbf{u}} \rangle^i) + [\nabla(\phi \langle \bar{\mathbf{u}} \rangle^i)]^T \right] \tag{4}$$

is the macroscopic deformation tensor, $\langle k \rangle^i$ is the intrinsic average of k and $\nu_{t\phi}$ is the macroscopic turbulent kinematic viscosity that is modeled similar to the case of the clear fluid flow;

$$\nu_{t\phi} = \mu_{t\phi} / \rho_f = c_\mu \langle k \rangle^{i2} / \langle \varepsilon \rangle^i \tag{5}$$

The last two terms in Eq. (2) represent the viscous and form drag forces felt by the fluid passing through the solid matrix. Although it is shown that the use of non-linear Forchheimer coefficient, c_F, and the permeability in the form-drag term instead of a single form-coefficient is incorrect [13], the $c_F/\sqrt{K}$ has been used in