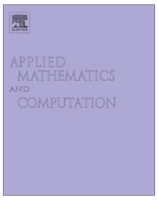
Applied Mathematics and Computation 243 (2014) 184–196

Contents lists available at ScienceDirect

Applied Mathematics and Computation

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



On the heat transfer and flow of a non-homogenous fluid

J. Fiordilino [a], M. Massoudi [b,*], A. Vaidya [a]

[a] Department of Mathematical Sciences, Montclair State University, Montclair, NJ 07043, USA
[b] US Department of Energy, National Energy Technology Laboratory (NETL), 626 Cochrans Mill Road, P.O. Box 10940, Pittsburgh, PA 15236, USA

ARTICLE INFO

Keywords:
Non-homogenous fluids
Variable viscosity
Variable thermal conductivity
Suspension flow
Slurry
Biomass

ABSTRACT

In this paper, we consider the flow a complex fluid such as coal–water slurry or biomass. We assume the suspension can be modeled as a non-homogenous viscous fluid whose viscosity is a function of spatial coordinates and temperature. We study the heat transfer and the steady fully developed flow of this complex fluid between two long horizontal plates subject to the no-slip condition at the plates. Two different correlations are proposed for the viscosity and the thermal conductivity and analytical and numerical results are presented for the velocity, temperature and the volumetric flow rate.

Published by Elsevier Inc.

1. Introduction

Traditionally, in fossil fuel combustion processes, coal–water slurry is prepared and in some cases heated prior to testing and use. Its rheological properties are determined using a basic type of viscometer. Coal slurries exhibit non-Newtonian flow characteristics. There are many other applications such as injection moulding or oil-well drilling where there are significant variations in the viscosity of the fluid, caused primarily by shear-rate and temperature (see [11]). With additional need for fossil fuels, the amount of waste materials and the environmental issues dealing with their disposal also increase. One of the promising approaches is the development of coal/waste co-firing technology. For co-firing, biomass has been considered as one of the fuels. It is estimated that biomass constitutes 14% of the world energy use, which makes it the fourth largest energy source (see [10]). Biomass can be considered any or a combination of wood residues, agricultural residues (crops, foods, animals), municipal solid waste, etc. (see [9]). Ekmann et al. [10] mention that from a technological point of view, for the biomass co-firing to become a viable source of energy "…both upstream and downstream impacts are important. Upstream impacts include handling, preparation (if any), and storage. Downstream ones include ash deposition (slagging and fouling), corrosion, and pollutants (reliable prediction of NO_x and SO_x reductions in particular." The major difficulties in modeling and using the co-firing of coal and biomass are: (1) the biomass fuels, especially the switchgrass and wood-residue are neither spherical nor disk-like in shape; most modeling approaches treat particles either as spherical or as disk-like, with a shape factor to account for other shapes. (2) Since most of the biomass particles are slender and rod-like, the directionality or anisotropy associated with the axis of the body, i.e., the orientation of the body, becomes an important controlling parameter (see [19,28]). (3) For co-firing applications, the density of the bio-mass fuels is, in certain cases, significantly different from that of coal. These issues in many ways determine the efficiency of the mixing process. Most computational fluid dynamics (CFD) codes treat the particles as a homogenous continuous medium with correlations which depend on the diameter and density of these spherical particles. An important combustion-related issue is the effectiveness

---

[*] Corresponding author.
E-mail address: massoudi@netl.doe.gov (M. Massoudi).

http://dx.doi.org/10.1016/j.amc.2014.05.117
0096-3003/Published by Elsevier Inc.

of handling and injecting of many non-Newtonian fluids such as coal–water slurries or coal–oil slurries. It has been demonstrated (see [34]) that substantial performance benefits can be obtained if the coal–water mixture is preheated. The effects of temperature change on coal slurry properties are controlled to a great extent by changes in the properties of the fluid.

The increasing demand and dependency on fuels has brought about a sense of urgency in the long term availability of non-renewable fuel reserves. A possible solution to this ubiquitous crisis is the development and characterization of new types of fuels, which could be environmentally safer and possibly more sustainable. Bio-fuels (a mixture of traditional fossil fuels, such as coal with other waste products such as chipped wood, grass, etc., forming biomass) seem to offer such a viable alternative (see [4]). Truck-based transport is currently the primary method of supplying feedstock to the biorefinery plants (see [15]). This type of transport consumes a large amount of fossil fuel in relation to the amount of biomass that is actually transported. In the context of pipeline transport of biomass [15], discuss biomass transport with simultaneous saccharification of corn stover. It is estimated that a temperature of 65 °C is needed for the process over a 36 h period. This could be achieved, for instance, by uniformly heating the pipeline. Both, the reduction in processing time and the cost are undoubtedly significant. In our study, we also show that the ability to modify the thermal conductivity of an inhomogeneous fluid allows us to potentially control the temperature distribution within a pipe by suitable choices of particulate materials. For instance, corn stover has a tendency to remain in the top layer of the channel and so in order to conduct the process of saccharification efficiently; we may choose to mix other solid particles into a corn-stover suspension. If the density and thermal conductivity of the other particles are suitably chosen one could induce appropriate temperatures in the channel for the saccharification. In other words, the pipeline can be heated non-uniformly and cheaper. Although biomass transport is used as motivation for the development of the model, the study is intended to be more general and can potentially be applied in several other settings with similar needs.

In this work, we study the behavior of a suspension, assuming that it can be represented by a constitutive equation for a non-homogenous fluid, where the viscosity is also a function of temperature. Note that the shapes of particles are not taken into account; the whole suspension (biomass particles and the host fluid) is treated as a non-linear fluid.

2. Governing equations

In the absence of any chemical and electro-magnetic effects, the governing equations of motion are the conservation of mass, linear momentum, and energy equations. These are (see [29]):

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \mathbf{u}) = 0, \tag{2.1}$$

where ρ is the density of the fluid, $\partial/\partial t$ is the partial derivative with respect to time, and $\mathbf{u}$ is the velocity vector. For an isochoric motion we have $\mathrm{div}\,\mathbf{u} = 0$.

Conservation of linear momentum:

$$\rho \frac{d\mathbf{u}}{dt} = \mathrm{div}\,\mathbf{T} + \rho \mathbf{b}, \tag{2.2}$$

where $\mathbf{b}$ is the body force vector, $\mathbf{T}$ is the Cauchy stress tensor, and d/dt is the total time derivative, given by $\frac{d(\cdot)}{dt} = \frac{\partial(\cdot)}{\partial t} + [\mathrm{grad}\,(\cdot)]\mathbf{u}$. The balance of moment of momentum reveals that in the absence of couple stresses, the stress tensor is symmetric.

Conservation of energy:

$$\rho \frac{d\varepsilon}{dt} = \mathbf{T} \cdot \mathbf{L} - \mathrm{div}\,\mathbf{q} + \rho r, \tag{2.3}$$

where ε is the specific internal energy, $\mathbf{L}$ is the gradient of velocity, $\mathbf{q}$ is the heat flux vector, and r is the radiant heating. Thermodynamical considerations require the application of the second law of thermodynamics or the entropy inequality. The local form of the entropy inequality is given by (see [16]):

$$\rho \dot{\eta} + \mathrm{div}\,\boldsymbol{\varphi} - \rho s \geqslant 0, \tag{2.4}$$

where $\eta(\mathbf{x}, t)$ is the specific entropy density, $\boldsymbol{\varphi}(\mathbf{x}, t)$ is the entropy flux, and s is the entropy supply density due to external sources, and the dot denotes the material time derivative. If it is assumed that $\boldsymbol{\varphi} = \frac{1}{\theta}\mathbf{q}$, and $s = \frac{1}{\theta} r$, where θ is the absolute temperature, then Eq. (2.4) reduces to the Clausius–Duhem inequality

$$\rho \dot{\eta} + \mathrm{div}\,\frac{\mathbf{q}}{\theta} - \rho \frac{r}{\theta} \geqslant 0. \tag{2.5}$$

Even though we do not consider the effects of the Clausius–Duhem inequality in our problem, for a complete thermo-mechanical study of a problem, the Second Law of Thermodynamics has to be considered (see [25,33,35]). In order to 'close' these equations, we need to provide constitutive relations for $\mathbf{T}$, $\mathbf{q}$, ε and r. In this problem, we assume that the radiation effects can be neglected. The specific internal energy, ε, is related to the specific Helmholtz free energy (see [8])

Download English Version:

https://daneshyari.com/en/article/4627724

Download Persian Version:

https://daneshyari.com/article/4627724

Daneshyari.com