Applied Thermal Engineering 78 (2015) 74–81

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Cylindrical particle modelling in pulverized coal and biomass co-firing process

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HIGHLIGHTS

- Co-firing of pulverized biomass and coal is modelled using CFD Software Fluent.
- Shape of biomass particles is taken into consideration in the model.
- Geometry of particles influences the process of devolatilization and combustion.
- Influence of the particle shape and size increases with the particle size.

ARTICLE INFO

Article history:
Received 11 June 2014
Accepted 19 December 2014
Available online 27 December 2014

Keywords:
Pulverized combustion
Biomass
Particle shape
Heat transfer
Mass transfer
Numerical model

ABSTRACT

Numerical analysis of co-firing pulverized coal and biomass in a vertical cylindrical laboratory furnace is explored. The ratio of coal and biomass in the fuel was 80:20 by mass for all cases. The mathematical model of combustion in the furnace was established by describing physical phenomena such as turbulent flow, heat and mass transfer, devolatilization and combustion.

A 3D-model of combustion in a laboratory furnace was created using the CFD software FLUENT. The shape of the biomass particles was estimated as cylindrical and was accounted for in the calculation of particle trajectories via a custom-developed model. Experimental measurements were conducted on a 20 kW laboratory furnace with controllable wall temperature. The temperature varied in the range from 1233 K to 1823 K, depending on the case. Excess air for combustion was set at 10% or 20%, depending on the case. The developed model shows better agreement with the experimental data than the existing models, which estimate particles as spheres. Analysis of the results shows that the influence of the particle size increases with the size of the particle. Also, the geometry of the cylindrical particles strongly influences the beginning and the intensity of the devolatilization process and subsequently the combustion process.

1. Introduction

Mechanisms of coal combustion in industrial furnaces are well understood today. Many mathematical and numerical models are developed on the basis of these insights that successfully describe the observed physical processes such as in Refs. [1–3]. However, it is unrealistic to expect that these models are applicable in the modelling of biomass combustion since biomass somewhat differs from coal in its physical and chemical properties. The variety of biomass particle shapes and sizes plays an important role in its combustion process as different particle surface to volume ratios directly affect the rate of the formation of volatiles and oxidation during combustion. The pulverized biomass particle can usually be described as a cylinder or disc. Both of these geometric shapes have a much higher surface to volume ratio than the spheres which are commonly used to describe coal dust particles. As a consequence, it is necessary to pay special attention to the influence of biomass particle shape and size when creating a biomass combustion model.

Most existing studies are applicable only to the individual particles or particles of a spherical shape and do not involve combustion. Only recently have a few studies appeared which include

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http://dx.doi.org/10.1016/j.applthermaleng.2014.12.047
1359-4311/

the combustion processes. In Ref. [4] the effect of temperature and particle size on biomass pyrolysis and combustion of char residue was studied. One step further was made in Ref. [5] and combustion of individual biomass particles of different shapes and of the same volume was modelled, which was described as disks, cylinders, or as nearly spherical. The combustion of pulverized biomass or the co-firing of coal and biomass in furnaces is generally modelled with spherical particles where, in some cases, unsphericity is taken into account only through the form factors. Thus, in Backreedy et al. [6] or in more recent papers [7,8], the drag coefficient for the particle flow model by Haider and Levenspiel [9] was used to model pulverized coal and biomass combustion.

The aim of this paper is to set a suitable mathematical model that would more accurately describe the physical process of co-firing pulverized coal and biomass. Special attention is given to the modelling of irregularly shaped biomass particles which are approximated by cylinders. The results obtained by numerical simulation are compared with the measurements performed on a 20 kW entrained flow reactor designed for co-firing pulverized coal and biomass, installed at the Faculty of Mechanical Engineering, University of Sarajevo.

2. Mathematical model

The commercial CFD code FLUENT 6.3 [10] was used with a number of parameters appropriate for coal combustion. CFD models for coal combustion contain a number of sub-models for turbulent flow, heat transfer and combustion of the coal. Many of these processes are common to the combustion of biomass but some aspects can be significantly different, particularly the particle shape and size, content and the nature of the volatiles and the kinetics of the devolatilisation process.

In this work, release of volatiles from the coal particles is described by the *Two Competing Rates* model [11], while the release of volatiles from biomass particles is described by the somewhat simpler *Single Kinetic Rate* model [12] due to the lack of necessary data for biomass such as the volatile release rate and the exact composition of the released volatiles.

Combustion of volatiles is modelled using the *EDM/Finite-Rate* model [10]. The basic chemical reactions for combustion of coal and biomass volatiles have been formulated with the assumption that the resulting complex hydrocarbons can be described by the general formula $C_xH_yO_zS_mN_n$. It was also necessary to include the radiation sub-model, as a significant portion of the heat released during combustion is transferred by radiation. Due to the specific geometry of the combustion chamber, this is done by the *Discrete Ordinates model* [13,14] which in combination with the *weighted sum of gray gases model* (WSGGM), offers the possibility of modelling the effects of non-gray gases as has already been proven in Ref. [3]. In addition to the processes taking place in the gas (continuous) phase, it was necessary to take into account the processes on the boundary between solid (discrete) and the gas phase. FLUENT contains a comprehensive model based on the Lagrangian approach to discrete phase combustion. User defined subroutines were implemented to approximate biomass cylindrical particles. The developed model, in addition to existing drag forces on coal spherical particles in turbulent flow, calculates the drag forces and lift forces on cylindrical particles of biomass. Particle combustion was modelled using the *Kinetics/Diffusion Rate-Limited model* [15,16] that takes into account the speed of oxidation on the surface of the particles and the rate of the diffusion of oxygen to the surface of the particles and takes the slower of the two as relevant. In post-processing, based on the calculated velocity and temperature field and concentration of the species, the pollutant concentrations NO and SO_2 are calculated.

2.1. Cylindrical particle model

Particle models available in FLUENT calculate drag force on the particle independently of the particle orientation; though lift force is not included, which is somewhat acceptable for modelling spherical particles such as of pulverized coal. Biomass particles, however, are of irregular geometry and those factors need to be included. It was, therefore, necessary to create a model of biomass particle trajectory calculation in turbulent flow that approximates its shape as a cylinder or a disc, including the lift forces acting upon it. Coal particles were, at the same time, approximated as spheres with models available in FLUENT where drag force on the particle is defined as:

$$\vec{F}_D = \frac{1}{2} C_D \rho A_{ef,1} |\vec{u} - \vec{u}_p| (\vec{u} - \vec{u}_p). \tag{1}$$

where C_D is the drag coefficient and $A_{ef,1}$ is the effective area representing the particle projected area in the direction of the drag force. For the spherical particle, it is equal to the circular area of the diameter d_p.

According to [17], where a large number of available correlations for drag coefficient calculation is processed, the model by Ganser [18], which takes into account the actual shape of the particle, has proven to be the most accurate. The effective area for a cylinder of length L and a diameter d_p is:

$$A_{ef,1} = \frac{{d_p}^2}{4} \pi \sqrt{\cos^2 \alpha + (4L/d_p \pi)^2 \sin^2 \alpha}. \tag{2}$$

It is dependant on the angle between the relative particle velocity $(\vec{u} - \vec{u}_p)$ and its axis $\vec{z}'$ (Fig. 1).

The drag coefficient for the cylindrical particle defined by Ganser [18] is:

$$C_D = \frac{24}{\mathrm{Re}_{sf} K_1} \left[1 + 0.1118 \left(\mathrm{Re}_{sf} K_1 K_2 \right)^{0.6567} \right] + \frac{0.4305 \cdot K_2}{1 + 3305 / \left(\mathrm{Re}_{sf} K_1 K_2 \right)}, \tag{3}$$

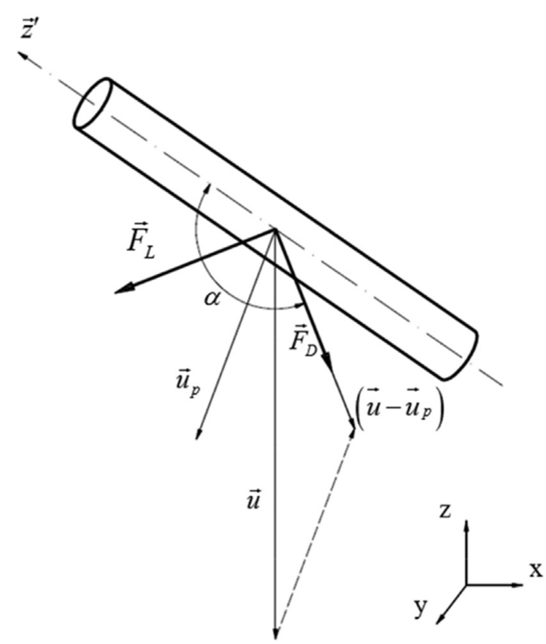

Fig. 1. Model of the cylindrical particle.