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Progress in Numerical Modelling of Packed Bed Biomass Combustion

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Abstract

Bio mass is a readily available renewable energy source for heating and power generation which reduces carbon dioxide emissions. Analysis of biomass combustion is complicated due to its large variations and physical structures. The physical and chemical processes involved in biomass combustion are necessary to understand which will improve applications of biomass in various sectors for energy use. Computer simulation of these combustion systems can be helpful to analyse different working conditions and to estimate the field values inside the whole domain. This simulation also helps to solve operation problems and may be used as a design tool. There are only a few numerical simulations of fixed bed biomass combustion employing complete model for both the solid and gas phases. The computational fluid dynamics (CFD) code available can model the gas phase combustion but it can't model all processes of packed bed biomass conversion. There are some recent works where numerical modelling of biomass combustion in three dimensional moving beds has been performed. In these works the bed contraction due to particle shrinkage is considered. The packed bed is considered as a porous zone and User Defined Functions (UDFs) platform is used to introduce the solid phase variables in the CFD. This article provides a review of the fundamental aspects and emerging trends in numerical modelling of packed bed biomass combustion. The published works on this area are reviewed and summarized in an organized manner with general conclusions. This paper also points the critical challenges to be resolved in future. This will help the researchers to decide the direction of further investigations.

Introduction

Biomass and municipal solid wastes are becoming an important fuel to produce thermal energy or electricity all over the world. Extensive research is going on the biomass combustion process to find efficient methods for conversion as well as to meet the strict environment regulations. Packed bed combustion of biomass reduces CO2 emission and land contamination. Biomass combustion in packed bed can be fixed or moving. The design, operation and maintenance of combustion furnace require detailed investigation of the burning process inside the bed. Many researchers have investigated the packed bed combustion of biomass fuels and wastes during the last two decades.

Biomass combustion study is a complicate process due to its large variation and physical structures. Multiple mechanisms and parameters involved in packed bed solid combustion makes the experimental data collection difficult. For this reason there are only a few experimental investigations with detailed data collection. Computational Fluid Dynamics (CFD) can be used to study the combustion phenomena in detail by combining experimental data and numerical simulations. This helps to analyse a large number of variables of the combustion process and different working conditions. It can also help to minimize the complication of experimental work by estimating the field values inside the whole domain and different places without disturbing the working condition of the system. Numerical simulations of biomass combustion systems employing complete models for all phases are limited in number. In this paper a review of the numerical modelling of packed bed biomass combustion system is presented.

Modelling

Yin et al. [31] has completed an extensive review of CFD modelling of fixed-bed biomass combustion system. A summary of the methodologies practiced by other authors are presented in this paper. The review of elaborations on packed bed modelling published in literature shows a broad variety of different model approaches to describe entire packed bed systems. According to the calculation of energy equation, these models are homogeneous and heterogeneous models. In homogeneous models the temperature of the gas and the solid phase are assumed to be equal and one overall energy balance equation is applied [16,27]. In heterogeneous models the gas phase and the solid phase have individual energy equations [22,24]. For packed bed combustion where there is a considerable temperature difference between the gas and solid phase, heterogeneous modelling is recommended. Based on the treatment of the solid phase in the heterogeneous models, they can be classified into continuous models [4,6,8,28] and discrete particle models [12, 17]. Continuous heterogeneous models treat both phases as if they are distributed continuously over the whole spacial domain. At each point in space both phases exist with distinguished properties. The common restriction of continuous packed bed model is that the intra-particle effects cannot be described sufficiently. Additionally, it is very difficult to model the inter-particle interactions in the packed bed with continuous models. The discrete particle model enhances the packed bed modelling by considering the packed bed as an ensemble of representative particles, where each of these particles undergoes thermal conversion processes. In this way the inter-particle effects, e.g. momentum and energy exchanges can be fully described.

The common modelling approach of packed bed is to divide the simulation in to the bed and the freeboard although there is a strong coupling in between them. Commercial CFD codes (Fluent, Star-CD, CFX, etc.) have been used to model the gas phase while the bed was simulated using separate models [24,32] in some studies. The bed and the freeboard are linked by a surface where mass and energy exchange occurs. This linking is considered one directional by some authors [9,23], which means the solution of the bed and the freeboard are independent of each other. Other authors [10,33] have developed different bed model mechanisms and include the variations in the solution of the freeboard in the simulation. Porteiro et al. [18] assumed that homogeneous combustion of the gases in the combustion chamber generates a strong radiative flux which induces the biomass decomposition in the bed. A zero-dimensional bed was modelled accounting key processes of the biomass conversion. To calculate various inputs of the gas phase model like gas temperature, species, velocities and particles, the bed model uses the incident radiation (calculated in the gas phase model). The treatment of the bed model to make it either one-dimensional or two-dimensional this mentioned methodology is helpful. Various authors have proposed different solutions of the bed. Kær [10, 11] presented a one-dimensional ''walking-column'' model for the comprehensive simulation of a 22 MW grate-firing boiler that accounts the heat transfer between the solid and the gas phases by including energy equations for both the phases. Yin [32] presented a CFD model of 108 MW biomass boiler employing the same bed model. To evaluate the effects of different factors in the CFD modelling of biomass grate-fired boilers, a sensitive analysis was conducted. Van der Lans et al. [27] proposed a two-dimensional moving bed discretised in several advancing columns in a steady simulation, where the bed position in the grate vary according to the amount of consumption. Another 2D bed-modelling program has been developed by The Sheffield University Waste Incineration Centre (SUWIC) which incorporates the various sub-process models and both the gas and solid phase governing equations are solved [28]. Numerical simulations of municipal solid waste [21] and biomass [29,30] without consideration of the channelling effect has been carried out in SUWIC. A reasonably close agreement between the modelling and actual measurements has been found when this model has been coupled with Fluent [21,30] through their boundary conditions. Collazo et al. [4] performed a three-dimensional CFD simulation of thermally thin particles by modelling the solid conversion of wood cell-by-cell in a dispersed porous media. A simple bed model was implemented in the CFD model to simulate an 18 KW pellet boiler by the same author [5]. The bed is considered as a perfectly stirred reactor. Following these works recently Gomez et al. [7] has used the CFD commercial code (Ansys Fluent) to simulate the transient packed bed biomass combustion in a complete three-dimensional modelling technique. A bed compaction model has been introduced and for the transient evolution the bed has been treated as a semitransparent porous media. In all these works the particles are modelled under thermally thin hypothesis, no gradients are calculated inside the particle and a sequential conversion of stages occurs.

In contrast, for thermally thick particles the dense discrete phase model (DPM) approach has been applied by some authors. Mehrabian et al. [13,14] employed DPM to form a three-dimensional bed of particles by computing the particle trajectories in a Lagrangian framework. Each solid particles thermal conversion is coupled with the gas phase. Particle layer approach has also been used by Ström and Thunman [25] to treat the thermally thick problem in CFD which predicts drying and devolatilisation in an inert environment. Thermal degradation of biomass particles has been described by Porteiro et al. [19,20]. Additionally, a one dimensional model with Thunman discretisation scheme has been used to treat a cylindrical particle [26]. To achieve acceptable resolutions they have increased the number of grid points. In a most recent work, Mehrabian et al. [15] has developed a transient 3D model where a validated comprehensive single particle model [14] for thermally thick biomass particle combustion is applied. Smooth shrinkage of the bed as well as bed collapse due to uneven consumption of fuel is taken into account.

Model Description

Among various packed bed models that have been mentioned earlier, some significant and important models will be described in detail here. In packed bed modelling the common approach is to divide the combustion system into two zones: biomass combustion in the packed bed (solid phase) and homogeneous reactions and heat transfer in the freeboard (gas phase). A combustion approach scheme is showing in figure 1.

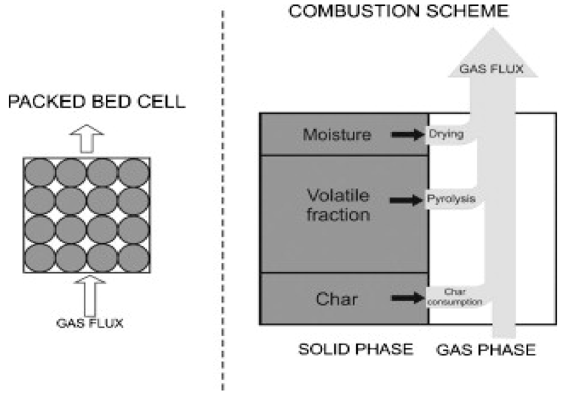

Figure 1. Illustration of the combustion approach. [7]

Solid Phase Modelling

Solid fuel particles forming the packed bed have a very important effect on the whole combustion system. Commercial CFD software's don't have the sub models for solving the solid phase. Hence authors used User Defined Functions (UDF) coupled with CFD codes to model the solid phase. Porteiro et al. [4,7,19] have used six user defined scalars to characterise the solid phase. These are (1) solid temperature, (2) solid fraction, (3) density of moisture, (4) density of dry biomass, (5) density of char and (6) particle characteristic volume represented by the third power of the characteristic diameter of the particle (Figure 2). The main steps of solid fuel conversions are drying, devolatization and char conversion where drying, devolatization and char generation are thermally controlled and char consumption can either be kinetically or diffusionally controlled. Moisture evaporation is considered to occur at 373.15K. Three parallel reactions in devolatization have been considered for the conversion of dry wood into gas, tar and char. The heterogeneous reactions of char include one direct char oxidation and two gasification reactions.

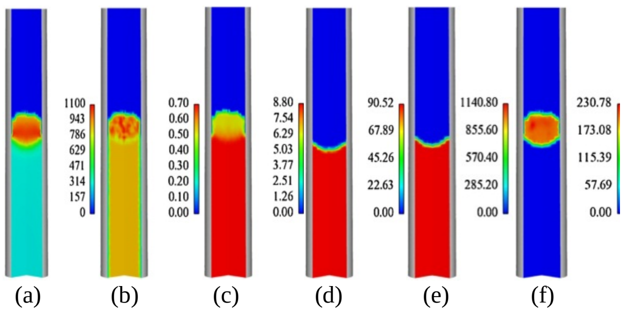

Figure 2. Estimated solid temperature (a), solid fraction (b), particle diameter (c) and densities of moisture (d), dry wood (e) and char (f) at t = 4000 s and air flux 0.05 kg/m^2 s [7].

Mehrabian et al. [14,15] investigated thermal conversion of thermally thick solid biomass particles by using a particle layer model to consider intra-particle transport processes and simultaneous sub-processes. For simplification temperature gradient in the radial direction of particle is considered. They have used Thunman approach [26] to apply the model for a finite cylindrical geometry. The layer model describes that the solid particle is divided into four layers according to the four fuel conversion stages: wet fuel, dry fuel, char, and ash (Figure 3). Drying, pyrolysis, and char burnout, these conversion sub-processes are used to define the boundaries between the layers. Mass change of each layer and movement of boundaries towards the particle centre occurs as the conversion proceeds. Therefore, during thermal conversion particle size and density varies.

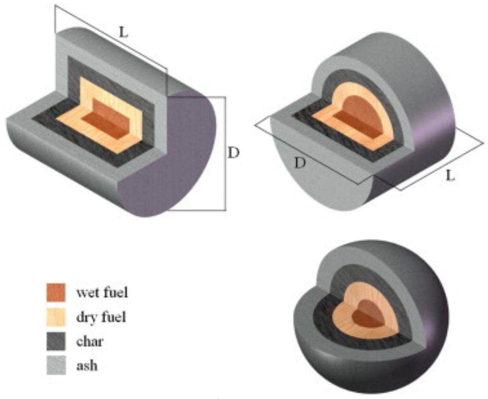

Figure 3. Discretisation scheme for spherical and cylindrical particles in layer model [14]

Bed Compaction

Fuel consumption influences two parameters of the packed bed: bed shrinkage and bed porosity. The common method for accounting bed contraction is considering constant bed porosity while particle shrinkage occurs in the bed. Collazo et al. [4] considered solid fraction consumption with varied porosity in the bed but the bed size remained almost constant. To solve this, Gomez et al. [7] presented a method similar to [4] which produces a continuous bed movement during solid consumption. This method works on energy and mass transfer between cells with mass grouping, by emptying the upper cells and filling the lower cells. Around a central cell, mass and energy is calculated between neighbour cells no matter which cell collapses. A loop over all cells changes every cell when conditions are fulfilled. Figure 4 shows schematic of the cells during compaction movement. In contrast the shrinkage of individual particle is considered to compute the bed shrinkage in the particle layer model [15]. To calculate the new position of particle user defined function is used. Particles are assumed to be always in contact with the beneath particles and move only in gravity direction. Looping procedure is applied to find the beneath particle. All particles in the packed bed arrange a compacted bed. Thus discontinuous shrinkage (bed collapse) and cavities occurs in the packed bed. Bed porosity is calculated at every time step which is used to calculate the gas phase pressure drop in the packed bed.

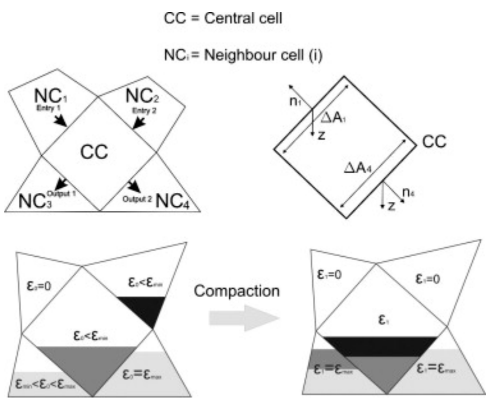

Figure 4. Schematic diagram of cells and solid fractions in a bed compaction movement. [7]

Gas Phase Modelling

The gas phase conservation equations are continuity, momentum, energy, turbulence, chemical species and soot. Most authors have used the commercial CFD software's built-in algorithm to solve these equations [7,15,18]. The standard k-epsilon model is used to account the effect of turbulence with enhanced wall treatment. Momentum equation (1) was modified with addition of a source term to account the effect of porosity on the gas flow. For homogeneous reactions, finite rate Eddy dissipation model is used which computes both the Arrhenius rate and Eddy dissipation rate and uses the lower one. Audai et al [1-3] has investigated the effect of multi stepped chemical reaction mechanism on the gas phase and solid phase of combustion.

$$S_p = -\left(\frac{\mu}{\alpha_p} v_i + C_2 \frac{1}{2} \rho_g |v| v_i\right) \quad (1)$$

where,

Permeability $\alpha_p = \frac{\psi^2 d_{eq}^2}{150} \frac{\varepsilon^3}{(1-\varepsilon)^2}$, Inertial loss, $C_2 = \frac{3.5}{\psi d_{eq}} \frac{(1-\varepsilon)}{\varepsilon^3}$

Sphericity $\psi = \frac{\pi^{1/3}(6V_p)^{2/3}}{A_p}$,Equiv. Diameter $d_{eq} = D_{cil}\left(\frac{3L_{cil}}{2D_{cil}}\right)^{1/3}$

Heat Transfer

Heat and mass transfer plays an important part in a combustion process. Heat and mass transfer is modelled for the solid phase and the interactions of solid with the gas phase. To model the heat and mass exchanges between phases, many authors [4,7,14, 18] have used the famous Wakao and Kaguei correlations for the calculation of Nusselt and Sherwood dimensionless numbers shown in equation (2) and equation (3), respectively.

$$Nu = 2 + 1.1\, Re^{0.6}\, Pr^{1/3} \quad (2)$$

$$Sh = 2 + 1.1\, Re^{0.6}\, Sc^{1/3} \quad (3)$$

These dimensionless numbers are used to calculate the convective heat transfer coefficient (h) and the mass transfer coefficient (k_m) as follows.

$h = \frac{Nu.k}{d_{eq}}$ and $k_m = \frac{Sh.D}{d_{eq}}$

Here radiation heat transfer has been modelled by discrete ordinates model (DOM). Gomez et al. [7] modified the standard DOM to calculate the difference in temperature between the solid and the gas phases and high absorptivity of the medium. Mehrabian et al. [15] have also calculated the radiative heat transfer between the particles.

Summary and Conclusions

A review on numerical modelling of packed bed combustion is made. Most significant works have been summarized. The usual practice for modelling packed bed by dividing the system into bed and freeboard has been performed by many authors. There has been significant effort to model the interactions between the solid and gas phases. Here numerical modelling of the solid phase remains a challenge for researchers due to complex mechanisms and experimental limitations. Initially, the bed contraction was modelled considering the porosity remained constant. But some recent works have completed the modelling of solid fuel consumption with varied porosity. Another challenge of calculating the inter-particle interactions like momentum and energy exchange has been overcome by researchers applying the discrete phase model considering the particles thermally thick. The published models have been validated against the temperature profiles at different heights of the packed bed, propagation rates of the reaction front and several species concentrations in the free board. Although there is extensive numerical modelling of packed bed biomass combustion, some limitations are still there to overcome by new researchers. The reaction front thickness of combustion like drying, devolatization and char consumption is over estimated by simulation of thermally thin particles. However for thermally thick particles heat diffusion in the packed bed and the conversion rate is slower than experiment. A modification of packed bed heat transfer model is required with specific physical properties to resolve this problem. There has been unrealistic ash layer at the end of the char burnout due to the consideration of particle movement only in the gravity direction. These issues need to be addressed for future development of the model.

Effects of different particle shape other than spherical need to be investigated on packed bed combustion. There is a strong need to study the environmental impacts of packed bed combustion. Limitations of detailed experimental result are a key factor that limits the validation of numerical works. From new researchers much experimental work is required along with the numerical work to validate detailed model successfully for further process optimization and hardware design. This will make the packed bed combustion a significant method of biomass conversion.

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