Fuel 165 (2016) 252–259

Contents lists available at ScienceDirect

Fuel

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

Effects of moisture release and radiation properties in pulverized fuel combustion: A CFD modelling study

Chungen Yin *

Department of Energy Technology, Aalborg University, 9220 Aalborg East, Denmark

HIGHLIGHTS

- Different fuel moisture release models are simulated and compared.
- Implementation of new gas and particle radiative property models is presented.
- The impacts of these models in PF combustion are successfully demonstrated.
- A guideline for radiative properties for combustion model is suggested.

ARTICLE INFO

Article history:
Received 8 July 2015
Received in revised form 7 September 2015
Accepted 14 October 2015
Available online 24 October 2015

Keywords:
CFD
Combustion
Fuel moisture
Particle radiation
Pulverized fuel
Utility boiler

ABSTRACT

Pulverized fuels (PF) prepared and fired in utility boilers always contain some moisture. For some fuels with high moisture contents (e.g., brown coals), the share of the evaporation enthalpy is quite significant compared to the heat released during combustion, which often needs to be reclaimed to improve the plant efficiency and is also expected to affect the combustion process. Thermal radiation is the principal mode of heat transfer in combustion. In PF furnaces, radiation consists of contribution from both participating gases and solid particles, in which gas and particle radiation properties play an important role. There are different methods or models in the literature to address fuel moisture release and radiation properties, some of which may be inappropriate and can produce misleading results. This paper compares the different methods and models and demonstrates their implementation and impacts via a computational fluid dynamics (CFD) study of a 609 MW_e pulverized coal-fired utility boiler. Overall speaking, it is suggested to add the free moisture in the fuel to the primary air stream while lump the bound moisture with volatiles in PF combustion modelling, although different methods for fuel moisture release may not induce distinct difference in combustion of PF with relatively low moisture content. For radiation, it has to be emphasized that particle radiation largely overwhelms gas radiation in PF combustion. The current tide of radiation research that over-focuses on gas radiation while over-simplifies particle radiation or even neglects particle radiation needs to be turned. For gaseous fuel combustion in which particle radiation is negligible, more generic model for gas radiative properties that can naturally and correctly accommodate the changes in combustion condition (e.g., oxy-fuel or air–fuel), account for the variations in CO_2 and H_2O concentrations in a flame, and include the impacts of other participating gases (e.g., CO and hydrocarbons) needs to be derived for combustion CFD community.

1. Introduction

Moisture in solid fuels is either remaining on the fuel particle surface (i.e., free moisture) or chemically bound in capillaries or pores in the solid matrix of the fuel particle (i.e., bound or inherent moisture). The former is released spontaneously once the particle temperature reaches the evaporation/boiling point, while the latter requires more energy to break the chemical bonds for the release. However, the precise boundary in terms of pore sizes between the free moisture and bound moisture is not yet well established [1]. Different methods can be found to handle fuel moisture release in PF combustion modelling, e.g., assuming all fuel moisture are released in the mills and it is the dried coal and the released water vapour that are fed into a furnace [2–5], assuming the fuel moisture is free moisture in the form of water droplets when fuel particles are fed into a furnace [6,7], or assuming the fuel moisture is bound moisture which is released in the furnace together with

* Tel.: +45 99409279; fax: +45 98151411.
E-mail address: chy@et.aau.dk

http://dx.doi.org/10.1016/j.fuel.2015.10.057
0016-2361/

volatiles [8,9]. These methods can make distinct difference in CFD results especially for fuels with high-moisture content, e.g., brown coal-fired plants, where the share of the evaporation enthalpy is so significant that the utility companies often try to regain the evaporation enthalpy instead of releasing it with the flue gas. The similar scenario also holds for combustion of biomass type fuels due to their relatively high moisture content, e.g., [10,11], in which the effect of bound moisture content of biomass is considered in CFD studies for improved performance.

The other issue presented in this paper is gas and particle radiation. Recently, gas radiation gains a lot of concerns, especially for oxy-fuel combustion in which efforts have been made to derive new CFD-oriented gaseous radiative property models. Different weighted-sum-of-gray-gases models (WSGGM) applicable to oxy-fuel combustion CFD can be seen in the literature, e.g., [12–15]. For air–fuel combustion modelling, the WSGGM proposed by Smith et al. [16] is still widely used for evaluating gaseous radiative properties, and the only alternative is the WSGGM refined recently for greater accuracy, applicability and completeness [8]. The two air–fuel WSGGMs are found to make distinct difference in CFD simulation of large-scale gaseous fuel combustion. Compared to gas radiation, very little attention is paid to particle radiation in both air–fuel and oxy-fuel combustion. In PF combustion modelling in the literature, particle radiation is either treated by using constant particle emissivity and scattering factor [9,17–21], or simply disregarded by assuming its impact is negligible [22].

The above issues, e.g., fuel moisture release and particle radiation, are however often neglected in the majority of the relevant literature. The former can be important in some cases, e.g., brown coal-fired furnaces; while the latter actually always plays a key role in radiation heat transfer in PF furnaces. The purpose of this paper is to present different methods for fuel moisture release, propose more realistic models for both gas and particle radiative properties, demonstrate in detail how to correctly implement these methods or models in PF combustion simulation, and evaluate their importance in PF combustion modelling via a comparative CFD study of a 609 MW_e pulverized coal-fired utility boiler. Prospects of developing more generic models for fuel moisture release and radiation properties are also discussed.

2. Modelling methodology

2.1. Physical model

The comparative CFD study is performed based on the 609 MW_e pulverized coal-fired utility boiler sketched in Fig. 1(a) and the fuel and operation conditions given in Table 1. The simulations are done using Ansys Fluent v15.0 [23], in which the new models for gas and particle radiative properties are implemented via user-defined functions (UDF) while the different methods for fuel moisture release are implemented directly via the graphical user interface.

The utility boiler whose details can be found in [2,3] is meshed into 3,191,580 hexahedral cells in total, in which $84 \times 74 \times 322$ = 2,001,552 cells are in the furnace under the furnace exit plane. The mesh on a horizontal cross-section in the furnace is shown in Fig. 1(b). The grid lines generally follow the main swirling flow direction to minimize the numerical diffusion. The mesh has a high quality whose mean equi-angle skew is 0.14 (maximum 0.56) and mean aspect ratio is about 2 (maximum 7.5). A preliminary simulation is done based on a coarse mesh of 454,776 hexahedral cells, which is refined to an intermediate mesh of about 2.5 million hexahedral cells and further refined to the final mesh as used in this paper. The comparison of the CFD results based on the 3 meshes shows that switching from the intermediate mesh to the final mesh yields a lot less distinct difference in the simulation results than switching from the coarse mesh to the intermediate mesh. As a result, the final mesh of 3,191,580 hexahedral cells is regarded to be dense enough to produce reliable and practically grid-independent solutions, as detailed in [24].

In all the simulations, the realizable k–ε model is used for turbulence. The realizable k–ε model shows substantial improvements over the standard k–ε model where the flow features include swirling, strong streamline curvature and rotation, as seen in this tangentially-fired PF furnace. The realizable k–ε model offers largely the same benefits and has similar applications as the RNG k–ε model, but is potentially more accurate and easier to converge than the latter. The SST k–ω model, showing great advantages where the viscous sublayer must be resolved to produce an accurate solution, e.g., in small-scale heat exchangers [25], is not really a good option in modelling of utility boilers due to the prohibitively fine near-wall mesh it requires in order to fully exploit its advantages. The Discrete Ordinate model is used to solve the radiative transfer equation, since it is applicable to all optical thicknesses and can properly account for particle radiation. The domain-based beam length is used in the different WSGGMs, to avoid grid-dependent solutions induced by cell-based WSGGMs. These sub-models have been commonly employed in CFD analyses of PF combustion in utility boilers [4,21,26–28].

The following sections mainly present the methods for addressing fuel moisture release and new models for gas and particle radiative properties. Other relevant key information used in the simulations is also described briefly.

2.2. Aerodynamics and heating of coal particles

Pulverized coal particles are assumed to be spherical in shape and follow the Rosin–Rammler size distribution (minimum, maximum and mean diameter: 15, 132 and 57 μm; spread parameter: 1.3). In the simulations, ten particle sizes are considered: 15, 28, 41, 54, 67, 80, 93, 106, 119, and 132 μm. Drag, gravity and pressure gradient force are retained in the equation of motion for particles to update their trajectories. The turbulent dispersion of particles is accounted for using the stochastic tracking model, in which 10 tries are employed. Totally 43,200 particle streams are tracked in each simulation.

When travelling through gas and interacting with gas in the furnace, the coal particles heat up, dry, release volatiles, and undergo heterogeneous char oxidation, creating sources for reactions in gas phase. The particle temperature is updated as follows,

$$m_p C_p \frac{dT_p}{dt} = hA_p(T_g - T_p) + \varepsilon_p A_p \sigma\left(\theta_R^4 - T_p^4\right) + \frac{dm_p}{dt}\Delta H \quad (1)$$

where m_p, C_p, T_p, t, h, A_p, T_g, ε_p, σ, θ_R, dm_p/dt, and ΔH denote the particle mass, specific heat, particle temperature, time, convective heat transfer coefficient, particle surface area, local gas temperature, particle emissivity, Stefan–Boltzmann constant, radiation temperature, conversion rate of particle in different sub-processes (e.g., evaporation, devolatilization, and char oxidation) and the corresponding heat effects (e.g., latent heat, and heat of reaction), respectively.

2.3. Drying of coal particles

The different methods to handle fuel moisture release in PF combustion modelling are implemented and compared in the CFD study here. The induced changes to the PF injections, primary air, combusting particles and volatiles are summarized in Table 2.

When the fuel moisture is lumped with the volatiles, the evaporation heat and formation enthalpy of the lumped volatile matters must be correctly calculated by taking into account the evaporation enthalpy of the chemically bound water. The modified latent