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Full Length Article

Comprehensive CFD modeling of the ash deposition in a biomass packed bed burner

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ABSTRACT

Ash-related issues such as fouling and slagging are likely the main operational problems of most commercial solid fuel burners. To study this kind of system, a full 3D-transient bed model embedded into the commercial CFD code ANSYS-Fluent was developed to describe the main processes that occur inside the bed. The model employs several sub-models that have been validated in previous studies (e.g., drying, devolatilisation, char reaction, radiation) and were combined with an ash evaporation model that functions in conjunction with a fine-particulate ejection model for predicting typical ash-related problems. In this work, the model is applied to simulate a pilot plant where the deposition of ash on refrigerated tubes is investigated. Several operational points were tested and simulated to assess the capability of the model to explain and predict the experimental fouling rates on the tubes, using which we show the relevance of the bed thickness variation and the primary air flow in the deposition profile. The ash evaporation and fine-particulate ejection models work symbiotically with the existing packed-bed biomass combustion model. The results obtained in this work show that this is a powerful tool for improving the operation of most existing appliances and contributes to the creation of a complex ash-layer deposition model.

1. Introduction

Currently, the use of biomass in residential and industrial thermal processes is increasing worldwide. The main reasons for its increased use include the rise of fossil fuel prices and the fact that biomass is the only carbon-based renewable fuel [1]. Its use in small-scale combustion systems for thermal energy production is an increasing trend and is not far from being cost-efficient when using high-quality fuels (e.g., wood chips and pellets); indeed, it would be enormously profitable if poorer or cheaper fuels could be used instead. However, these fuels present low thermal power output, high ash content and inadequate physical and flow properties [2–6].

The combustion of such biomass fuels, due to their high alkali metal and chlorine contents, causes several operational problems, such as fouling in the heat transfer zones of the systems and slagging [7,8]. Approximately three times more deposit has been observed for biomass fuels than for coal (normalized to the ash introduced with the fuel) [9].

In addition, wood combustion appliances are a major emission source of fine particles and volatile organic compounds. The smallest diameters produce respiratory and cardiovascular diseases, and the largest diameters cause air and soil contamination in the surrounding areas [10].

The amount and composition of the ash that is released from the bed depend on the fuel ash composition [11] and the optimal combustion conditions. Small-scale boilers that burn wood logs in batch-mode result in higher emissions of products due to incomplete combustion. However, pellet-fired boilers that operate under a continuous feed show lower emissions. At the same time, a good design of the bed, combustion chamber and secondary air can help reduce the emissions of pollutants [12].

Packed-bed biomass combustion facilities typically show a bimodal particle size distribution in the flame region, including a fine mode in the range of 0.05–0.5 µm and a coarse mode in the range of 0.5–100 µm. Far from the flame region, the bimodal distribution usually vanishes, and the distribution is unimodal [13].

Fig. 1 shows that sub-micrometre particles are produced by the vaporization, homogeneous condensation and nucleation of ash elements or from the production of soot, whereas the coarse mode is produced both from mechanical ejection and agglomeration [12,15–17].

The physical phenomena and stages of fouling are summarized as follows [18]:

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Nomenclature

Symbol	Parameter (Units)
a,b,c,d	Impaction efficiency coefficients (−)
C_D	Drag coefficient (−)
D_{KCl}	Diffusivity of potassium chloride (m^2/s)
d_p	Released particle diameter (m)
G	Gravity (m/s^2)
k	Turbulent kinetic energy (m^2/s^2)
k_e	Erosivity of impacting ash particles towards the deposit (−)
M	Mass transfer coefficient for spheres (m/s)
Mw_{KCL}	Molecular weight of KCl specie (kg/mol)
$Prob_{particle}$	Sticking probability of the particle (−)
$Prob_{wall}$	Sticking probability of the wall (−)
P_{vap}	Vapour pressure (Pa)
sa/vol	Surface area to volume ratio of the bed particle (1/m)
R_{gas}	Universal constant of gases (J/mol K)
Re	Reynolds number (−)
Sc	Schmidt number (−)
S_{KCl}	Source term of gaseous potassium chloride (kg/m^3 s)
Stk	Stokes number (−)
t_η	Temporal scale of turbulent eddies near the wall (s)
T_{sol}	Temperature of the solid (K)
TSP	Total Sticking Probability (−)
u', v' and w'	Gaussian distributed random velocity fluctuation (m/s)
u_τ	Fluid friction velocity (m/s)
Greek symbols	
Γ	Impaction efficiency (−)
ε	Solid fraction (m^3_{solid}/m^3_{cell})
ζ	Normally distributed random number (−)
μ	Dynamic viscosity (Pa s)
μ_S	Dynamic viscosity at the temperature of the surface (Pa s)
ν	Kinematic viscosity (m^2/s)
ρ_g	Gas density (kg/m^3)
ρ_{KCl}	Potassium chloride density (kg/m^3_{cell})
ρ_p	Particle density ($kg/m^3{}_{solid}$)
$\tau_p{}^+$	Particle relaxation time (s)
ϕ_{el}	Elutriation diameter (m)
ϕ_{eq}	Equivalent diameter of the average pellet present inside the cell (m)

- Dispersion: This is a basic phenomenon that governs the transport of particles from the core of the duct to the walls. Gas turbulence helps in the process, which tends to homogenise the concentration of particles in the gas.
- Deposition: In this stage, the particle crosses the boundary layer until it contacts the wall. All of the forces acting on the innermost part of the boundary layer are fundamental. Two zones are distinguished: the region away from the wall where dispersion is dominant and the region near the wall where turbulence is attenuated and other forces, such as thermophoresis, become dominant.
- Adhesion: This is a very complicated phenomenon in which many different mechanisms may intervene. Chemical, mechanical and electrostatic forces may be responsible for the adhesion of a particle to the wall, which can be covered by previously deposited material.
- Detachment: The re-entry of the particle to the gas phase.
- Ageing: A stage in which the physicochemical properties of deposition on the walls are modified, resulting in sintering, condensation or partial collapse.

The main mechanisms that act over particles inside the boundary layer (i.e., the viscous and transition sublayer) and affect the transport of particles toward the wall are divided into four groups [19]:

- Fluid dynamics: drag, lift, friction (Saffman), free rotation support (Magnus), turbulent support (Basset) and virtual mass forces.
- Static forces: hydrostatic pressure.
- External forces: gravitational, electromagnetic and electrostatic forces.
- Molecular forces: Brownian motion and thermophoresis.

Previous studies [10,14,20] used thermodynamic balances, based on the minimization of the Gibbs energy, to account for some of the aforementioned processes. These tools work well for ash chemistry but require a large amount of experimental data to have good predictive abilities.

In this work, a full 3D-transient bed model that employs several submodels for every stage of biomass combustion (all of which have been validated in previous studies) is improved with an ash evaporation and condensation model and a fine-particulate matter ejection model based on the Discrete Phase Model (DPM) of the commercial CFD code ANSYS-Fluent.

Using this full 3D-transient bed model, the ash deposition modelling benefits from the accuracy given by a model that accounts for the geometry of the boiler and transient combustion conditions of the bed.

2. Methodology

2.1. Pilot plant

A pilot plant of 12 (kW) nominal power that was specifically designed to test deposition over cooled surfaces was tested in previous studies [13,21], which have provided the experimental data used in this work.

Primary air enters through the bottom of the plant and reaches an inclined grate (dashed line) through a matrix of holes. This bed is side-fed by a screw. Secondary air enters the combustion chamber through a row of holes that are equally spaced at a distance between 0.35 and 0.45 (m) above the surface of the bed. The deposition sampling probe is a water-cooled pipe that has an outer diameter of 25 (mm) and a thickness of 1 (mm) and is made of stainless steel. It is placed 0.192 (m) above secondary air inlet. In current domestic boilers, it is common for water pipes to be in areas that are very close to the flame due to the considerable reduction of the volume of the combustion chamber owing to the requirement of compactness of the design. The selected position corresponds approximately to the typical distance in domestic boilers.

This facility allows the user to control four parameters: the separate control of the total air flow rate in the primary and secondary inlets, the temperature of water entering the deposition probe and the fuel mass delivered per unit of time. However, to avoid the side effects caused by a partially uncovered grate, the latter is controlled through a bed level controller. If the bed level drops, uncovering part of the gate, it acts over the feeding system to feed extra fuel. Therefore, for this study, deposition has been studied for the remaining three parameters: water temperature, primary-to-secondary air ratio and total air flow rate. The fuel used for this work is summarized in Tables 1 and 2. Although it is not a low-quality fuel, it was chosen because this fuel allows the steady operation of the system for a longer period of time, therefore leading to a much lower uncertainty of the results.

Fig. 2 shows a schematic diagram of this plant and the section of the CAD for the CFD simulations. The CFD model presents the correct orientation of the secondary air inlet because the schematic view is reoriented for an easier representation.