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APPLICATION OF NUMERICAL MODELLING TO BIOMASS GRATE FURNACES

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ABSTRACT

The direct combustion of the biomass is the most advanced and mature technology in the field of energetic biomass utilisation. The legislations on the amount of emitted pollutants and the plant efficiency of biomass combustion systems are continually being restricted. Therefore constant improvement of the plant efficiency and emission reduction is required Numerical modelling is gaining increasing importance for the development of biomass combustion technologies. In this paper an overview about the numerical modelling efforts deal with the most relevant phenomena in biomass grate firing systems is given. The numerical modelling results in a deeper understanding of the underlying processes in biomass combustion plants. Therefore, it leads to a faster and safer procedure of development of a new technology.

INTRODUCTION

Biomass as a renewable energy source is widely applied for heat and power production and its importance will gradually increase in the next decades, because of its sustainability which can be partly CO_2 neutral and depletion of fossil fuels.

The conversion of solid biomass to useful energy can be achieved through one of two major pathways, (1) biological (fermentation) and (2) thermal. Biological conversion is perhaps the most ancient means of biomass conversion [1]. Thermal conversion of biomass into gases came much later. Commercial usage of small biomass gasifiers began during the Second World War. The four principal routes for thermal conversion are: combustion, gasification, pyrolysis and liquefaction. The last three routes are indirect process where biomass converted to an energy carrier (i.e.char, gas or liquid).

Combustion involves the high temperature conversion of biomass in excess air directly into heat. Gasification, in contrast involves a chemical reaction in an oxygen deficient environment to produce gas and char at the first stage, and the subsequent reduction of the product gases by the charcoal. Pyrolysis is the fundamental chemical reaction process that is the precursor of both the gasification and combustion of solid fuels. Pyrolysis takes place without the participation of oxygen. The pyrolysis process is attractive to use when high tar and char yield are of interest, while gasification are more suited for gas production. In liquefaction, the large biomass molecules are decomposed into liquids with smaller molecules. This occurs in the presence of a catalyst and at a relatively low temperature and high pressure. These small molecules are unstable and reactive, and can repolymerise into oily compounds with a wide range of molecular weight distribution.

The direct combustion of the biomass is the most advanced and mature technology of biomass thermal conversion. It is, however, a complex process involving heat and mass transfers, fluid dynamics, homogeneous as well as heterogeneous reactions. Three main types of furnaces for direct combustion of biomass are existing: fluidised bed combustion (FB), pulverised combustion and fixed bed combustion.

Within a fluidised bed furnace, a mixture of biomass and inert bed material is suspended by primary air introduced from below. In the pulverised burners the biomass particles with small size (preferably < 0.01 m) are injected into the combustion chamber. The particles burn out as they flow through the burner. It is the most common technology for biomass co-firing. In the fixed bed combustion system the biomass forms a pile on the grate and it burns where the primary combustion air is fed below the grate.

Among different combustion technologies mentioned above grate firing is one of the suitable technologies for biomass to energy conversion and in many applications it is even the preferred technology [2]. Therefore modelling efforts for simulation of relevant processes of grate firing systems are discussed in this paper.

GRATE FIRING TECHNOLOGY

The grate firing technology has the advantage that it is able to burn fuels with high moisture content (up to 60 wt%), different particle sizes (0.005 - >0.1 m), high ash content and blended fuels. However the capability of mixing of woody biomass and herbaceous fuels are limited. High excess oxygen (5 – 8 vol%) is a major drawback of the system which reduces the boiler efficiency and increase the emissions potential. Capacities of grate firing boilers range from 10 kW_{th} to 50 MW_{th} [3]. Modern grate furnaces consist of the following elements: fuel feeding, grate, primary combustion chamber (PCC), secondary combustion chamber (SCC), flue gas recirculation (FGR) and an ash removal system, as it is shown in Figure 1.

It is important to keep consistent and uniform fuel feeding and avoid any batch wise feeding that raises emission potential. For biomass fuels that are very heterogeneous in size, a stoker is needed to reduce the tendency that the different sizes separate themselves and spread the biomass evenly on the grate. Typically mechanical stokers are used in biomass grate firing systems and they can be divided into three main categories based on the way the biomass is fed onto the grate: crossfeed, overfeed and underfeed stokers. In the overfeed stoker the fuel is fed onto the top of the bed and moves downward as it is consumed. In the underfeed stoker, the fuel is fed upward at the bottom of the bed. In the crossfeed stoker the fuel cross the horizontal or inclined grate and it burns as it moves along the grate.

The grate, on which fuel bed is resting until it burns out, can be fixed, travelling, reciprocating, rotating or vibrating. The main functions of a grate are to provide a uniform consistency of the fuel bed and distribute the primary air entering beneath the fuel bed. An uneven fuel bed inclines the burning toward certain areas which stimulates hot spots and dead air zones within the furnace. In most of the industrial boilers multiple zones of primary air distribution under the grate are used to achieve a complete and stable combustion, a more favourable temperature distribution and low dust emissions

The primary combustion chamber starts from top of the fuel bed until the secondary air nozzles. In modern grate firing boilers the primary combustion chamber has fuel rich condition (air-fuel equivalence ratio $\lambda < 1$) in order to reduce nitrogen oxides (fuel NO_x) formed during the solid biomass combustion on the grate. Additionally if too much oxygen is available in the PCC ($\lambda > 1$), the volatiles burn in th PCC and release thermal energy at the bottom of the furnace instead of in the upper parts where the heat exchanger is located. This premature combustion impairs the boiler efficiency and can damage the grate by exposing to high temperatures. In order to efficiently control the temperature and, additionally, to improve turbulent mixing in the primary combustion chamber, modern grate firing systems are equipped with the flue gas recirculation. The flue gas recirculation (FGR) can be staged, it means entering a fraction of the FGR below the grate and the rest above the grate. The FGR improves mixing in the PCC by breaking up the strains arising from channelling in the fuel bed. Furthermore it has the porpuse to achieve a more efficient reduction of NO_x and CO emissions.

The secondary air supply systems provide the most flexible way to retrofit the grate firing systems for a better burnout and lower emissions. The secondary air nozzles can be optimised in terms of number, diameter, spacing, location and orientation to enhance mixing, to prolong the mean residence time of the flue gas, to distribute the temperature more evenly and reduce the flame temperature peaks.

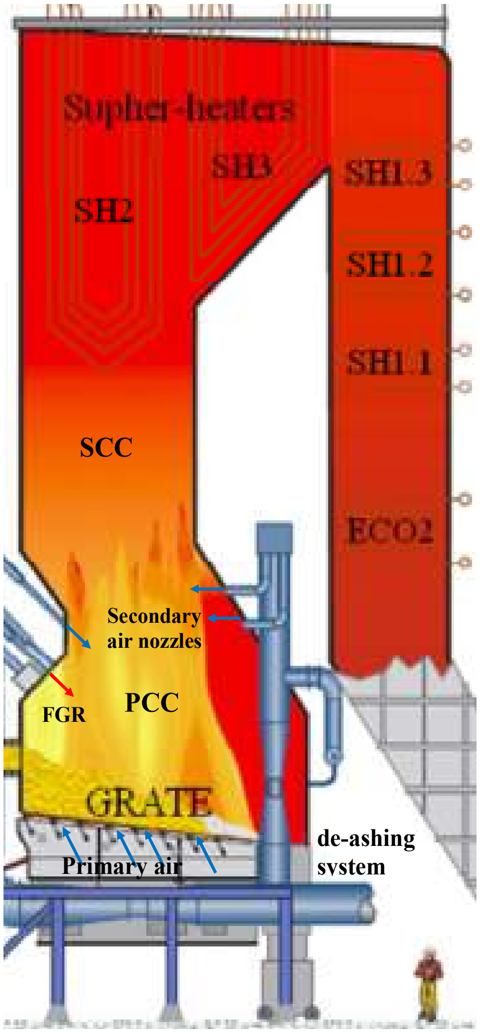

Figure 1: Sketch of a biomass grate firing furnace [2]

NUMERICAL MODELLING OF GRATE FURNACES

The legislations on the amount of emitted pollutants and the plant efficiency of biomass combustion systems are continually being restricted. As a result the energy producers and boiler manufacturers, in the heat and power sector, are forced to improve the combustion efficiency and optimise the plant operation continually. Theoretical investigations aided by numerical modelling are using to understand and describe the relevant phenomena in the system as a basis for optimisation and new design. Numerical modelling provides much more detailed information on the underlying processes and freedom to investigate the effect of geometry, in contrast to the experimental investigations. The success of the numerical modelling is highly dependent on the accuracy of the physical-chemical models and the numerical methods applied. Therefore it is essential for numerical models to be validated experimentally. In the following sections an overview about the numerical models for relevant phenomena in biomass grate firing systems is given.

FUEL BED THERMAL CONVERSION

The common approach in grate furnace simulations is to separately model the biomass thermal conversion in fuel bed and the gas phase combustion in freeboard, although there is an intensive interaction between them. The 1D empirical models serve to provide the temperatures and species release profiles as boundary conditions for the pursuing simulation of gas phase [4, 5]. The 1D empirical models are not able to sufficiently provide information about combustion on the grate and relevant influencing parameters in different grate systems. Therefore, research work in different groups is focusing on the development of 2D or 3D models for biomass fuel bed combustion. However, there are a few studies, where the combustion model of the fuel bed is incorporated in the entire simulation domain of the biomass grate firing system [6-8]. The review of elaborations on fuel bed modelling published in the literature shows a broad variety of different model approaches to describe packed bed systems [2]. Fundamentally, they are either homogeneous or heterogeneous models. The difference lies in the calculation of the energy equation. In homogeneous models the temperatures of the gas and the solid phase are assumed to be equal, and a single, overall energy balance equation is applied [9-12]. The physical properties which appear as constants in the energy equation are described by their effective values over the entire bed. In heterogeneous models the gas phase and the solid phase have individual energy equations [13-18]. They have different temperatures, and heat and mass transfer between the two phases are described by means of Nusselt and Sherwood correlations.

Based on their treatment of the solid phase, heterogeneous models can be classified into continuous models [19-21] and discrete particle models [22, 23]. Continuous heterogeneous models treat both phases as if they were distributed continuously over the whole spatial domain. At each point in space both phases exist with distinguished properties. The common limitation of the continuous packed bed models is that intra-particle effects cannot be sufficiently described. Additionally, it is very difficult to model the shrinkage of the packed bed using continuous models. The discrete particle models enhance packed bed modelling by considering the packed bed as an ensemble of representative particles in which each particle undergoes thermal conversion processes. This enables the inter-particle effects, e.g. momentum and energy exchange, to be fully described. The main drawback of the discrete particle models is the high calculation time.

An example of a 3D model for biomass packed bed combustion, which enable a direct link of the bed model with the gas phase combustion models in the freeboard is shown in Figure 2. In this model the biomass combustion is modelled by a thermally thick particle model which considers the effect of temperature gradients in the particle. Figure 2 illustrates the positions of the three thermal sub-processes, e. i. drying, pyrolysis and char burnout along the particle paths on the grate. As it can be seen they occur sequentially with an overlap between each other, especially where pyrolysis and char burnout take place.

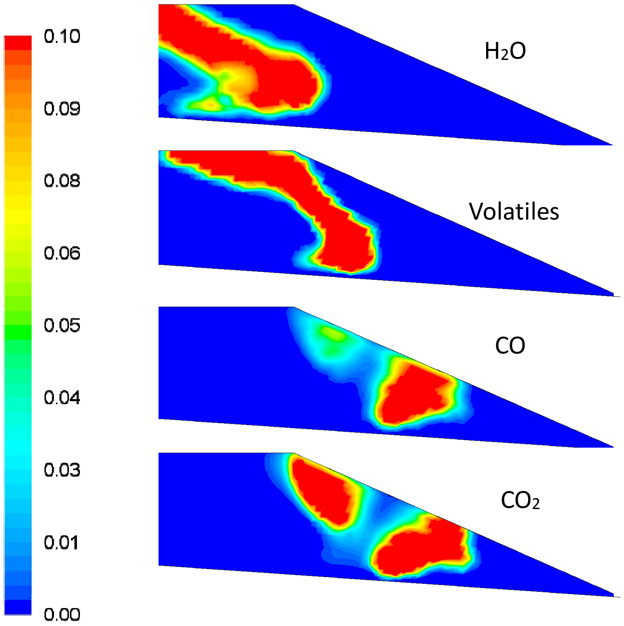

Figure 2: Simulation of a 180 kW biomass grate furnace fuel: wood chips; contours of release rates of different species [mg/s] from biomass particles at a vertical cross section in the fuel bed [24].

GAS PHASE COMBUSTION

The combustion of volatile species above the fuel bed highly depends on the mixing of reactants in the flow because of the fast combustion reaction rates. Turbulence greatly enhances the heat and mass transfer and promotes mixing of reactants. Therefore it is essential to take into account the effects of turbulence on the reaction rate. The turbulent mixing between the reactants occurs in a rather nonlinear manner and it poses one of the challenges in simulation of turbulent reacting flows.

The Eddy Break-Up combustion models proposed by Magnussen and Hjertager [25] are usually applied to model the turbulence chemistry interaction of the gas phase combustion in biomass grate furnaces. They are successfully able to optimise the nozzles for the injection of secondary air and flue gas recirculation to enhance turbulent mixing and flue gas burnout. The Eddy Break-Up models assume the reaction chemistry to be infinitely fast and the combustion process depends on the turbulent mixing. However, in laminar to moderate turbulence zones such as in small-scale biomass combustion plants the Eddy Break-Up combustion models are not valid because they were originally developed for highly turbulent flows. Therefore a hybrid gas phase reaction model was developed which is sensitive to local flow conditions [26]. The model reliably distinguishes between the mixing or kinetically dominated zones. It calculates the effective reaction rate from the laminar finite rate kinetics and the turbulent reaction rate and weights them depending on the local turbulent Reynolds number.

Moreover the porous nature of the fuel bed leads to streak formation influencing gas mixing and combustion above the fuel bed. The concentration of oxidiser and reactants in the gas released from the biomass fuel bed are strongly spatial dependent. Recently some studies [20, 21] dealt with the channelling and its effect on the combustion of biomass fuel bed. Shiehnejadhesar et al. [27] developed a streak model based on the mixing function to describe the mixing process above the fuel bed. The mixing function is a combination of the mixing time, the necessary residence time to reach the fully mixed condition, and the flue gas residence time in the region above the fuel bed. The model has been successfully tested with a real-scale biomass grate furnace. The selected results of this model are shown in Figure 3.

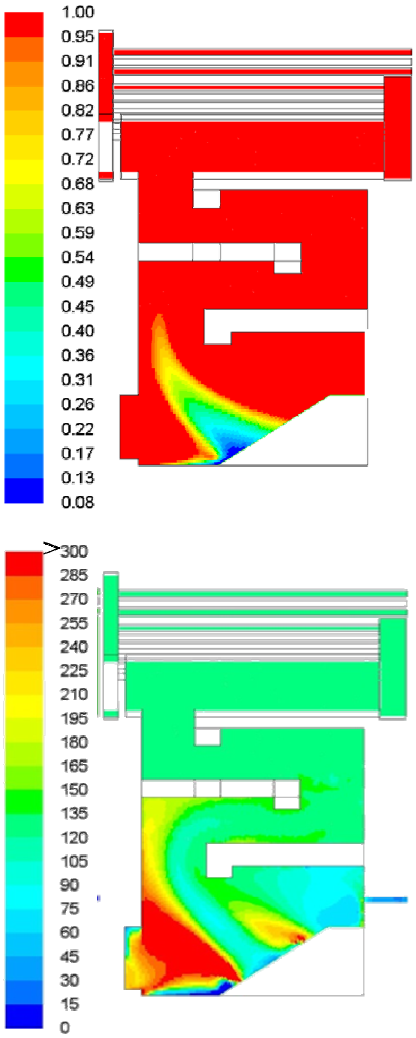

Figure 3: Simulation of a 180 kW biomass grate furnace, fuel: wood chips; top: Mixing function [-]; bottom: NO_x concentration [mg/Nm^3 d.b., 13 vol% O_2] calculated with considering the effect of streaks arising from the fuel bed [27].

As it can be seen in Figure 3 (top) the mixing function indicated that a major part of the reaction zone above the packed bed is influenced by streak formation. The NO_x emissions calculated with the hybrid-streak formation model is (bottom in Figure 3) in better agreement with measured value [27] due to a more accurate prediction of the species mixing process above the fuel bed and, therefore, of radicals, that are important for NO_x formation processes.

For gas phase combustion in biomass grate furnaces usually global reaction mechanisms are applied [4, 5]. The global reactions describe an overall process by which reactants are converted to anticipated products at the end of the process. Therefore they may not be sufficiently accurate to predict the formation and emissions of NO_x and unburnt CO for a broad range of operating conditions. Additionally, due to a strong interaction between the freeboard and the fuel bed, an accurate model for the combustion chemistry in the freeboard is of high relevance. Hence, some studies used detailed and reduced reaction mechanisms to model the homogeneous combustion in freeboard [8, 24, 28].

POLLUTANTS FORMATION AND EMISSIONS

Biomass combustion is a source of air emissions which destruct the global environment and human health to some extent. The formation of pollutants not only depends on the fuel but also depends on the furnace operating conditions, e.g. temperature, equivalence ratio (λ), flue gas residence time, etc. It is therefore important to know how the pollutants are formed and find a way to lower emissions of pollutants.

The combustion process itself always entails pollutants formation and the combustion of renewable fuels, like biomass, has some particular emissions which emanates from the biomass fuel characteristic. The pollutants originate from biomass combustion can be divided into two different groups: gaseous emissions and inhalable particular matter (PM). Emissions in the first group are NO_x, SO_x, CO, CO_2, unburned hydrocarbons (UHC), polycyclic aromatic hydrocarbons (PAH) (partly found on the surface of PM), dioxins and furans (PCDD/PCDF) (partly found on the surface of PM). The second group includes, soot, condensable organic compounds, aerosol and coarse fly ash particles. Hereinafter, the latest efforts of modelling nitric oxide (NO_x) formation and emissions as well as the ash related problems are presented.

Due to continually stricter emission limits and increasing demand of the combustion of new agricultural and herbaceous biomass fuels with high nitrogen contents, there is a need for efficient design tools for low NO_x furnaces. There are three generally accepted mechanisms for NO_x formation: thermal NO_x, prompt NO_x, and fuel NO_x [29, 30]. Thermal NO_x is formed by the high-temperature reaction of nitrogen with oxygen, by the well-known Zeldovich mechanism. Prompt NO_x is formed by the relatively fast reaction between nitrogen, oxygen, and hydrocarbon radicals (e.g. CH and CH_2). The products of these reactions could lead to formation of amines and cyano compounds that subsequently react to form NO. Fuel NO_x is formed by the direct oxidation of organo-nitrogen compounds contained in the fuel. As a result of the comparatively low combustion temperatures in biomass grate firing systems, the fuel NO_x is the major source of NO_x [31]. Therefore the most crucial point is the release of the NO_x precursors from the fuel bed to the freeboard under different environments for different biomass fuels. Klason and Bai [32, 33] assumed that all the fuel-N released into NH_3 and HCN with 50/50 molar ratio during the devolatilisation and no char-N is considered. With these assumptions they simulate NO_x formation and emissions of a small-scale wood pellet grate boiler and an industrial grate furnace burning wood chips. Yang et al. [34] studied the effect of operating conditions on the performance of a 38 MW_e power plant. The biomass fuel was straw and they model the NO emissions. They split the fuel-N into volatiles and char. The volatile-N was assumed to be only NH_3 and char-N was directly oxidised to NO. Widmann et al. [35] defined the release profiles for the most relevant N-species (NO, NH_3 and HCN) of the NO_x precursors during solid biomass combustion on the grate. Validation simulations showed that with this model all relevant trends concerning NO_x emissions in dependence of fuel nitrogen content, air staging, flue gas residence times and temperatures could be reproduced.

Ash related problems like aerosol formation and ash deposition as well as corrosion are of major relevance in biomass combustion plants especially when firing fuels with high ash content (e.g. waste wood, herbaceous and agricultural fuels). It is well known that the particular matters are formed by two different ash formation procedure [2, 3]. The main rout of particle formation is nucleation and condensation of alkali compounds. A considerable fraction of inorganic volatile species such as K, Na, S, Cl, Zn and Pb is released to the gas phase due to the high temperature during char combustion. These ash forming vapours later start to nucleate and form submicron particles or condensate on the surface of coarser particles or directly on the heat exchanger surfaces. These submicron particles are called aerosols and having diameters between 0.01-1 μm. The second route is the ash fusion and coagulation of non-vaporised ash residuals such as Si, Ca, Mg, Fe and Al. It leads to formation of coarse fly ash particles which entrained to the flue gas from the packed bed. It is worth to note that the aerosols are formed by phase change when flue gas temperatures are lower than the saturation point of the ash forming vapours, while the coarse fly ashes are always in solid phase.

There are some modelling efforts on the aerosol formation such as work of Jöller et al [36, 37] where the amount and the chemical composition of particle emissions in biomass grate furnaces were investigated. They used a plug flow model and thermodynamic equilibrium calculations together with a kinetic approach to model gaseous sulphate formation. Glarburg et al. [38] developed a reaction mechanism for sulphation of alkali metals, since the gaseous alkali sulphates may yields aerosols and also contribute to deposition and corrosion. Schulze et al. [39, 40] developed a model for release of fly ash particles and ash forming vapours from the fuel bed of biomass fired boilers and they coupled the model with a commercial software (ANSYS FLUENT) to solve the transport and deposition of them on the boiler walls. The model considered the condensation of ash vapours, deposition of coarse fly ash particles, erosion of the deposit layer by non-sticky particles, aerosol formation and deposition. The model, additionally, can simulate the time dependent ash deposit formation and its influence on heat transfer in the furnace in dependence of fuel type and plant operation conditions.

In Figure 4 the simulation results for a 70 kW pellet boiler are shown. As it can be seen the fine particle formation mainly initiates ate the entrance of the heat exchanger because temperatures in the primary combustion chamber is too high for ash forming vapours condensation.

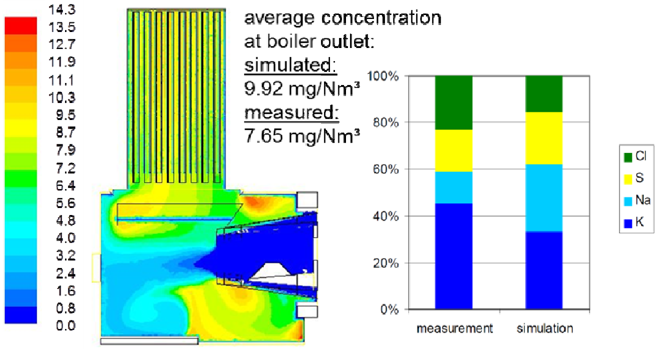

Figure 4: Simulation results regarding aerosol formation in a 70 kW fixed bed pellet boiler: left) total particle concentrations [mg/Nm^3 d.b., 13 vol% O_2]; right: chemical composition of fine particles. [40]

OUTLOOK

The continually higher standards for operation of biomass grate furnaces and increasing demand of new biomass fuels and new combustion technologies indicate that more research is still required. The most significant fields of modelling activities in biomass grate firing systems have been summarized in this paper. In each category outlined there are still potentials for further improvements.

Modelling of biomass packed bed combustion is highly important, because it describes not only the process underlying in the packed bed but it also determines the precursors of combustibles, NO_x and ash forming volatiles. Despite the significant efforts have been done in this filed the developed models are not sufficient and need to be strengthened. More endeavours are needed to develop adequate models which take into account the channelling effect and uneven consumption of the biomass fuels on the grate which leads to spatial dependent porosity in the fuel bed. The heat transfer models in the packed bed, particularly particle-wall heat transfer, still have some space for improvement. Mixing of the biomass fuel on the grate and the effect of the grate movement on it is a challenging topic which needs to be addressed, specially by considering the effect of different particle shape and size.

Despite the valuable efforts for modelling the release profiles of NO_x precursors and ash forming vapours as well as inorganic elements, they are still preliminary. Therefore it needs sophisticated fundamental understanding without introducing too many assumptions and simplifications. The deposition models show an encouraging potential to estimate the deposition formation in biomass grate boilers. However, they need to be extended in order to reliably calculate the particle size distribution, composition and stickiness of the coarse fly ash particles as well as the heterogeneous reactions on the entrained particle surfaces.

Gas phase combustion in the freeboard has been extensively investigated and many achievements have been already accomplished. However development of a detailed reaction mechanism which is exclusively for biomass fuels to build up a CFD model is still missing. The already applied gas phase reaction mechanisms need enhancement concerning the transformation and conversion features of the relevant species such as heavy hydrocarbons (tars), NO_x and SO_x precursors, PAH and soot.

It is worth noting that besides the modelling activities, there is a great need of comprehensive experimental investigations on biomass grate furnaces. Lack of reliable measurements, particularly in the fuel bed, suffers the packed bed combustion models for further enhancements.

CONCLUSION

This paper focuses on the biomass grate firing .technology and the most relevant modelling activities in this field. It is stated that numerical modelling provides an approximate overview of biomass grate firing systems. It helps to diagnose and solve operational problems as well as providing assistance when dealing with new designs to reduce emissions and increase the overall efficiency. The numerical modelling should finally lead to a reduction of design and optimisation procedure of new technologies, by providing a deeper understanding of the fundamental processes in the plant.

Therefore the current models should be improved and linked to the new innovative numerical models with the final objective of a “virtual biomass combustion plant” to simulate all relevant processes.

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