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Simulation of biomass drying in fixed bed of experimental grate combustion reactor

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The simulation of grate combustion process is an important part of the models of grate boilers combusting biomass, municipal solid waste or other fuels. This work reports the first phase of the development of a new software tool for the simulation of fixed fuel beds. The presented simulations are transient, with one space coordinate (height of the fixed bed). Description of the mathematical model and of its numerical implementation is provided. The model is applied to the drying of straw, which is frequently used as a biomass fuel and equally frequently studied by researchers.
The new software tool is validated by data published by other authors. Solution procedure, convergence and stability are discussed and proposals for future developments are summarised.

1. Introduction

Biomass mostly contains a sizeable amount of water. The amount of moisture in biomass is typically higher than in fossil fuels or municipal solid waste. Based on Bellais (2007) the moisture content of wood chips made from green wood varies from 40 to 60%. After a year of covered storage, the moisture content may decrease to 30%. Even pellets, which are industrially dried during their manufacture, have a moisture content of approximately 10%. Hence, the moisture content is one of the key parameters of biomass fuel and it is of crucial importance to the grate combustion process in terms of both burning rate and energy generation rate. Water stored in biomass fuel has the effect of increased volume of flue gases and decreased flame temperature. It may not be critical for the efficiency of the boiler, as the energy needed to evaporate water may be recovered by condensation from the flue-gas, but it is extremely important for the combustion process and consequently for the design of combustors.
Water content is also very important in the modelling of biomass combustion processes. Moisture content M is usually expressed as a mass percentage and it is defined as

$$M = \frac{m_{H_2O}}{m_{biomass}}, \tag{1}$$

where the components of the fraction are the total mass of water in particle and the mass of the particle completely dried out at 102°C ± 3°C. But moisture content is often

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defined on a wet basis as well. Therefore one has to know the basis used for water content calculation when adopting data from literature, as a misinterpretation may produce large errors.

Biomass usually contains two types of water. These include primarily the liquid water (also called free water) which is stored in the pores due to capillary forces and also bound water that is built in the biomass structure by intra-molecular forces.

According to Bellais (2007) the drying models may be sorted into three different types. Most often used is the heat sink model. It is based on the assumptions that drying occurs at a fixed boiling temperature and that the drying zone is infinitely thin. This means that there is no resistance to mass transfer and that the water vapour instantaneously leaves the particle. The drying rate is then completely controlled by the heat transfer. Various approaches to the implementation of this model exist, see for example Horttanainen (2000) or Peters (2002).

The second type of drying model is a first-order kinetic model. The model is easy to implement as it is sufficient to add water and its vaporisation heat to the kinetic scheme, evaporation is not limited by saturation pressure. This scheme is generally unable to describe condensation

Third model, called equilibrium model, is based on the hypothesis that water vapour is in equilibrium with the liquid. Therefore the partial pressure of water vapour is fixed by the saturation pressure. This assumption is typical of models for low-temperature drying. Equilibrium models depend not only on heat transfer but also on mass transfer. Examples of application of this type of model may be found in Fredlund (1993), Larfeld et al. (2000), Di Blasi et al. (2003) or Zhou et al. (2005).

It is worth to mention a possible combination of the heat sink and equilibrium models to emphasize the rate of drying at the boiling temperature, e.g. Yang et al. (2007).

2. Bed modelling

As shown in Figure 1, a simple laboratory-scale experimental furnace of a cylindrical shape is considered. The (possibly preheated) primary air enters the bed through a grate at the bottom of the furnace and flows in plug flow through the fuel layer to the top.

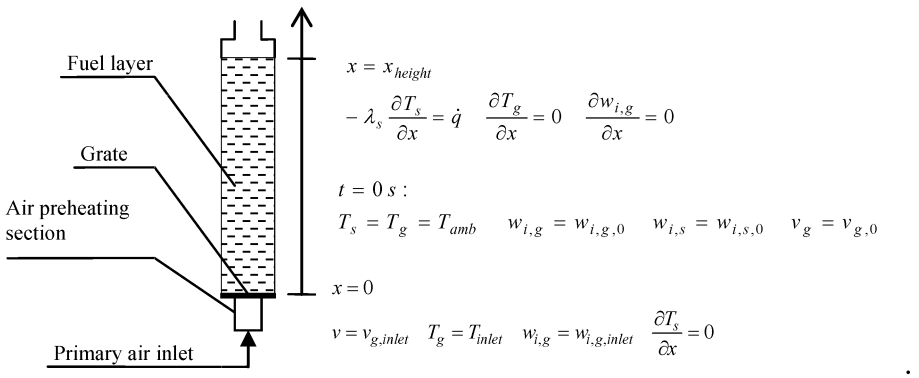

Fig. 1 Schematic diagram of the reactor and boundary/initial conditions

2.1 Mathematical model

In this work it is assumed that the furnace is a thermally insulated cylinder and all cross-flow gradients are zero. All processes take place in one direction only and the gas is described as ideal incompressible (expands when heated but remains constant when pressure changes). The bed can be considered stationary, as primary air-flow rates are below 0.3 $kg \cdot m^{-2} \cdot s^{-1}$, (Zhou et al., 2005).

The governing equations along with other thermo-physical properties and relations are adopted from (Zhou et al., 2005). In order to compare the available types of drying models, two models adopted from the literature are used to compute the drying rate, namely the first-order kinetic rate model of Miltner et al. (2008) and the diffusion-limited rate model of Zhou et al. (2005) (i.e. equilibrium model) . While the first-order kinetic rate model provides easy, fast and numerically stable computation, the diffusion-limited model entails several complications. Due to the absence of explicit dependence on instantaneous water content in the solid, it produces a shock change of the drying rate each time that moisture is completely evaporated from a control volume. In this work we therefore propose a measure to smooth it out by multiplying the drying rate by moisture mass fraction in solid as shown in equation (2).

$$r_{H_2O} = k_d \cdot S \cdot (C_{H_2O,surf} - C_{H_2O,g}) \cdot w_{H_2O,s} \qquad [\mathrm{kg \cdot m^{-3} \cdot s^{-1}}] \tag{2}$$

Various correlations for Sherwood and Nusselt numbers have been found and tested, (Shin et al., 2000), (Yang et al., 2007), (Kaer, 2005). Finally, those of (Shin et al., 2000) and (Kaer, 2005) were adopted.

2.2 Discretization technique

The governing equations are discretised by the finite volume method. The fuel layer is meshed by a number of non-overlapping control volumes. Convective terms are treated by the power-law scheme (Patankar, 1980), while diffusive terms are discretised by the central differencing scheme. Equations are integrated over time using the implicit Euler method. Since they are nonlinear, discrete time solutions are obtained by an iterative procedure, which is repeated until a converged solution is reached. Also other common techniques like under-relaxation and adaptive time stepping are employed.

2.3 Initial and boundary conditions

The system of governing partial differential equations is solved to obtain solid mass and temperature field, gas velocity, temperature and species mass fraction distributions along the bed height. Initial conditions reflect the state just before turning the primary air and heat source on. Boundary conditions at the grate are given by the operating conditions (zero temperature gradient is prescribed for solid phase). At the bed top, irradiation heat flux is prescribed and zero gradients are assumed for species mass fractions. All the boundary conditions are shown schematically in figure 1.

2.4 Model implementation

The discretised mathematical model has been implemented into a computer program written in MATLAB programming language. MATLAB provides an environment in which it is easy to work intuitively with matrices and numerical algorithms generally. A library of MATLAB functions has been created as a general modelling toolbox for the prediction of the processes that occur during grate combustion of biomass.

3. Simulation

The purpose of the present work was mainly validation of the implemented toolbox to several purely fuel drying scenarios (with no devolatilization or chemical reactions). At this moment of the work, the authors have no recourse to experimental data. Therefore the validation is performed on the basis of physical reasoning and results published by other authors. However, this task is by no means as simple and straightforward as it may seem, due to various errors and inconsistencies in data, collected from the literature. Therefore, a reconciliation of model parameters had to be performed. Also, not all necessary properties of biomass fuels have been found in open-access databases. That makes it quite complicated to match other authors' experiments or simulations.

To the best of the authors' knowledge, the implemented models produce physically correct behaviour. Two distinct scenarios are presented in the following to support this statement and demonstrate the capabilities of the program. Their specifications are listed in the table 1.

Tab. 1 Specification of the two scenarios

	Scenario 1	Scenario 2
Bed height [m]	1	0.19
Bed diameter [m]	0.154	0.25
Primary air-flow rate [$kg \cdot m^{-2} \cdot s^{-1}$]	0.18	0.0905
Primary air temperature [°C]	100	300
Initial (ambient) temperature [°C]	20	20
Initial moisture in fuel [w%] (dry basis)	0.1	0
Bed porosity [-]	0.6	0.57
Particle emissivity [-]	0.9	0.4
Particle radius [mm]	0.7	3.5
Time step [s]	0.02	0.2
Space step [m]	0.001	0.001

3.1 Scenario 1 – drying with dry hot air without additional heat source

This scenario should show the propagation of the drying front in the fuel bed until all moisture contained in the fuel is evaporated. Steady state should be reached after a certain period depending on the temperature and velocity of the primary air. Cut straw has been used as the fuel and its properties were taken from (Zhou et al., 2005).

Figure 2 a) shows propagation of the drying front along the fuel bed. It can be seen that both models predict almost identical propagation rates. Thus the steady state is reached after the same time as may be easily seen in figure 2 b), which shows total mass of solid as a function of time. However, the drying fronts of the two models are different in terms of both intensity and thickness. While the first-order kinetic rate model predicts non-zero drying rate values wherever solids contain any moisture, the diffusion-limited model significantly bounds the zone to much thinner domain. Also maxima of the drying rates differ by one order of magnitude.

Mass decreases due to moisture evaporation almost linearly and it is kept constant, after the process reaches the steady state. It is interesting to note the agreement with almost linear mass loss during grate combustion process documented e.g. by Lans et al. (2000). The drying process is clearly rate-limiting also for the combustion process.

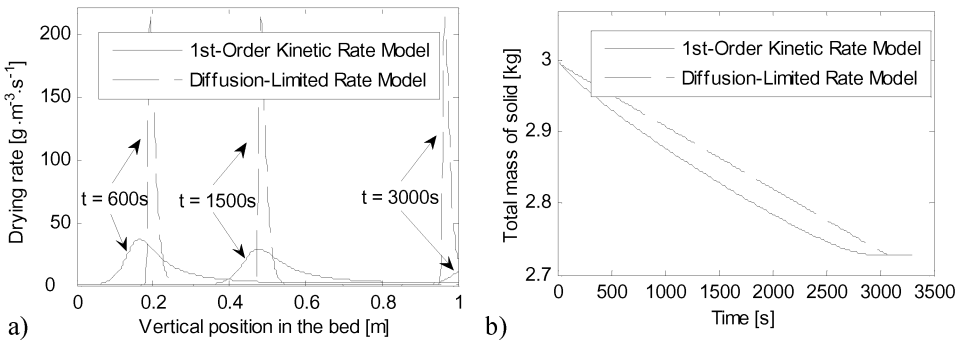

Fig. 2 Scenario 1: a) drying rate, b) total mass of the solid fuel on the grate

3.2 Scenario 2 – 'Aluminium straw' heat conduction

Peters et al. (2002) used a particle resolved modelling approach to simulate heat-up and drying of a packed bed. In order to validate predictions of heat transfer by this approach, they compared measurements to simulations of the heat-up of aluminium and slate particles as representatives of high and low conductive materials.

This scenario simulates heat conduction process in a packed bed of straw particles made of aluminium. In this case, effects of heat conduction, radiation in the bed and heat convection may be analysed in detail.

Figure 3 b) shows solid temperatures at different locations of the fuel bed as functions of time. Temperatures at locations near the grate are rising faster due to the intensive heat transfer between solid and gas phases. The resulting temperature profiles are qualitatively similar to those of (Peters et al., 2002).

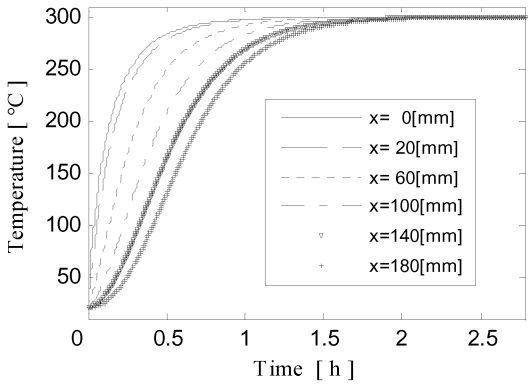

Fig. 3 Solid temperatures in scenario 2

4. Conclusions

The present work provides an introduction of a new simulation tool for the prediction of combustion processes in a fixed bed. The modelling approach is described as well as its implementation into a computer program. The code's capability to simulate bed drying processes is demonstrated by a sample of results of two scenarios, first of which also

compares two different drying models. Future work will lead from implementation of other models published in the literature (drying, devolatilization, char oxidation, gas reactions) to the development of improved modelling capabilities and applications to various biomass fuels.

5. Acknowledgements

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