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Influence of stoking on the combustion of beech wood particles of different shape in an agitated bed

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ABSTRACT

Mass loss of beech wood particles during combustion was measured in a batch reactor which allows stoking of the fuel bed. The test rig allows air staging, where primary air is flowing through the fuel bed and secondary air is added in the freeboard above the bed. The bed is ignited by radiation from electrically heated walls. The shape of the biomass particles (spheres, cylinders and cubes) and the primary to secondary air mass flow ratio were varied. Influence of stoking has been assessed by determining a mixing index for the top particle layer. Results show the general influence of stoking on the mass loss rate of the bulk in different combustion regimes. Stoking delays volatile ignition above the bed but accelerates fuel bed mass loss during combustion. Increased radiative heat flux from the flame into the bed when the bed is stoked was identified as the main reason for accelerated mass loss. Particle shape influences bulk mixing which is reflected in the combustion behavior. In particular, ignition of the volatiles is delayed by increased bulk mixing.

1. Introduction

Domestic heating systems are very often based on fixed bed combustion (e.g. tiled stoves). The same holds true for automated domestic boiler systems with the difference that pellets are fed continuously to the fuel bed, thereby inducing certain stoking and, hence, mixing into the bed (e.g. underfeed stoker). Recent developments on straw pellet firing in domestic heating suggest to use stoking to avoid bed agglomeration caused by the low ash sintering temperatures of straw [1]. In larger scale grate firing systems like municipal waste incineration or wood chips combustion for power production stoking is a standard. Stoking is used to transport the fuel across the grate and causes severe mixing in the fuel bed. Based on this background the current study tries to examine the major differences between fixed bed and stoked combustion.

In fixed bed experiments primary air passes through a stationary bed of solid fuel particles, thus they are designed as batch processes. The basic principle is shown in Fig. 1a. After ignition of the top particle layer a reaction front is formed which travels counter-current to the primary air. The structure of this front subdivides the fuel bed into a top ash layer, a char layer, the devolatilization region followed by a drying zone. Very typically, the reaction front travels with a constant velocity through the bed, resulting in a constant mass loss rate of the fuel bed for a given primary air mass flow. Depending on the amount of primary air mass flow, three different combustion modes can be identified according to Porteiro [2]. In the oxygen limited mode at low primary air mass flows (sub-stoichiometric), the velocity of the reaction front is limited by the oxygen supply to the front. Consequently, the higher the primary air mass flow, the higher the combustion rate. With increasing mass flow (stoichiometric) the reaction limited mode is obtained, where sufficient oxygen is available, but kinetics limits the rate of conversion. With further increase (super-stoichiometric) the region of extinction by convective cooling is reached, where too much heat is transported away from the reaction front to sustain conversion.

During batch operation three sequential combustion regimes can be observed. Preheating of the bed with associated devolatilization before ignition of the volatiles (I), the travelling of the reaction front through the bed (II) as described above and, finally, the char burn-out phase (III) at the very end of the combustion process. The reaction progress is not only influenced by the primary air flow. Further parameters influencing combustion rate are fuel type, moisture, air pre-heating, particle size and particle shape. Examinations on the influence of fuel range from wood [3,4] to different type of waste based fuels [5–7]. With increasing moisture the reaction front velocity is decreasing as well as the mass loss rate of the fuel bed [4,7]. Nicholls [8] and van Kessel et al. [9] examine the influence of air pre-heating on fixed bed combustion. They did find an increased combustion rate with higher air preheat temperature as expected. Van Kessel et al. state that findings from fixed bed experiments can't be transferred to experiments with stoking because of the missing mixing effect in fixed bed combustion. With the size of the

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Nomenclature

A	cross-section of the bowl, m^2
Ac	actuator
Air_i	air fuel ratio, kg Air/kg fuel burnt
Air_S	stoichiometric air demand, kg Air/kg fuel burnt
cub	cubes, –
cyl	cylinders, –
$dm*/dt$	dimensionless mass loss gradient, –
dm/dt	mass loss rate, kg/s
HPU	hydraulic power unit
Δh_{inner}	stroke length inner element, m
Δh_{outer}	stroke length outer element, m
M	mixing index, –
m	mass, kg
m_0	initial mass of the bulk, kg
$\dot{m}_{air}$	air mass flow rate, kg/s
sphe	spheres, –
T	temperature, °C
v	velocity, m/s
ϕ	porosity, –
λ_{pr}	excess air ratio in the bulk, –
ρ_{air}	density of air, kg/m^3

Subscripts

0.3	with primary to secondary air ratio = 0.3
0.5	with primary to secondary air ratio = 0.5
0.7	with primary to secondary air ratio = 0.7
bowl	burner bowl
cub	cubes
cyl	cylinders
fixed	experiments with fixed bed conditions
pr	primary air
sphe	spheres
stoked	experiments with stoked conditions
wall	heated wall

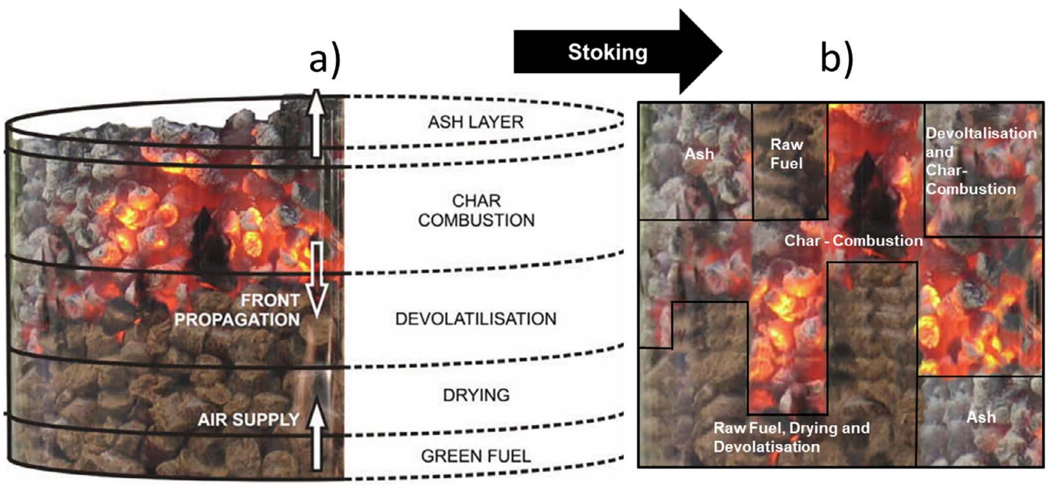

Fig. 1. (a) Reaction fronts in a fixed bed (Reprinted from Copyright (2010), with permission from Elsevier). (b) Influence of stoking on a fixed bed.

particles the gas flame temperature after bed ignition increases and the mass conversion rate decreases [3,4]. Bleckwehl [4] compared the combustion of beech wood spheres, cylinders and cuboids and Rönnbäck et al. [8] that of pine cylinders and cubes. Bleckwehl states that different shapes lead to different bed porosities ϕ. He detected an increasing mass loss rate with increasing porosity ($\phi_{spheres} < \phi_{cylinders} < \phi_{cuboids}$) because, in particular, radiative heat transfer is facilitated by larger porosities. Simulations for fixed bed combustion, are for example presented by [4,10,11], based on a continuum approach for the packed bed, whereas [12] present a particle based approach using the discrete element method.

The question arises how stoking of the bed is influencing the processes described above. Stoking is enhancing mixing in the fuel bed, thereby, destroying the distinct separated solid layers (see Fig. 1b, right) which occur in fixed bed combustion and, at the same time, rearranging the void space passed by the gas. To clarify whether this disturbance of the separated layers accelerates or decelerates the combustion rate and to quantify the influence motivates our work.

A variety of investigations is available on how stoking is influencing residence time and mixing on grates. The numerical studies can be subdivided into those using a particle based approach (Discrete Element Method) [13–17] and the ones based on a continuum model for the fuel bed [18–21]. Experimental studies include the examination of mixing and transport of spherical particles [22], wood chips [13] and municipal waste [20]. However, to the best knowledge of the authors, no detailed quantitative information is available how stoking influences the combustion rate. The publication by Sudbrock et al. [23] might provide a first indication. They examined the drying of silcagel and beech wood spheres in a fixed bed and a bed agitated by grate bars (batch operated) and obtained higher drying rates for the agitated bed, however, such results cannot be transferred directly to combustion.

2. Experimental setup

A test rig has been designed which allows to examine the influence of stoking on the combustion rate by measuring the mass loss of the fuel. Therefore, the principle of the fixed bed has been expanded with the possibility of controlled stoking (Figs. 2 and 3).

The test rig consists of a cylindrical burner bowl containing the fuel bed and a cylindrical gas phase combustion chamber above the fuel bed. The wall of the combustion chamber is formed by a quartz glass tube surrounded by an electrical heating element. The heating unit allows to control the wall temperature. Primary and secondary air are supplied by separate air supply lines, each equipped with mass flow meters. The burner bowl sits on a balance to measure mass loss. Accuracy is ± 0.1 g of the value displayed. Details of the burner bowl are shown in Fig. 3. The bottom of the burner bowl is formed by circular elements. The area above the rings is further referred to as burner bowl