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Size, shape, and density changes of biomass particles during rapid devolatilization

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HIGHLIGHTS

- A particle conversion model based on optical particle properties is presented.
- Shape and density transformations of devolatilizing biomass particles were quantified.
- Shape descriptors for biomass particles assessed with important differences found.
- The method and model is suitable for implementing in in-situ applications.

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ABSTRACT

Particle properties such as size, shape and density play significant roles on particle flow and flame propagation in pulverized fuel combustion and gasification. A drop tube furnace allows for experiments at high heating rates similar to those found in large-scale appliances, and was used in this study to carry out experiments on pulverized biomass devolatilization, i.e. detailing the first stage of fuel conversion. The objective of this study was to develop a particle conversion model based on optical information on particle size and shape transformation. Pine stem wood and wheat straw were milled and sieved to three narrow size ranges, rapidly heated in a drop tube setup, and solid residues were characterized using optical methods. Different shape descriptors were evaluated and a shape descriptor based on particle perimeter was found to give significant information for accurate estimation of particle volume. The optical conversion model developed was proven useful and showed good agreement with conversion measured using a reference method based on chemical analysis of non-volatilized ash forming elements. The particle conversion model presented can be implemented as a non-intrusive method for in-situ monitoring of particle conversion, provided density data has been calibrated.

1. Introduction

Using pulverized biomass in oxygen blown pressurized biomass gasification has proven efficient for obtaining high gas quality, reducing the need for gas cleaning before further upgrading and use. Design and optimization of entrained-flow biomass gasification aims at a high fuel conversion degree while at the same time keeping residence times (reactor size) short. For these reasons, fuel particle size and size distribution are important aspects to consider. Efficient milling of biomass to an acceptable size distribution is one of the bottlenecks in the development of systems based on entrained-flow gasification since rather small (<1 mm) [1] particles are required, but conversely fine milling is energy demanding and resulting fibrous materials with low bulk densities are associated with feeding problems [2]. Besides the difficulties in fuel preparation and feeding, the size of biomass particles is known to have an effect on the gas and liquid products, where larger particles lead to reduced fuel yields and an increase in tar formation, increasing overall costs [3].

The physical properties of biomass particles such as particle size, morphology and porous structure affect the particle transport and fuel conversion behavior inside entrained flow gasifiers [4]. By determining these morphological changes, namely swelling/shrinkage, shape and density change behavior during devolatilization, their effect on biomass gasification inside the entrained flow

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Nomenclature

$A_{particle}$	Area of a 2D image of a particle (μm^2)	v_{in}	Gas velocity at inlet (m/s)
D_c	Diameter of smallest circumscribed circle outside shape (μm)	v_{out}	Gas velocity at outlet (m/s)
D_{eq}	Sphere equivalent diameter (μm)	x_{min}	Shortest cord length across shape (μm)
D_{0eq}	Sphere diameter of raw fuel (μm)	x_{max}	Longest cord length across shape (μm)
D_i	Diameter of largest inscribed circle inside shape (μm)	X_{ds}	Dry substance conversion degree
$D_{2D,in}$	Particle diameter at inlet (μm)	β	Diameter evolution coefficient
$D_{2D,out}$	Particle diameter at outlet (μm)	γ	Initial stage density evolution coefficient
D_{2D}	Circle equivalent diameter (μm)	δ	End stage density evolution coefficient
l	Length (fall height in DTF) (m)	ρ_{geo}	Density based on geometry (kg/m^3)
m_{sample}	Mass of a given sample	ρ_{0geo}	Geometric density of raw fuel (kg/m^3)
$p_{particle}$	Perimeter around shape (μm)	ϕ_{Cox}	Cox circularity
t	Residence time (s)	ϕ_{Riley}	Riley circularity
		ψ	Sphericity

gasifier can be quantified [5–7]. Morphological changes of particles have been studied both during pyrolysis and char gasification, though mainly for coal [7–13]. For small biomass particles (<1.0 mm) and high heating rates (>1000 K s^{-1}), few studies that investigated particle morphological changes qualitatively during pyrolysis can be found [7,14–19].

Through the study of fuel conversion and morphological changes, this paper focuses on how reaction parameters affects pyrolysis behavior of two different fuels: pine stem wood and wheat straw. The objective was to develop a detailed particle devolatilization model including information on particle size, shape, density and mass changes. Drop tube furnace experiments were performed with varying residence time (i.e. fall height) and temperature settings, using two biomass fuels with three initial particle (sieve) size classes. Optical information on particle size and shape was used as model input.

2. Material and methods

2.1. Fuel samples

Pine stem wood and wheat straw were milled to 0.1–1.0 mm in a Retsch SM 2000 cutting mill after drying at 105 °C. The biomass particles were sieved to various size ranges: 125–150, 400–425 and 600–630 μm. Fuel analysis of the raw fuels is presented in Table 1. The ash content of wheat straw particles differed depending on sieve size, which has also been previously shown by others [20]. These differences are probably due to fractionation of different parts of the plant during milling and sieving. High ash content components seem to break into smaller fragments more easily than low ash components. This was not observed for the more homogeneous stem wood.

Ash and volatile contents were determined by methods EN 14775 and EN 15148, respectively. Carbon, hydrogen, and nitrogen contents determined by method EN 15104, where oxygen is calculated by difference. Estimated uncertainties for the analysis of inorganic elements can be found in Supplementary Material (S1).

2.2. Drop tube furnace

A drop tube furnace (DTF) with an alumina (Al_2O_3) reactor tube with an inner diameter of 50 mm and a height of 2 m was utilized. The DTF was operated under atmospheric pressure at 900 °C and 1100 °C using five individually controlled heating zones (354 mm long). A syringe feeder [21] was used to supply the biomass at a fuel feeding rate of 5 g h^{-1} and a N_2 flow rate of 0.38 $_nL$ min^{-1} carrying the fuel particles. Secondary N_2 was also supplied from the top of the reactor with a flow rate of rate of 5.0 $_nL$ min^{-1}, preheated to 350 °C using a Leister heater, and further heated in the first zone before merging with the fuel laden carrier gas. The particle injection tube had an inner diameter of 6 mm and was encased in a water-cooled jacket. Volume fractions of oxygen and carbon monoxide in the product gas were recorded at the exit to validate a leak-free system and stable fuel feeding. Biomass particles were entrained in the N_2 flow and were devolatilized as they travelled down the reactor. Particle residence time was varied by changing

Table 1
Fuel analyses for pine stem wood and wheat straw based on dry substance (ds).

Composition		Pine	Wheat straw 125–150 μm	Wheat straw 400–425 μm	Wheat straw 600–630 μm
Ash Content	$wt\%_{ds}$	0.4	8.2	7.1	6.4
Volatile Matter	$wt\%_{ds}$	84.8	73.4	74.7	75.3
Fixed Carbon	$wt\%_{ds}$	14.8	18.4	18.2	18.3
Carbon	$wt\%_{ds}$	50.6	45.3	46.0	46.4
Hydrogen	$wt\%_{ds}$	6.2	5.8	5.8	5.9
Nitrogen	$wt\%_{ds}$	0.2	0.7	0.6	0.6
Oxygen (by difference)	$wt\%_{ds}$	42.6	40	40.5	40.7
K	mg kg^{-1}	813	13500	13500	12100
Na	mg kg^{-1}	17	188	189	177
Ca	mg kg^{-1}	838	4560	3950	3260
Mg	mg kg^{-1}	229	1120	936	806
Al	mg kg^{-1}	31	568	520	431
Fe	mg kg^{-1}	30	419	358	275
Si	mg kg^{-1}	183	19400	14700	12600
P	mg kg^{-1}	161	760	680	600
S	mg kg^{-1}	121	1270	1180	1130
Cl	mg kg^{-1}	26	3630	3540	3240