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Modeling and pilot plant runs of slow biomass pyrolysis in a rotary kiln

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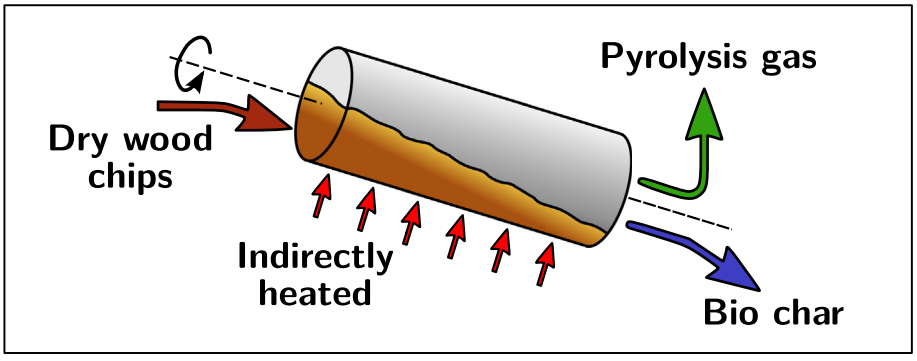
HIGHLIGHTS

- Rotary kiln pyrolysis is used in multistage gasification or as own-standing process.
- A modular numerical model for pyrolysis of biomass in a rotary kiln is presented.
- Model is validated against experimental data obtained from a pilot scale pyrolyzer.
- Good agreement between model and experiments for moderately high heat supply.
- We find complex interplay between rotation rate, heat transfer, and pyrolysis yield.

GRAPHICAL ABSTRACT



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ABSTRACT

Pyrolysis of biomass in a rotary kiln finds application both as an intermediate step in multistage gasification as well as a process on its own for the production of biochar. In this work, a numerical model for pyrolysis of lignocellulosic biomass in a rotary kiln is developed. The model is based on a set of conservation equations for mass and energy, combined with independent submodels for the pyrolysis reaction, heat transfer, and granular flow inside the kiln. The pyrolysis reaction is described by a two-step mechanism where biomass decays into gas, char, and tar that subsequently undergo further reactions; the heat transfer model accounts for conduction, convection and radiation inside the kiln; and the granular flow model is described by the well known Saeman model. The model is compared to experimental data obtained from a pilot scale rotary kiln pyrolyzer. In total 9 pilot plant trials at different feed flow rate and different heat supply were run. For moderate heat supplies we found good agreement between the model and the experiments while deviations were seen at high heat supply. Using the model to simulate various operation conditions reveals a strong interplay between heat transfer and granular flow which both are controlled by the kiln rotation speed. Also, the model indicates the importance of heat losses and lays the foundation for scale up calculations and process optimization.

1. Introduction

Gasification is a thermal conversion process where organic materials react with a sub-stoichiometric amount of oxygen (in the form of air, O_2, or steam) to form a product gas consisting of CO, CO_2, H_2O, H_2, CH_4, and other molecular and particulate species. Gas cleaning and upgrading converts the product gas into syngas, i.e. a mixture of mainly H_2 and CO, that can be used as a fuel or as a feedstock for other processes [1,2]. The main problem of current biomass gasification technologies is the selection of engineering solutions for cleaning and upgrading of the product gas

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Nomenclature

A_i	kinetic prefactor reaction i, 1/s
$C_{p,i}$	heat capacity species i, J/(kg K)
D	inner diameter kiln, m
d_p	particle size wood chips, m
E_i	activation energy reaction i, J/mol
$\bar{E}_i$	black body radiation surface $i, \bar{E}_i = \sigma T_i^4$, W/m^2
F_i	mass flow rate of species i, kg/s
f_{ij}	view factor between surface i and j, –
G	heat production due to reaction, J/(m^3 s)
H	bed height, m
$h_{a-b}^{r,c,d}$	heat transfer coefficient, W/(m^2 K)
Δh_i	specific heat of reaction, J/kg
J_i	radiosity surface i, W/m^2
K_i	reaction rate factor reaction i, 1/s
k_i	thermal conductivity, W/(m K)
L	length of the kiln, m
M_i	molecular weight species i, kg/mol
n	total number of species, –
n_j	number of species solid bed domain, –
n_k	number of species gas phase domain, –
p	pressure, Pa
Q	volumetric flow rate, m^3/s
q	heat transfer flux, J/(m s)
R	kiln radius, m
r_i	reaction rate of species i, kg/(m^3 s)
S_{bed}	cross section area solid bed domain, m^2
S_{gas}	cross section area gas phase domain, m^2
T_b	solid bed temperature, K
T_g	gas temperature, K
T_w	wall temperature, K
u_b	average solid velocity in axial direction, m/s
u_g	average gas velocity in axial direction, m/s
V_{bed}	total bed volume, m^3
z	axial coordinate, m

Greek symbols

β	kiln inclination, –
ε	solid bed porosity, –
ε_i	emissivity of surface i, –
η	relative fill level, –
θ	dynamic angle of repose, –
$\Lambda_{a-b}^{r,c,d}$	surface area per unit length of kiln, m
ν	kinematic viscosity, m^2/s
ρ_i	density of species i, kg/m^3
ρ_p	true density wood i, kg/m^3
σ	Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W/(m^2 K^4)
φ	half central angle of the solid bed, –
χ	dimensionless film thickness, –
ψ	kinetic parameter, ratio inert tar to total tar, –
ω	revolutions per second, 1/s

Indices and acronyms

c	species index: char
fg	index for flue gas
g	species index: gas
is	species index: intermediate solid
it	species index: inert tar
j	index solid domain species
k	index gas phase domain species
MRT	mean residence time
rt	species index: reactive tar
w	species index: wood

downstream to the gasifier [3–5]. Present gas cleaning processes for the removal of tars and inorganic impurities, such as S and N compounds, are optimized for large-scale facilities found in the refinery industry. Small to medium scale gas cleaning technologies are currently commercially not available and adopting existing technologies calls for investment costs that initially are too high to achieve a cost efficient system. In order to tackle this problem, novel gasification concepts aim at dividing the gasification process into different process steps and to operate them in separate (or partly separate) units [6]. Such division allows for optimization and better control of the individual process steps which ultimately lowers the amount of tar and inorganic impurities in the product gas, thus reducing the need for downstream cleaning and upgrading.

The WoodRoll® process developed by Cortus Energy AB is a novel multistep process for the gasification of biomass, including wood, forestry residuals, and other bio-based waste materials. The process schematically shown in Fig. 1 employs three separate units for drying, pyrolysis and gasification. Biomass enters the dryer in form of particles (or chips) with sizes up to 5 cm. The dryer is designed as a rotary drum operating at 105–150 °C. The dried biomass with moisture content below 5% is fed to the pyrolyzer consisting of a rotary drum operated at 360–400 °C under a weakly pressurized inert atmosphere. The two streams leaving the pyrolyzer contain the biochar (30–40 w% of the dry biomass) and the pyrolysis gas, consisting of combustable and non-combustable compounds (CH_4, CO, H_2, CO_2, H_2O; together ca. 60 w% of the gas stream) and tars (ca. 40 w% of the gas stream). The char is ground to around 100 μm and fed to the gasifier that is built as an entrained flow gasifier operated at ambient pressure at 1100 °C using steam as oxidation agent. The gasifier is heated indirectly by burning the pyrolysis gas in cylindrical burners that are integrated into the gasifier unit. The flue gas from the burners is used to indirectly heat the pyrolyzer and the dryer, i.e. by flowing it co-currently along the walls of the rotary drums.

The WoodRoll® process assigns a central role to the pyrolysis step. Not only does it produce the char that, when gasified, results in a low tar product gas, but also does it produce the gas to heat the entire process [7]. This critical role motivated us to undertake a thorough investigation of pyrolysis in a rotary kiln by means of numerical simulations and pilot plant trials. Thus, the aim of this work is to develop a mathematical model for simulating pyrolysis of lignocellulosic biomass in a rotary kiln and to compare it to experimental data obtained from a pilot scale pyrolyzer.

Apart from the application in mind, i.e. multistep gasification, pyrolysis of biomass in a rotary kiln is an important process on its own. Rotary kilns are the preferred reactor configuration for the thermal treatment of particulate solids and considerable research has been undertaken to study their behavior for the treatment of biomass [8–12]. For example, Sanginés et al. [12] studied the slow pyrolysis of olive stones in a batch type rotary kiln. Among various characteristics, the study found that the gentle mixing in the rotary kiln smoothens the char particle surfaces which makes them more round and which eventually enhances their flowability in downstream processes. Chun et al. [8] studied the pyrolysis of sewage sludge in a specifically designed rotary kiln

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