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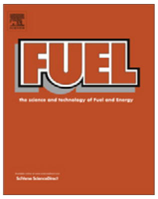

Modelling of an indirectly heated fixed bed pyrolysis reactor of wood: Transition from batch to continuous staged gasification

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HIGHLIGHTS

- ▶ Experimental study of the pyrolysis is made on a batch reactor.
- ▶ A batch reactor model is developed and compared to the experimental results.
- ▶ The developed batch reactor model is extended to describe the continuous pyrolysis.

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ABSTRACT

Gasification is today a mature technology and staged processes know an important development. The design of this kind of reactor is still a sensitive work, and numerical simulation, as a flexible and economic tool, has to be developed. The present work concerns the first pyrolysis stage of a staged gasification process and is organised into two parts. The first part deals with the calibration of the effective thermal conductivity of the bed. This is the key parameter in the heat transfer modelling. The calibration is obtained by comparison between experimental and modelling results in batch reactor. The second part is the development of a transient two dimensional model of a continuous indirectly heated fixed bed pyrolysis reactor. The model uses a finite difference formulation to solve mass and energy balances in a cylindrical vessel. The assumptions of local thermal equilibrium, constant particle size and thermally thin particles are considered. The simulations are used to design a pyrolysis reactor in function of the type of biomass, the wall temperature and the direction of gas circulation. The parametric study is presented to highlight the limitations of the external heating regarding the wood conversion rate.

1. Introduction

There is an increasing interest in the use of biomass for heat and power production considering the growing concern for future energy supply. Gasification is an attractive technology for the thermochemical valorization of biomass. This paper focuses on middle and small size power (<500 kW_e) biomass gasification systems for local Combined Heat and Power production (CHP units) using biomass residues.

Gasification involves three main steps including: (1) the first initial rapid devolatilization of biomass (production of char, tar and gases), (2) the second exothermic incomplete oxidation of volatile substances (tars are broken down into smaller incondensable molecules by thermal cracking reactions), and (3) the third subsequent gasification of the char generated. This process leads to a fuel gas (CO, H_2) with a high calorific value, suitable for efficient gas engine feeding.

Fixed bed gasifiers are the preferred type for small scale power generation from biomass. Among the available fixed bed gasification processes, biomass can be used as fuel. According to Jayah et al. [1], in downdraft gasifiers, the pyrolytic and gasification reactions proceed vertically within stratified layers. Downdraft gasifiers produce a gas with a relatively low tar content compared to other fixed bed technologies, which is adapted for small scale power generation. The classical downdraft gasifier with its typical throat has limited scale-up possibilities. Most units have a wet gas cleaning system and use an engine to drive a generator of typically 20–100 kW_e capacity. Only rarely these units have shown a satisfactory performance [2].

In a two-stage gasifier, the biomass pyrolysis and the char gasification take place in physically separate zones. The pyrolysis products are partially oxidised between the pyrolysis and the gasification zone by means of air addition. Thus the tar content in the volatiles is reduced by a factor of 100 compared to downdraft

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Nomenclature

A	pre-exponential factor (s^{-1})
Bi	biot number (–)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	particle diameter (m)
D_R	reactor diameter (m)
E	activation energy ($J\,mol^{-1}$)
H_R	reactor height (m)
H	specific species enthalpy ($J\,kg^{-1}$)
HR	wood Relative Humidity (%)
L_R	reactor length (m)
L_{conv}	conversion length (m)
L_v	latent heat ($J\,kg^{-1}$)
$\dot{m}_w$	mass flow rate of wood ($kg\,h^{-1}$)
$\vec{n}$	normal vector (–)
Q_{reac}	reaction heat flux (W)
r	radial coordinate (m)
R	kinetic rate constant (s^{-1})
R_R	reactor radius (m)
$\Re$	universal gas constant
SFR	specific feed rate ($kg\,h^{-1}\,m^{-2}$)
t	time (s)
T	temperature (°C)
T_1^0	reference temperature at 20 °C
T_2^0	reference temperature at 100 °C
T_{in}	biomass inlet temperature (°C)
T_{init}	biomass initial temperature (°C)
T_{wall}	temperature at the reactor wall (°C)
u	species velocity ($m\,s^{-1}$)
z	axial coordinate (m)
Greek letters	
ΔH	enthalpy of pyrolysis reaction ($J\,kg^{-1}$)
ε	bed porosity (–)
λ_{eff}	effective Thermal conductivity of the bed ($W\,m^{-1}\,K^{-1}$)
λ^s	solid thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ^s_{rad}	radiative solid thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_{solid}	ambiant thermal conductivity ($W\,m^{-1}\,K^{-1}$)
ν	stoechiometric coefficients (–)
ρ	Density ($kg\,m^{-3}$)
ρ_{app}	Apparent wood density ($kg\,m^{-3}$)
σ	Stephan–Boltzmann constant
Subscripts	
c	char
e	electrical
i	solid species
j	gas species
k	all species
g	gas
m	moisture
s	steam
t	tars
w	wood
0	initial value

gasifiers [3] and thermal energy for the endothermic char gasification is generated. Henriksen et al. [3] precised that the resulting tar content in the produced gas is less than 15 mg N m^{-3}. As the tar content decreases, the gas cleaning system is much easier to operate.

In a staged gasification process, the pyrolysis zone can be either internally or externally heated. Internally heated pyrolyzers are well studied in the literature [4]. Externally heated pyrolyzer is recently developed by DTU and Cirad in a two staged gasification process [3,5]. The exhaust gas from the connected gas engine (450 °C) or/and the product gas (syngas) (700 °C) [3,6] can be used for indirectly heating of the pyrolyzer. These gasifiers have a product gas with a low content of nitrogen and a high electrical output. The DTU and Cirad gasification processes use a horizontal screw conveyer to transport the biomass through the pyrolysis reactor.

In this study, the transport of the solid through the pyrolyzer is considered vertically and by gravity. External heating process has a high radial conductive resistance in the bed. It is unclear whether, in the case of a continuous fixed bed pyrolyzer, this resistance could limit the heat transfer and thus inhibit the complete conversion of the biomass at the heart of the reactor. As far as we know, this point is not discussed in the literature and a modelling approach is used here to make the transition from batch experiments to the model of a continuous reactor. This work focuses on the modelling of an externally heated gravity moving bed pyrolyzer in a two staged gasification process. It presents results from batch experiments to calibrate the bed effective thermal conductivity. Then temperature and wood conversion fields in a continuous indirectly heated fixed bed pyrolyzer of wood pellets are simulated. The model includes rate equations that consist of mass and energy balances for the pyrolysis reactions and result in a set of algebraic and ordinary differential equations.

2. Background

Gasification models are steady state, quasi-steady state or transient state. Quasi-steady state and transient state models do not neglect the time derivatives. They are based on the mass and energy balances [7,8]. The steady state models are further classified as kinetics-free equilibrium and rate models. Kinetics-free, equilibrium models can predict the product gas composition, given the solid composition and the equilibrium temperature based on the assumption that the gasifier reactions are in thermodynamic equilibrium [9,10]. Rate models are used for reactor design. Steady state rate models are used to compute the gas composition and the temperature profile along the reactor axis. Several researchers have developed detailed numerical rate models of wood pyrolysis and/or gasification applied for bed of particles [7,11–13]. In these studies, quasi-continuous models are often established where the solid phase and the gas phase are treated as they were continuous phases (Euler–Euler description). Only a recent study [14] incorporates a particle model in a reactor model.

The quasi-continuous models include mass and energy conservation. Gas phase and solid phase are assumed to coexist at every point of the spatial domain. Key points of these models are now discussed.

For heterogeneous reactions, differences between temperatures and concentrations in the bulk fluid phase and those inside or at the surface of the solid have to be taken into account while establishing heat and mass balance equations. The latest results in pseudo homogeneous and heterogeneous models [15] show that heterogeneous models are of particular importance for the simulation of fixed bed processes operating under severe conditions and with chemical reactions. In this study, the primary assumption is the local thermal equilibrium between the solid and the gaseous