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Modelling of an updraft fixed-bed gasifier operated with softwood pellets

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ABSTRACT

This paper presents a one-dimensional steady state mathematical model for the simulation of a small scale fixed-bed gasifier. The model is based on a set of differential equations describing the entire gasification process of softwood pellets and is solved by a two step iterative method. The main features of the model are: homogeneous and heterogeneous combustion and gasification reactions, one-step global pyrolysis kinetics and drying, heat and mass transfer in the solid and gas phases as well as between phases, heat loss, particle movement and shrinkage within the bed. The pyrolysis model has been improved by partially cracking primary tar into lighter gases according to experimental data. The model is used to simulate a laboratory scale fixed-bed updraft gasifier. Good agreement is achieved between prediction and measurements for the axial temperature profiles and the composition of the producer gas. Moreover, results are presented for different air to fuel ratios and varying power inputs. The gasification process is improved by increasing the power input of the gasifier as a result of higher temperatures. Furthermore, a higher air to fuel ratio lowers the efficiency of the gasification process.

1. Introduction

The gasification of renewable solid biomass to produce CO_2-neutral fuels for heat and electricity production is still in the development stage. Softwood pellets are presently used in small-scale residential combustion units. As the market is expected to further increase within the next years, pellets may also be used in small-scale fixed-bed gasifiers for heating purposes as well as regarding micro-CHP applications (e.g. Stirling engine or micro-turbine) in the near future. Due to the high tar content of the producer gas (up to 150 g/m^3), updraft gasifiers are not suitable for engines and gas turbines without comprehensive gas cleaning. For the proper design of such gasifiers and for a better understanding of the gasification process appropriate models are needed. This paper presents a one-dimensional mathematical model as well as its validation and application.

Various models [1–7] dealing with the simulation of updraft fixed-bed gasifiers can be found in literature, but some of them are quite old or contain simplifying assumptions regarding physical properties and kinetics. Furthermore, the majority of the models have been applied to the gasification of coal. Focusing on the gasification of softwood pellets, only one model has been proposed so far [3]. An important fact is that mathematical models often contain complex differential equations resulting in extensive numerical solutions. One possibility to reduce the complexity of the numerical solution is to use time-independent mathematical models, which is acceptable when focusing on steady-state operation. However, a description of the dynamic behaviour of the gasifier, which is primarily relevant for control purposes, is not possible.

The scope of this work was the modelling of the steady-state operation of a fixed-bed gasifier operated with softwood pellets with respect to proper reactor design and influence of changed operating conditions on the gasification process. Moreover, experiments have been carried out with a lab-scale gasifier and a comparison between model predictions and measurements is provided.

2. Mathematical model

Fig. 1 shows the basic geometry of the updraft gasifier presented in this paper.

The fuel (pellets) is fed continuously from the top of the gasifier, which can be considered as a simple cylindrical shaft, and forms a packed bed on the grate. The gasification air is injected from the bottom below the grate and passes through the fuel bed. Hot product gases exit the gasifier from the top, while the pellets descent toward the grate and are heated up successively by the gases. The fuel ash falls through the grate. The overall gasification process can be separated into four different reaction zones stratified along the reactor height – drying, pyrolysis, gasification and combustion. On the gasifier top the fuel is heated up by the hot gases and evaporation of fuel moisture usually starts immediately. Above

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Nomenclature

AF	air to fuel ratio (kg kg^{-1} wb)
A_i	preexponential factor
A_p	particle surface area (m^2)
cp_i	heat capacity (kJ kg^{-1} K^{-1})
D_V	reactor diameter (m)
d_p	volume-equivalent particle diameter (m)
$d_{cylinder}$	diameter of cylinder (m)
E_i	activation energy (J $kmol^{-1}$)
k_i	mass transfer coefficient (m s^{-1})
L	length of fuel bed (m)
$l_{cylinder}$	length of cylinder (m)
M_i	molecular weight (kg $kmol^{-1}$)
m_{water}	mass flow water (kg h^{-1})
p	pressure (Pa)
Pr	Prandtl number
R	universal gas constant (J $kmol^{-1}$ K^{-1})
r_i	reaction rate (kmol m^{-3} s^{-1}, kg m^{-3} s^{-1})
Re	Reynolds number
Sc	Schmidt number
s_h	heat transport
s_q	heat transfer
t	time
T	temperature (K)
u	storage term
v_i	velocity (m s^{-1})
W	heat flux (kJ s^{-1})
x	space (m)
X	molar concentration (kmol $kmol^{-1}$)
Y	mass concentration (kg kg^{-1})
z	space (m)

Greek letters

α_w	heat transfer coefficient (kJ m^{-2} s^{-1} K^{-1})
$\Delta H_{r,i}$	heat of reaction (kJ kg^{-1}, kJ $kmol^{-1}$)
ε	void fraction
ζ	correction factor for heat transfer
λ	thermal conductivity (W m^{-1} $K_{\cdot}^{1}$)
μ	gas viscosity (N s m^{-2})
ν_{char}	fraction of char for reaction p1 (wt% d.b.)
ρ	mass concentration (kg m^{-3}) for gas and apparent density for solids (kg m^{-3})
σ	Stefan-Boltzmann-constant (W m^{-2} K^{-4})
χ	CO/CO_2 ratio (mol mol^{-1})

Subscripts

c	combustion reactions
cc	coefficient for CO/CO_2 ratio
CO	carbon monoxide
chem	chemical reaction
dry	dry base
g	gasification reactions
gas	gas phase (all components)
gw	gas to wall
H_2O	water vapour
i	species
ox	combustion reaction 1
$p1$	primary pyrolysis
$p2$	secondary pyrolysis
rad	radiation
sg	solid to gas
solid	solid phase (wood, moisture, char)
sw	solid to wall
$s0$	solid phase (thermal conductivity)
w	reactor wall
wood	dry biomass
wg	water gas shift
0	value at ambient or initial conditions

temperatures of around 500 K pyrolysis of the fuel takes place and char particles and volatiles are formed. The char particles move downwards, heat up and get reduced by hot gases as gasification processes start above approximately 1000 K. Finally the char is oxidised by the supplied air at the bottom of the gasifier, supplying heat necessary for the overlying processes.

2.1. Governing equations

The gasification process is modelled by means of governing equations of the solid and gas phase. The equations are one-dimensional differential mass and energy balances on the solid and the gas phase. However, radial gradients exist. But, due to the fact that the gasifier is well isolated and heat losses through the reactor wall are approximately 7% of the power input, radial gradients can be neglected. The general form (Eq. (1)) of the energy equation is

$$\frac{\partial u}{\partial t} + \frac{\partial s_h}{\partial x} + s_q = \frac{\partial}{\partial x}\left(\lambda * \frac{\partial T}{\partial x}\right) \tag{1}$$

Detailed energy balances for the solid and the gas phase are given with Eqs. (2) and (3). On the left side of Eq. (1) the first term is the storage term, the second is the transport term and the third term is the transfer or source term [8]. The term on the right-hand side of the equation is the diffusion term. As mentioned before this paper focuses on steady-state operation, consequently the storage term is not considered. The transfer or source term contains the heat loss through the reactor walls, the solid to gas heat transfer and the heat flux due to chemical reactions and supplementary for the solid phase the evaporation enthalpy.

Some previous models assume that the gas and solid temperature in a packed bed are equal, which is incorrect as shown by other authors [1,11,12]. Therefore, separate equations for the solid and the gas phase are required.

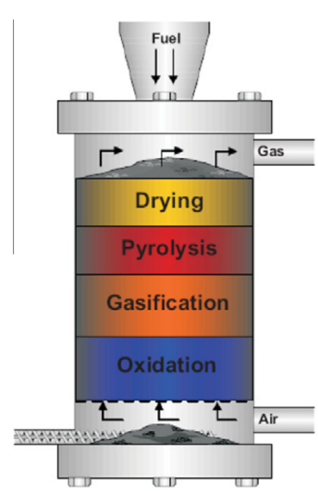

Fig. 1. Fixed-bed updraft gasifier.