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Compartment model for a dual fluidized bed biomass gasifier

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ABSTRACT

A variety of novel processes are being proposed in order to face global challenges such as degradation of the environment and the efficient utilization of energy. Modeling and simulation tools play a crucial role in the understanding and enhancing of the execution, design and construction of these processes. Although different computational tools are available to quantify the process at different levels, they are normally utilized independently and on a stand-alone basis. This decoupled approach may undermine the true potential of these tools. The present study highlights the advantages of interlinked process modeling at different levels. This study focuses on a promising gasification technology, namely the dual fluidized bed gasifier. A computational fluid dynamics (CFD) model was used to understand the flow patterns inside a fluidized bed. This elevated the understanding of the hydrodynamics of the gasifier freeboard, which is neglected by the conventional two-phase methodology. The CFD simulation was utilized to perform a residence time distribution (RTD) analysis of the reactor. Four tracer approaches namely the frozen velocity approach, the snapshot approach, the data sampling approach and the transient approach, were compared. The RTD analysis formed the basis of a steady-state compartment model that was developed in ASPEN Plus simulation software. The ASPEN Plus gasifier model decoupled the pyrolysis, gasification, and combustion sections of the gasifier to affect a better comprehension of the process and results. The model predicated satisfactory results upon validation. Additionally, the model could also be used to predict the output for different biomass feedstocks.

1. Introduction

Biomass is a renewable energy source that finds its use in a wide range of applications such as heat, power, fuel and chemicals. Biomass gasification is considered to be an important technology for the future production of biomass products. The different biomass gasification technologies may be grouped under updraft gasifier, downdraft gasifier, bubbling fluidized bed gasifier, circulating fluidized bed gasifier, dual fluidized bed gasification and entrained flow gasification. The strengths and weaknesses of each technology are dependent upon the biomass being gasified, the scale of gasification under consideration and the product-gas quality required. This study focuses on the state-of-the-art, dual fluidized bed gasifier (DFBG) (Fig. 1). The choice of the gasifier stems from its successful operation for over a decade in the domain of biomass gasification, which has a handful of success stories (Knoef, 2012). As the name suggests, the DFBG's operate by utilizing two interconnected fluidized beds. A bubbling fluidized bed (BFB) is used to gasify the biomass, which results in gases, tars and char. The bed mate-

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Nomenclature

a,b,c,d	Constants
$C_{10}H_8$	Naphthalene
C_6H_6	Benzene
C_6H_6O	Toluene
C_7H_8	Phenol
g	Gravity (m/s^2)
K_{gs}	Gas/solid momentum exchange coefficient
$K_{\theta s}$	Diffusion coefficient for granular energy (kg/m s)
p	Pressure (Pa)
T	Pyrolysis temperature (°C)
v	Velocity (m/s)
Y_i	Mass yield of pyrolysis products

Acronyms

ANN	Artificial neural network
BFB	Bubbling fluidized bed
CFD	Computation fluid dynamics
CHP	Combined heat and power
CSTR	Continuous stirred tank reactor
DFBG	Dual fluidized bed gasifier
FFB	Fast fluidized bed
KTGF	Kinetic theory of granular flows
PFR	Plug flow reactor
QET	Quasi-equilibrium temperature
RKS-BM	Redlich Kwong Soave Boston Mathias
RTD	Residence time distribution

Greek symbols

α	Volume fraction
ρ	Density (kg/m^3)
$\overline{\overline{\tau}}$	Stress tensor (Pa)
θ	Granular temperature (m^2/s^2)
$\overline{\overline{I}}$	Unity matrix
$\gamma_{\theta s}$	Collision dissipation of energy (kg/s^3 m)
$\varnothing_{gs}$	Transfer rate of kinetic energy (kg/s^3 m)

Subscript

g	Gas
s	Solid

rial and char then flow due to gravity to the fast fluidized bed (FFB), in which the char along with additional fuel, if any, is combusted, which results in the reheating of the bed material. This reheated bed material is supplied to the gasifier and it provides the heat that is needed for the gasification of the biomass. The advantages of DFBG's are yield of nitrogen free product-gas, lower tar production and feedstock flexibility.

Computer modeling is an efficient tool in the optimizing of gasifier operations. It is also a potent tool that can be used for the recommendation of novel process variations. The biomass gasification simulation models can be grouped under four major methodologies, namely, equilibrium model, kinetic model, Computational Fluid Dynamic (CFD) model, and artificial neural network (ANN) model (Basu, 2010). These modeling approaches are often mutually exclusive and are used on a stand-alone basis.

Equilibrium models are often the most favored due to the ease of their formulation and wider applicability. These models are based on the assumption that the reacting system reaches its most stable composition of all compositions. In other words the Gibbs Free Energy is minimized or the entropy is maximized. However at the normal gasification temperatures of 700–1000 °C, thermodynamic equi-

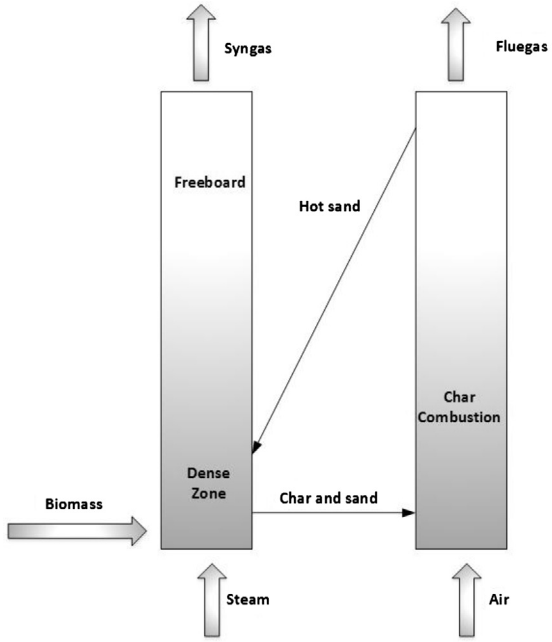

Fig. 1 – Dual fluidized bed gasifier.

librium is not achieved (Puig-Arnavat et al., 2010). In order to counter the deviation from experimental data, which arises from the above assumption, researchers use a quasi-equilibrium temperature (QET) approach (Puig-Arnavat et al., 2010). In this approach, the simulation software calculates the system equilibrium for a temperature that is lower than that which is the actual operating temperature. The QET can be defined either for individual reactions or for the whole reactor on the basis of the flowsheet configuration. The results predicted by the equilibrium models are independent of reactors. Their advantage lies in their ability to predict the thermodynamic viability; however, their accuracy in different types of gasifiers is limited. Equilibrium models for DFBGs have been proposed by Doherty et al. (2013); He et al. (2012); Schuster et al. (2001); and Kaiser et al. (2000).

Kinetic models are preferred over equilibrium models, when the design of the gasifier and other physical parameters need to be accounted for. Kinetic models find their application in the modeling of fluidized bed reactors, because the process is kinetically limited. Ideally, reaction kinetics must be solved simultaneously with bed hydrodynamics. This, however, makes the simulation very complex and is sometimes neglected. A semi-detailed kinetic model for gasification in a DFBG using ASPEN Plus has been presented by Abdelouahed et al. (2012). The initial pyrolysis was considered to be instantaneous and was modeled with the help of empirical correlations. The homogenous and heterogeneous gasification reactions were modeled on the basis of chemical kinetics. The dense phase region and the freeboard of the reactor were assumed to be continuous stirred tank reactor (CSTR) and plug flow reactor (PFR), respectively. Another model for the DFBG, which uses an equation-oriented steady-state software, IPSEPro, is presented by Pröll et al. (2007).

The performance of a fluidized bed gasifier is very strongly dictated by hydrodynamics. Nonlinear interactions between gases and the solid particle movement gives rise to very complex hydrodynamics (Loha et al., 2014a). Conventionally, fluidized beds have been modeled by using two-phase models (or three phase models) (Levenspiel, 1999). In two-phase models, the dense bed of the fluidized bed is divided into two phases, namely, the bubble phase and the emulsion phase. The hydrodynamics of the fluidized bed is characterized by using correlations in order to approximate the mixing and reactivity within each phase rather than by solving the momentum equation for each phase. Thus, the applicability of these models is constrained by the validity of the assumptions (Loha et al., 2014a). Recent studies have predicted that these models underestimated the process parameters when compared with the CFD results (Loha et al., 2014a; Atsonios et al., 2015). Moreover,