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Research article

Gasification of wood particles in a co-current packed bed: Experiments and model analysis

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ABSTRACT

This study focuses on addressing the propagation front movement in a co-current downdraft gasification system. A detailed single particle modeling analysis extended to the packed bed reactor is used to compare with the experimental measurement as well those available in the literature. This model for biomass gasification systems considered pyrolysis process, gas phase volatile combustion, and heterogeneous char reactions along with gas phase reactions in the packed bed. The pyrolysis kinetics has a critical influence on the gasification process. The propagation front has been shown to increase with air mass flux, attains a peak and then decreases with further increase in air mass flux and finally approaches negative propagation rate. This indicates that front is receding, or no upward movement, rather it is moving downward towards the char bed. The propagation rate correlates with mass flux as $\dot{m}''^{0.883}$ during the increasing regimes of the front movement. The study clearly identifies that bed movement is an important parameter for consideration in a co-current configuration towards establishing the effective bed movement. The study also highlights the importance of surface area to volume ratio of the particles in the packed bed and its influence on the volatile generation. Finally, the gas composition for air gasification under various air mass fluxes is compared with the experimental results.

1. Introduction

The biomass gasification process depends on a number of complex chemical reactions involving; pyrolysis, partial oxidation of pyrolysis products, gasification of the resulting char, conversion of tar and lower hydrocarbons, and gas phase reactions. Thermodynamic equilibrium and kinetic models are used to understand the complex biomass gasification process and optimizing gasifier design. Several authors have used various models to study the gasification process under various operating conditions and have carried out parametric studies with respect to equivalence ratio, gasification medium like steam, oxygen and its ratio, etc. to evaluate the influence on the output gas. Patra and Sheth have concluded that the widely used thermodynamic equilibrium model does not provide an insight into the process as equilibrium conditions are never attained in the reactor [1]. The study suggests that modeling of individual particles and packed bed including both transport and kinetic conditions is essential towards obtaining realistic predictions [1]. The study also observed that limited efforts have been directed for arriving at detailed kinetic models for downdraft gasifier; with a few contributing to address only part of the process involved in the overall gasification process like, pyrolysis, combustion, reduction zones, etc. Baruah and Baruah explored various equilibrium models for fluidized bed and downdraft gasifiers, and this study concluded that the equilibrium models has limitations due to the non-existence of equilibrium conditions inside the reactor [2]. However, modified equilibrium models with certain empirical relations based on experimental results improve its accuracy. This study also stated that the kinetic models are accurate and provide results close to the experimental results. Melgar et al. developed a mathematical model based on chemical and thermodynamic equilibrium and investigated the effect of air/fuel ratio, moisture content on the gasification performance and suggests that the reaction temperature is the driving parameter for the overall gasification process [3]. Mahmoudi et al. used eXtended Discrete Element Method (XDEM) as a framework for simulating a co-current configuration gasification system and compare the results with the experiments [4]. The experiments are conducted using diluted air (using nitrogen) and it is not evident the purpose of such dilution, except that one can infer that sub-process like pyrolysis and char gasification can be handled separately. It is also not evident based on the 25 °C air and 3% oxygen in the air, how the flaming pyrolysis process can proceed and similarly with 10% oxygen in the air in the ambient condition, enable char conversion process. The aspects related to the variation of properties like thermal conductivity, specific heat with temperature, along with the properties of the reacting fluid media have an impact; which the authors seem to have been neglected in the study. Dasappa et al. have shown that in single particle analysis, below 14% oxygen, the particle quenching (combustion ceases or reaction does not proceed) occurs at nearly ambient conditions [5]. In a separate study,

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Nomenclature

$\dot{m}$	mass flow rate, kg/s
$\dot{m}_p$	gasification rate of one particle, kg/s
$\dot{m}''$	mass flux, kg/m^2 s
v_{pm}	flame front propagation velocity, mm/s
Δx	distance between two thermocouples, mm
Δt	time required to reach the reference temperature between two thermocouples, s
t	time, s
ϵ	particle porosity
ϵ_b	bed porosity
ρ	density, kg/m^3
$\overline{\rho}$	average particle density, kg/m^3
ρ_c	density of wood char, kg/m^3
Y_i	mass fraction of i^{th} species
$Y_{i,s}$	i^{th} species concentration at gas film surrounded the particle surface
T	temperature, K
T_{gas}	gas temperature, K
T_∞	ambient temperature, K
T_S	particle surface temperature, K
T_j	temperature of latitude section, K
D	diffusivity, m^2/s
D_e	effective diffusivity, m^2/s
n	number of particles per unit volume
K_D	mass transfer coefficient, kg/s
h	heat loss coefficient, W/(m^{2}K)
h_l	reactor heat loss coefficient, W/(m^{2}K)
$\dot{\varpi}_i'''$	volumetric reaction rate of i^{th} specie, kg/(m^3 s)
$\dot{\varpi}_c'''$	volumetric char reaction rate, kg/(m^3 s)
κ	thermal conductivity, W/(m K)
H_R	heat generation due to reaction per unit volume due to gas phase reaction, kJ/m^3
H_C	enthalpy of carbon (summation of $C + CO_2$, $C + O_2$ and $C + H_2O$ reactions), kJ/kg
H	enthalpy of reaction, kJ/kg
C_P	specific heat, kJ/(kg K)
A_s	particle surface area, m^2
A_{sr}	surface area of the reactor, m^2
v	fluid velocity, m/s
r	particle radius, m
r_p	pore radius of wood char, m
M_g	molecular mass of the mixture of gases, kg/kmol
M_i	molecular mass of the i^{th} species, kg/kmol
V	volume of the biomass/char particle, m^3
Q	total radiative flux incident on the surface, W/m^2
τ	tortuosity factor
α	absorptivity (or emissivity) of the surface
σ	Stefan–Boltzmann constant, W/m^2 K^4
f_j	view factor
H_R''	radiative heat transfer, kJ/m^2

Subscripts

i	species CO, CO_2, H_2, H_2O and N_2
s	surface
∞	free stream

Mahmoudi et al. have addressed pyrolysis process in detail using similar modeling procedure to validate the devolatilization process [6].

Dasappa et al. modeled wood char gasification process using one-dimensional species and energy conservation equations for a single particle and extended the process to a packed char bed [5]. The process is modeled with char reacting with different reactants, diffusion and convection of species and energy in the porous medium and heterogeneous reaction between species and char. The detailed reaction mechanism for char conversion with O_2, CO_2 and H_2O are used and individually the mechanisms are validated. In the packed bed modeling, an important aspect related to flame propagation front movement against the air flow in a co-current configuration is evaluated and compared with the experimental results. It is observed that the reaction front velocity initially increases and then decreases with the increase in air mass flux and it is concluded that this happens due to the heat balance in the system. It is also found that at higher air mass flux, convective cooling of the reaction front reduces the propagation front movement. This study has been limited to charcoal as the fuel and with wood other complications like pyrolysis and the products of pyrolysis interacting within the bed poses different challenges. Sandeep and Dasappa have developed a model for packed bed biomass gasification process with dynamic variation in the evolved ambient conditions and temperature [7]. This study shows that the conversion time of the particles has a significant impact in the packed bed with varying surrounding conditions. Ranzi et al. developed a mathematical model considering pyrolysis of biomass particle, homogeneous gas phase reaction and heterogeneous reactions of the residual char at the particle level and reactor scale [8]. This study observed that residence time is an important parameter for the gasification process. Di Blasi reported a one-dimensional model for fixed bed counter-current gasifier to address the reaction front movement and gasification behavior [9]. The study analyzed in details the heat and mass transport for devolatilization, char gasification, and combustion of both char and gas species. The results arrive at the existence of a regime of decreasing temperature and propagation speed of the combustion front at near extinct conditions, attributed due to the convective cooling of the reaction front by excess air.

1.1. Propagation of flame front in packed bed

The propagation front in a packed bed can be classified as counter-current and co-current propagation relative to the direction of the air and solid fuel movement. In the case of counter-current propagation, flame front propagates in a direction opposite to that of air flow. In the case of a co-current (downdraft) configuration, apart from the flame front moving upwards into virgin fuel, the bed moves (contributed by size reduction during pyrolysis and fuel consumption) downward [10,11]. The flame front movement into the fuel bed in the upward direction against the air flow. Effective propagation rate is calculated as a sum of flame propagation rate and bed movement. Hence, the effective propagation rate has two components, the front velocity (flame propagation rate) moving into the virgin fuel bed against both the air flow and the fuel bed, and the bed movement moving downwards. In the case of, counter-current configurations, as solid fuel does not move, the effective propagation rate solely depends on the flame propagation rate.

Fig. 1 presents the schematic diagram of different reactor configurations. In the case of updraft or counter-current as well as reverse down draft configurations, air is in contact with the fuel immediately, where both the pyrolysis as well as the char combustion occurs in the reaction/combustion zone. Most of the packed bed configurations studied here is the reverse downdraft (Table 1) where the top fuel layer ignited initially, and the propagation front moves downwards into the virgin fuel bed, and the oxidiser (air) comes in contact with fuel in the combustion zone as in the case of updraft [12–16]. The front movement in reverse downdraft configuration is directly linked to the oxidiser and fuel vapor combustion zone movement. In both the above cases, there is no fuel (bed) movement which affects the propagation front. In the case of downdraft configuration, fuel, and air both moves downwards. With the flame front moving upwards into the fresh fuel, the effective or overall propagation rate is dependent on the reaction zone movement (upward) and also the bed movement (downward) due to fuel