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Numerical and experimental investigation of downdraft gasification of wood chips

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ABSTRACT

Biomass is widely perceived as a potential renewable energy source. Thermo-chemical conversion technologies including gasification, co-firing, and pyrolysis are of primary interest due to their higher conversion efficiency and throughput when compared with the low temperature digestion and fermentation for lignocellulose and wood-based feedstock. In this paper, a small scale, air blown, downdraft gasification system is operated using wood to investigate its conversion efficiency. Wood chips of 0.5 cm thickness, 1–2 cm width, and 2–2.5 cm length constitute the feedstock to the downdraft gasifier that is assembled and instrumented at Masdar Institute's Waste-to-Energy laboratory. The experimental investigation of the temperature field inside the gasifier is followed by high fidelity numerical simulation using CFD to model the Lagrangian particle coupled evolution. The numerical simulation is conducted on a high resolution mesh accounting for the solid and gaseous phases, k–ε turbulence, and reacting CFD model. The temperature distribution and the evolution of species are computed and compared with the experimental results and with the ideal equilibrium, zero dimensional case.

1. Introduction

The world reliance on biomass energy has increased to 14% of total energy consumption. This figure is higher than that of coal (12%) and is competing with gas (15%) and direct electricity (14%) energy consumption [1]. Although biomass is primarily consumed in third-world countries as an energy source, many industrialized countries are re-considering the involvement of biomass in their energy systems due mainly to its CO_2 neutrality and renewable nature [2]. Wood as a biomass feedstock is characterized by high volatile and low sulfur and ash contents thereby, maximizing its potential to be used as a feedstock for energy generation [3–5]. Fig. 1 shows the position of wood and other biomass types composition as compared to coal on the O/C–H/C graph known as Van Kreveln diagram.

One of the promising thermo-chemical conversion technologies that can be used to convert biomass to useful energy forms suited for small to medium size throughput is downdraft gasification. It is an ideal choice for small-scale gasification processes where the maximum electricity generated is about 500 kW [6]. Chemical and physical phenomena that occur during gasification of wood are essentially similar to typical carbonaceous material thermal decomposition. This includes drying, devolatilization (which includes release of volatile flammable gases, flaming combustion of the volatiles, and glowing combustion of fixed carbon), heat conduction, fissuring, shrinkage, and fragmentation of solid particles [5].

These reactors are distinguished by the concurrent flow of feedstock and gasifying agent. Four primary gasifier zones can be tracked based on the dominant reactions occurring in each one. From top to bottom, these are: Drying, pyrolysis (volatile release), combustion, and reduction/gasification zones [7]. A schematic of the reactor used in this study is shown in Fig. 2. Reactor parameters of primary importance that influence its performance are the size of the reduction zone (located under the air nozzles towards the bottom of the gasifier) and its stabilization location, thus controlling the residence time of the biomass particles within the reactor. The reduction zone signifies the location of the bulk of the gasification reactions including char reduction reactions and tar cracking and hence it controls to a great extent the yield of syngases which in turn define the gasification efficiency. Wood char reactions are essentially slow and require relatively long residence time compared to the gas-phase reactions thus imposing a minimum limitation on the reduction zone size [6]. The gasifier is also characterized with low producer-gas tar content due to the relatively high temperatures (greater than 1000 °C) within the reduction zone [3,4,8]. A downside to these types of gasifiers is the low overall efficiency due to the high sensible heat swept by the producer gas which leaves at temperatures of 900–1000 °C adding the convective surface heat loss to the surrounding [8]. In addition, the high particulate matter that carried by the producer gas due to the inhomogeneous oxygen mixing and its consequent temperature fields within the gasifier. Other limitations include feedstock moisture content which is limited to a maximum of 25% by mass, ash content up to 30%, and the complexity of scale up [7].

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Nomenclature

A	pre-exponential factor	m_i	transport species
CFD	computational fluid dynamics	m_p^0	initial particle mass
CGE	cold gas efficiency	O/C	oxygen to carbon ratio
$D_{i,m}$	diffusion coefficient	S_ϕ	source term
DPM	discrete phase method	S_{ot}	turbulent Schmidt number
DSC	differential scanning calorimeter	T_{evp}	vaporization temperature
ε	turbulent dissipation rate	TG	thermo gravimetric
E	activation energy	u	fluid phase velocity
ER	equivalence ratio	v	stoichiometric coefficient
f_v	volatile fraction	Φ	dependent variable
HHV	high heating value	η	reaction rate
H/C	hydrogen to carbon ratio		
K	reaction constant		

Several scientists approached downdraft gasification technology using wood as a feedstock and studied the various parameters that affect the producer gas quality including moisture content of wood chips, oxidizer (air) flow rate, chip size, location of air inlet nozzle and reduction zone length (and thereby particle residence time) [4]. Hsi et al. [3] experimentally studied the effect of airflow rate, air preheating temperature, and moisture content of wood pellets on the producer gas composition and its heating value using an air-blown fixed-bed stratified downdraft reactor. The conversion rate of wooden pellets increased with increasing cold airflow, while the heating value of the producer gas reached a maxima at 15 Nm^3/h then decreased as a result of dilution by cold air. Preheating the air to 573 K did not affect significantly the heating value of producer gas. Whereas, the moisture content of wood pellets was found to significantly lower the conversion rate of the pellets and the heating value of the producer gas. The optimum mean higher hating value (HHV) with a moisture content of 18% and cold air was found to be 5.2 MJ/Nm^3. A one dimensional model predicted the axial temperature profile and species distribution was in agreement with experimental findings.

Zainal et al. [4] studied the effect of equivalence ratio in downdraft gasifiers on conversion of furniture wood and wood chips. They found that the H_2 production increased linearly with the equivalence ratio (in terms of gasification), whereas CO, CH_4, and the calorific value of producer gas reached a maxima and then declined as the equivalence ratio further increased due to the shortage of air as expected. Zainal et al. also explained the temperature fluctuations in the combustion zone by referring to the effect of the interrupted contact between the ignited, glowing wood pellets and the thermocouple on one hand and the relatively colder voids on another. More importantly is the phenomenon of bridging that Zainal et al. observed. This phenomenon occurs when relatively large shredded chips create a bridge that obstructs the continuous flow of the wood pellets and thus causes high localized temperatures inside the gasifier. Their work showed that bridging was reduced by using a 60° angled-throat which is higher than the repose angle of wood chips (45°) at ambient temperatures. This angle provides smooth gravitational flow of wood through the combustion zone and facilitates the cracking of tar without bridging.

Kumar et al. [5] studied the effect of fuel particle shape and size on devolatilization time using Casuarina wood in a fluidized bed combustor. Various shapes like disc, cylinder, rod, sphere, and cube, with 5–30 equivalent sphere diameter and aspect ratio 0.2–10 were tested. The fluidized bed reactor (130 mm diameter) used a 550 μm sand grains for the bed material and its operating temperature was 650–850 °C. It was found that the devolatilization time increases with increasing feedstock particle size and density,

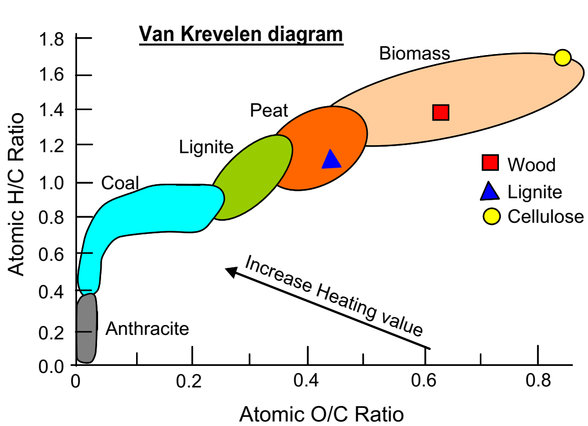

Fig. 1. Van Kreveln diagram illustrating the relevant composition and heating value of wood compared to other fuels.

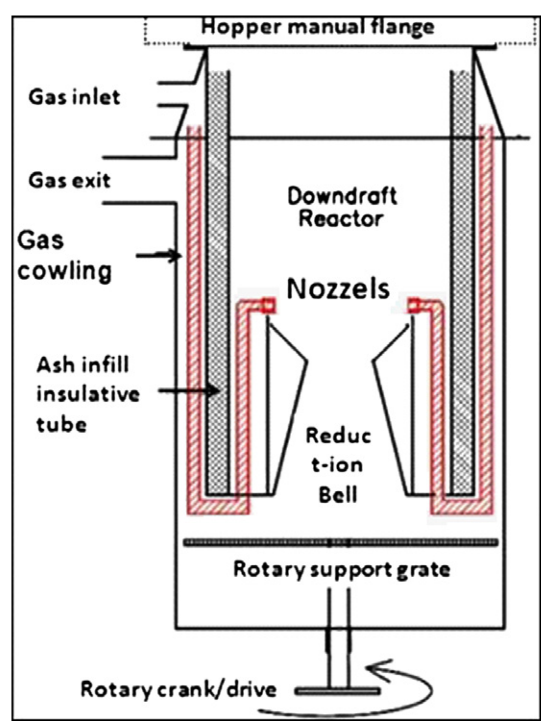

Fig. 2. Schematic of the downdraft gasifier.