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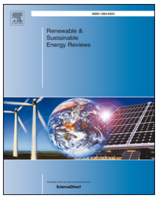

Biomass gasification in fluidized beds: A review of biomass moisture content and operating pressure effects

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ABSTRACT

The global dependence on fossil reserves as well as the environmental aspects related to them are some of the factors that propel research on renewable energy forms. Gasification, a thermochemical process that converts carbonaceous resources into syngas, is an advantageous alternative due to its relatively low costs, high efficiencies, and syngas' wide variety of applications. Although gasification is a very promising heat, power, and fuel production technique, there is still a field of improvement in gasification in fluidized beds when it comes to operation under high pressure and with feedstocks containing moderate or high moisture contents. Thus, to provide enough information to address such questions, the present work aims at bringing an overview of gasification concepts, as well as an in-depth discussion based on simulation, laboratory- and demonstration-scale works of the effects of biomass water content and pressure on different parameters of several fluidized bed gasifiers. Moreover, diverse strategies for handling high-moisture content biomass materials are presented, as well as the achievements and technical difficulties encountered by worldwide development and demonstration plant projects that designed and used pressurized fluidized-bed gasifiers.

1. Introduction

Along the last decades, renewable energy resources have been researched due to concerning factors such as the aggravation of global warming, the depletion of fossil reserves, and the world's growing energy demands [1–5].

Among the many existing renewable energy options, biomass conversion accounts for over 70% of all renewable energy production [6] and up to 10% of the world's total energy supply [7]. Bioenergy consists in an attractive alternative due to a number of factors: it is the only form of energy conversion that can be applied to produce either heat, electricity, and transportation fuels [4], enhancing diversity of energy supply [6]; it has the potential of generating a great variety of solid, liquid, and gaseous fuels that can be stored, transported, and employed far away from where it was harvested [6,8]; it usually involves low costs due to its abundance in many countries [9]; it is environmentally friendly because it can absorb part of the CO_2 that is emitted during fuels consumption, reducing greenhouse gas emissions [5,6]; it can foment waste management control [6]; and finally, it can instigate regional and socioeconomic development in the areas where such technologies are explored [8], providing jobs and income for rural areas [6]. Biomass resources are generally found as agricultural or forestry

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Abbreviations: ASU, Air separation unit; ATR, Autothermal reforming; BFB, Bubbling fluidized bed; BIGCC, Biomass integrated gasification combined cycle; BtL, Biomass-to-liquids; CCE, Carbon conversion efficiency, %; CCG, CHOREN coal gasification technology; CCS, Carbon capture and storage; CEDER, Centre for the Development of Renewable Energy Sources; CFB, Circulating fluidized bed; CGE, Cold gas efficiency, %; CHOREN, Carbon Hydrogen Oxygen Renewable; CHP, Combined heat and power; CHRISGAS, Clean Hydrogen-Rich Syngas Project; CH_xO_y, Simplified formula for biomass sources calculations; DME, Dimethyl ether; DOE, Department of Energy; e_{agent}, Chemical exergy of gasifying agent, kJ/kmol; $e_{ch,biomass}$, Chemical exergy of biomass, kJ/kg; $e_{ch,syngas}$, Chemical exergy of syngas, kJ/kmol; $e_{ph,syngas}$, Physical exergy of syngas, kJ/kmol; ER, Equivalence ratio; FEED, Front-end engineering and design; FICFB, Fast internally circulating fluidized bed; FTS, Fischer-Tropsch synthesis; GTI, Gas Technology Institute; G_V, Gas yield, m^3/kg; HGCU, Hot gas clean-up unit; HHV, Higher heating value, MJ/kg; HRSG, Heat recovery steam generator; HTL, Hydrothermal liquefaction; HT-WGS, High-temperature water-gas shift process; IEA, International Energy Agency; IGCC, Integrated gasification combined cycle; IGT, Institute of Gas Technology; IRENA, International Renewable Energy Agency; KIT, Karlsruhe Institute of Technology; $LHV_{biomass}$, Biomass lower heating value, MJ/kg; LHV_i, Lower heating value of a component gas i, MJ/kg; LHV_{syngas}, Syngas lower heating value, MJ/kg; $M_{biomass}$, Biomass feed, kg; MSW, Municipal solid waste; MW_e, MW of power generation; MW_{fuel}, MW of fuel input; MW_{th}, MW of heat generation; n_{agent}, Molar amount of gasifying agent, kmol; n_{syngas}, Molar amount of syngas, kmol; PAH, Polycyclic aromatic hydrocarbon; PCA, Principal component analysis; PDU, Process development unit; PFB, Pressurized fluidized bed; PFD, Process flow diagram; PICHTR, Pacific International Center for High Technology Research; PLS, Partial least squares; RDF, Refuse-derived fuels; S/B, Molar steam-to-biomass ratio; SCO, Selective catalytic oxidation; SEA, Swedish Energy Agency; SNG, Substitute natural gas; SOFC, Solid oxide fuel cell; TPS, Termiska Processer AB; UCG, Ultra Clean Gas process; V_g, Syngas volume under standard conditions, m^3; VTT, VTT Technical Research Centre of Finland; WGS, Water-gas shift; wt%, Weight percentage; x_i, Volume percent of component gas I; ψ, Exergy efficiency, %

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residues, which include wood, sugarcane, corn, wheat, rice, and soy wastes [10].

Despite the obvious bioenergy potential, more than half of it is related to the traditional use of biomass, which consists in the use of wood, charcoal, animal dung, and agricultural residues for residential cooking and heating. The conventional use of biomass usually produces very low efficiencies and harmful emissions that can lead to health issues [6,7,11]. Thus, to develop a sustainable bioeconomy, not only the efficiencies of traditional biomass conversion must be enhanced, but also modern renewable practices must be developed [11].

Modern renewable biomass conversion pathways may include biochemical or thermochemical routes. Biochemical routes use enzymes and microbial cells, which are added to heat and chemicals [12] to convert biomass into bioalcohols, biodiesel, biocrude, and bio-synthetic oils [13]. Once the lignocellulosic matrix is strongly intermeshed and bonded through covalent and non-covalent bonds, biological paths must involve pretreatment steps to overcome lignocellulosic biomass recalcitrance [14,15]. Such pretreatment stages are usually expensive since they require the use of enzymes and acids, and they are also time-consuming [9,15]. Thermochemical routes, on the other hand, use heat and catalysts to transform high carbon content materials into intermediate products [12,16,17], like bio-oil and syngas [13]. Differently from biological routes, thermochemical conversion processes are robust and flexible considering they accept a wide range of feedstocks [12].

Gasification is one of the most attractive options for biomass thermoconversion, not only for being environmentally friendly, but also for offering higher efficiencies when compared to combustion and pyrolysis [4,18,19]. Gasification is defined as the conversion of carbonaceous solids or liquids mainly into a combustible gas at temperatures around 600–1500 °C under the presence of a gasifying agent and an oxygen feed below oxidation stoichiometric values.

If gasification is carried out at lower temperatures, the combustible gas is known as product gas or producer gas and may be composed of hydrogen, carbon monoxide, carbon dioxide, methane, low hydrocarbon amounts, and other contaminants [16,17,20,21]. However, if the producer gas undergoes post-cleaning processes, or biomass gasification occurs at higher temperatures, the resultant gas mixture is called synthesis gas or syngas, which can be mainly composed of hydrogen, carbon monoxide, carbon dioxide, water, and fewer contaminants [22]. In this work, the terms “syngas” and “synthesis gas” are used for all gas mixtures produced via gasification. Syngas has a wide range of low and high added value applications, such as electricity and heat generation by syngas combustion in engines or gas turbines [20], and catalytic and biocatalytic processes to synthesize organic acids, alcohols, esters, and hydrocarbons [16], respectively.

Despite the broad range of syngas applications, only costs and performance data will demonstrate syngas’ potential to become a competitive energy. Syngas final price may be subject to fluctuations since it depends on factors such as plant design, ultimate production objectives, feedstock type, co-products generated, and local conditions. Table 1 compares syngas costs to other energy sources, such as coal, diesel, and naphtha. Although biomass-derived syngas is more expensive than coal-derived syngas, it may still be a competitive energy source in comparison to diesel and naphtha, which propels research to make it even more compelling.

Table 1
Comparison of prices of different fuels [23–25].

Fuel	Price [20,21]	Lower heating value [22]	Estimated price (US $/MJ)
Coal (wet basis)	0.06 US$/kg	22.7 MJ/kg	0.003
Diesel	1.34 US$/L	42.8 MJ/L	0.031
Naphtha	0.52 US$/kg	44.9 MJ/kg	0.012
Syngas from biomass for FT uses	0.10 US$/$m^3$	10 MJ/m^3	0.010

Gasification can occur in different gasifier configurations such as fixed bed, fluidized bed, and entrained-flow reactors. Fluidized beds are the most used gasifier types due to advantages such as feeding flexibility, scalability, good mixing capacities, high heat and mass transfer rates, and high reaction rates and conversions [19,20]. Although biomass gasification in fluidized beds is a subject that receives much attention either academically or industrially, gasification technology still faces improvement opportunities. Among these challenges, one can cite issues related to high moisture content feedstocks and gasifier's operating pressure.

Feedstocks containing high moisture contents lower the reactor's temperature and slow down certain endothermic reactions, in a way that 15 wt% water contents are usually advised for most biomass sources. However, this value is recommended regardless the particularities of the raw materials employed [26,27]. Additionally, the relationship between moisture content and other parameters like biomass particle size, equivalence ratio, biomass feed rate, and residence time is not fully elucidated, neither how it explicitly affects products yields, distribution, and syngas heating values.

Higher operating pressures may be beneficial for gasification because the former accelerates some reactions. Moreover, higher pressures enhance energy and exergy efficiencies since downstream processes generally require pressurized gas streams. However, the operational challenges related to the complexity of the project, construction, and operation of biomass pressurized gasifiers [10,20] still prevent the use of such equipment in commercial scales.

Even though many reviews in the field of gasification have been published [17,20,28,29], these operating parameters have received little attention. Thus, to address such gaps, this paper aims at presenting an overview of gasification concepts, emphasizing on the effects of biomass moisture content and gasifier pressure from a chemical and operational sight, based on simulation, laboratory-, development-, and demonstration-scale projects.

The gasification section of this paper reviews the concepts, reactions, equipment configurations, and operating conditions to address the main subjects of this study.

The biomass moisture content section presents the main effects of this parameter on the performance of fluidized bed gasifiers, as well as different strategies to handle materials that contain high moisture contents.

Finally, the high operating pressure section discusses the influence of gasifier pressure on fluidized beds. In addition, it brings the main findings and operational drawbacks of different development and demonstration plant projects that developed pressurized fluidized bed gasification technology, such as the RENUGAS® technology and its pilot and demonstration plants, the VTT pressurized fluidized bed gasifier, the BIOFLOW project, the CHRISGAS project, the Bio2G initiative, and the CHOREN Carbo-V® technology.

2. Lignocellulosic biomass and main characteristics

Biomass is a generic term for biodegradable and non-fossilized organic matter [30], usually produced directly or indirectly by photosynthesis and used as feedstock to produce fuels and chemicals [31]. Although wood is the most abundant biomass energy resource [32], many other biomass sources can be used for bioenergy production, such as: sugar and starch crops (corn, wheat, sugar, and cereals in general); oil crops (palm, rapeseed, canola, and sunflower); non-food crops such as lignocellulosic plants (miscanthus, willow, and eucalyptus); lignocellulosic biomass residues from forestry and agriculture industries; and wet organic wastes (sewage sludge, animal wastes, organic liquid effluents, and the organic fraction of municipal solid waste – MSW) [6].

Lignocellulosic biomass resources play an essential role in biorefineries due to their abundance, low costs, and possible non-alimentary features [33,34]. They can be either found in the form of woody biomass (e.g. hybrid poplar, poplar, white oak, red oak, walnut, maple,