



Synergistic effects in steam gasification of combined biomass and plastic waste mixtures



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HIGHLIGHTS

- Examined steam gasification of biomass with plastic wastes in semi-batch reactor.
- Polycarbonate, polyethylene terephthalate, polypropylene and pinewood are gasified.
- Co-gasification led to enhanced H₂ by up to 3 times individual gasification.
- Synergy observed led to enhanced syngas yield with no loss in carbon conversion.

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ABSTRACT

Steam gasification of combined biomass and plastics at different mass ratios of biomass to plastic was investigated in a semi-batch reactor at 1173 K and atmospheric pressure using different types of plastics. The specific plastics examined were black polycarbonate (BPC), polyethylene-terephthalate (PET), and polypropylene (PP). The chemical composition of the syngas yield evolved measured using a microGC revealed synergistic effects on the role of biomass and plastics during gasification. The observed synergy was quantified from a direct comparison of the results on cumulative gas yields from biomass-plastics mixtures as compared to the corresponding weighted aggregate results from the gasification of separate feedstock components. The results showed that the total syngas as well as H₂, CO, and CO₂ yields enhanced using mixtures, while the light hydrocarbon gas yields reduced in the order of PP > BPC > PET. The increase of H₂ and CO with the reduction in hydrocarbon yield revealed synergistic enhancements from the secondary steam reforming reactions. TGA data from co-pyrolysis of BPC and PET with biomass revealed significant interaction while no such interaction was observed with PP. The carbon conversion and energy efficiency results showed enhancement for the BPC case. Increase in product gas yield suggests greater reformation of biomass plastic mixtures during gasification. Further studies are required to understand fundamental reaction mechanisms as well as demonstrative gasifier studies to understand both the kinetics and practical feasibility.

1. Introduction

Plastic use continue to grow at an annual rate of 5% since 1990 [1]. Increased use of different types of plastics without adequate recycling has caused global issues of waste management. Continued increase in fossil fuel consumption and increased waste production also means that this demand is not sustainable given the finite amounts of fossil fuels resources for energy and limited space for landfills. Complete recycling of plastics is not possible due to the varying recycling value for different type of plastics along with the challenges posed to separate them from the waste stream, as well as impurity removal before using them as raw material for renewable plastics [2]. Separation of plastics based on

density is difficult, if not impossible, due to very close densities of different types of plastics and that complete removal of impurities from waste plastics is not possible [2]. Landfilling of plastics has been the traditional alternative to recycling although this process is neither sustainable, due to limited land availability, nor clean, due to leaching and landfill gas emissions [2]. More than 60% of total plastic wastes are landfilled while around 20% of plastics collected are recycled, which is not ideal waste management statistics given the issues of landfills and the loss of potential fossil fuel energy feedstock in the form of plastic wastes [1,2]. An alternate to plastic waste management includes thermochemical conversion for energy, fuel, chemical and value added products. While incineration can be used for energy production, the

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efficiency of solid waste feedstock combustion is limited due to diffusion, mixing, and maximum temperature limits in the furnace section of incinerators. Gasification provides ideal pathway in such circumstances of waste to energy conversion from versatile feedstock and the product syngas which can be used for power generation, liquid fuel production via Fischer Tropsch synthesis, and synthesis to other value added chemicals.

Gasification is the process of decomposition of solid carbonaceous material in the presence of steam, air/O₂, or CO₂ at high temperatures to reform the feedstock materials to generate product gas of higher heating value with major gaseous components being H₂, CO, CO₂, CH₄, C₂H₆ and trace amounts of other higher series of hydrocarbons. At high temperatures during gasification, while polymer cracking reactions and the reforming of cracked hydrocarbons lead to gas yields, re-polymerization and incomplete cracking leads to formation of mixture of heavy aromatic hydrocarbon residues, referred to as tar. Tar is a undesirable by-product for syngas applications and must be cracked or reformed into syngas using thermal or catalytic techniques to enhance the syngas yield [2–4]. Traditional gasification mainly have used coal and biomass as feedstocks with research and development carried out for different feedstocks, such as, plastic wastes, landfill wastes, municipal solid waste, agricultural waste, sludge, and animal waste [5–7]. While state of the art gasification literature focuses mainly on biomass gasification without and with catalysts of different types, operational temperature or gasifier designs [5–11], feed flexibility is important to counter high-moisture and high ash content biomass and waste feedstocks. Plastics are highly viscous in nature at moderate temperatures so that they are difficult to gasify in solo and may need co-gasification with other stable and efficient feedstocks [9].

Plastic wastes contain different types of polymers having low and high density materials, such as, polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polystyrene (PS), polycarbonate (PC). Although each of these polymers have different monomer composition with different carbon, oxygen and ash content, the common feature among plastic waste is the high volatile content, high viscosity with low melting points and high energy density due to very low moisture and ash content [12]. Gasification of plastics in fluidized bed have often faced issue on agglomeration of bed particles with plastic particles [13]. This has led to extensive investigations into co-firing of different types of plastics with biomass, coal and shale oil in gasification, and other techniques [13–22]. These results reveal that co-gasification as an important and efficient strategy to counter the lack of off-seasonal biomass supply, providing efficient conversion of low-grade feedstocks such as poultry and other animal litter as well as municipal solid wastes (MSW) and others with high moisture and ash content feedstocks [23–28]. Investigations on co-gasification include various blends, such as, biomass with plastics, biomass with refuse derived fuel (RDF) and refuse plastic and paper fuel (RPF) [29,30]. Fixed-bed thermo-gravimetric analysis (TGA) has mainly been used to understand the kinetics of co-pyrolysis of different feedstock blends and the effect of feedstock composition on decomposition rates and temperature ranges [31–33]. Demonstration studies using fluidized bed were conducted on gasification of blends of feedstocks to primarily understand the effect of gasification parameters, such as, temperature, gasifying agent, and equivalence ratio [14,34]. These investigations infer that pyrolysis and gasification kinetics of biomass and plastics may cause synergistic effects when mixed together in the feedstock leading to different results than those obtained from individual material feedstocks. These synergistic effects are the main focus of this paper.

Investigations found that catalytic or synergistic effects in co-gasification and co-pyrolysis with radicals released by one component enhancing decomposition of the other component in the feedstock [21,35–37]. Decomposition rate of PP and PET were enhanced in the presence of PS [1]. Co-pyrolysis of plastics with coal was faster and in a narrow temperature range compared to pyrolysis of individual components [38]. The same study also reported this interaction to be

maximum at a temperature that occurred at peak plastic de-volatilization with HDPE > LDPE > PP > PET > PS being the order of temperature of de-volatilization peaks [38]. Carbon conversion increased with plastic content during steam gasification of wood waste with refuse derived fuel (RDF) and refuse plastic fuel (RPF) [29]. Addition of PE to biomass gasification also enhanced H₂ yield while reducing CO yield [36]. Co-gasification of wood chips with PE under steam gasification conditions revealed non-additive H₂ and syngas yield enhancement with plastic addition [37,39,40]. PE addition to biomass gasification also provided less yields of tar and char [21]. The synergistic effects given above were attributed to various reasons. The promotion of polymer degradation by radicals evolved from degradation of biomass with lower stability is one of the majorly considered reason [36,37]. The H/C ratio of the feedstock blend is also an important factor as it dictates the OH and H radical evolution which helps to crack aromatics and ease in the yield of gases [36]. Biomass devolatilization temperatures lie in the range of 473–673 K while that of plastics range are in the range of 573–773 K [37]. Overlap of temperatures regimes of pyrolysis of plastics and biomass is necessary for the onset of such interactions. Co-gasification enhanced reforming of aromatics by hydrogen donor radicals from other feedstock component [36]. Interaction between coal and plastic wastes was attributed to coal promoting radical formation that foster polymer cracking to enhance lighter hydrocarbons production while the formed radicals from the polymer act as H-donor to enhance coal conversion [40]. Biomass and plastics comprises of different monomers; an emphasis on decomposition of these in the presence of each other is necessary to further understand their important role. The effect of composition, H/C and O/C of the monomers involved can help one to better understand this non-linear interaction. In this paper we examine gasification of biomass with different but homogeneous plastics in the presence of steam to understand the effect of different monomers of plastics to enhance or deteriorate the product gas yields.

This present paper provides results on the isothermal gasification of different compositions of 100% pine wood pellets in the presence of three different types of plastics at 1173 K using steam as the gasification medium. Plastics in the amounts of 0, 60, 80, 100% were mixed with biomass. Three different kinds of plastics examined here were polypropylene (PP), black polycarbonate (BPC), polyethylene terephthalate (PET). All of these plastics were post-consumer recycled with PP and BPC being pellet extrudes while PET being small size flakes.

2. Experimental facility and operating condition

2.1. Reactor facility

Investigations into steam gasification of mixtures of biomass and plastics were carried out using a laboratory scale semi-batch reactor, see Fig. 1. Various gas species were quantified by flowing a known flow rate of N₂ as tracer gas for all the experiments. Steam was generated from the stoichiometric combustion of H₂-O₂ mixture. The exhaust gases from the reactor were analyzed using gas chromatography to ensure that no H₂ or O₂ was present in the gasifying agent. A preheating electric reactor was installed that was set to the same temperature as that of the main reactor so as to preheat the mixture of gasifying agent and tracer gas to the same temperature as the main reactor. This mixture was then allowed to enter the main reactor located immediately downstream of the preheat reactor. The reaction of the biomass-plastic mixture sample occurred under quasi-isothermal conditions. After the reactors reached the set-point temperature, the feedstock sample was in the quartz sample holder and inserted through back using a quick disconnect coupling. Reaction time was recorded starting from the time of sample insertion into the reactor.

Product gas mixtures evolving from the reactor were first condensed in an ice bath followed by a water bath to remove tar and moisture. While most of the tar free syngas was vented out, a portion of it was

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