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Energy recovery from co-gasification of waste polyethylene and polyethylene terephthalate blends

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ABSTRACT

Among various energy recovery technologies from waste materials, gasification has emerged as a promising technology to develop a sustainable waste management system that would significantly reduce pollutions in landfill and maximize energy recovery. Co-gasification of plastics, biomass and coal has been extensively studied during recent years in an attempt to produce a high calorific producer gas. The present work provides a detailed simulation analysis on the product composition and conversion efficiencies of co-gasification of waste polyethylene (PE) and polyethylene terephthalate (PET). Co-gasification of PE and PET with only steam results in higher heating value gas, and better cold gas efficiency than PE gasification with air and steam. By adjusting the blend ratio of feedstock, it is possible to predict and, hence control the quality (composition) of syngas, thus enabling feedstock selectivity for various applications.

1. Introduction

The development of efficient waste management strategies has changed the perception of municipal waste as a sustainable form of energy resource rather than waste material. Over 1 million ton of waste was generated in the emirate of Abu Dhabi in the year 2011 where all the non-biodegradable waste ended up in landfill and dump sites [1]. Of all the wastes, plastics possess a higher heating value and hydrogen content even compared to biomass or other municipal solid wastes. However, majority of the generated waste plastic is disposed through landfills or incineration, and only less than 10% of the waste is being recycled [2]. Over the last decade, there have been many ventures to develop processes that recover energy or generate useful fuels or petrochemical feedstocks from waste plastic materials. The main five plastic polymers found in waste (PE, PET, PP, PS, and PVC) are also the polymers consumed in largest amounts with slightly different shares explained by the different efficiency of collection of the different plastic products, and the different lifetimes of the products. PE polymers (LLDPE, LDPE and HDPE) are overall the most abundant polymers in waste plastic because of their predominance in packaging applications, which account for more than half the total waste plastic [3].

Among various thermal and non-thermal energy recovery technologies, gasification has displayed tremendous potential to be a more sustainable waste management technique that would not only reduce environmental hazards and burden on landfills, but would also maximize energy recovery [4–6]. Over the last decade, gasification technique has been well explored and developed for agricultural products, animal waste, food waste, and other fossil fuels. The aim of gasification is to maximize conversion of carbonaceous material into gaseous products typically of high heating value, such as syngas that can either be used to produce electricity or can be converted as chemical feed stock such as methanol, hydrogen, or as a diesel, fuel, waxes, olefins, and gasoline, using Fischer Tropsch (FT) synthesis.

The economic success of the gasification process depends not only on the quality of product gas, but also on the efficient use of energy required for the conversion process. Since gasification is an endothermic process, significant energy has to be supplied to convert the solid fuel to syngas. The energy required to promote the gasification reaction is supplied by partial oxidation of a fraction of the fuel to liberate heat. Partial oxidation of the fuel is accomplished by the combustion of fuel with oxygen or sometimes air to form carbon dioxide and water. The net heating value of syngas depends on the choice of oxidizing agent used for the process. For e.g., oxygen gasification results in a syngas with a HHV of 10–18 MJ/m^3 while air gasification yields significantly low heating value gas of 4–7 MJ/m^3 [7] due to the dilution effect of nitrogen. However, in some cases the required energy is supplied through an external direct or indirect heating source. Steam is another vital reactant that is supplied as a gasification agent to carry out the conversion process. The steps involved in the thermo chemical process of gasification include drying or dehydration, pyrolysis or devolatilization, combustion, and fuel gasification. Drying is an

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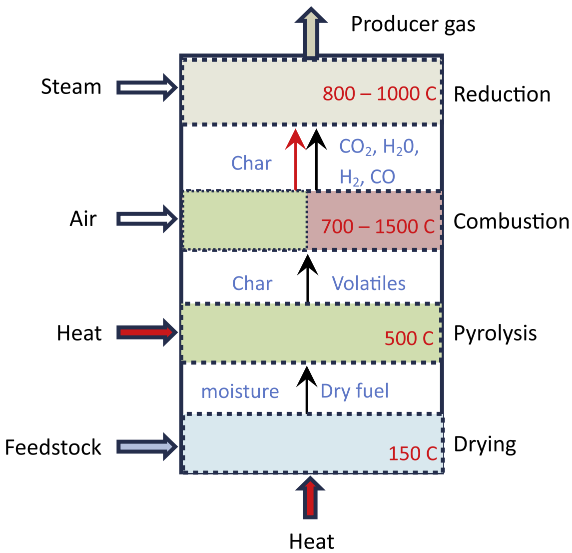

Fig. 1. Steps involved in a typical gasification process.

important, yet optional step in gasification when the moisture content of the fuel is very high. Drying is a very rapid process and essentially gets completed even before temperature reaches 250–300 °C. Moreover, plastics do not contain any significant moisture and whatever little present is expected to be released completely before 150 °C. Pyrolysis involves breaking up of the solid fuel into lighter hydrocarbon gases (volatiles made up of CO, H_2, CH_4 etc.), char and tar (unconverted volatile matter made of high MW hydrocarbons) in the absence of air. Since plastics contain significant amount of volatiles, pyrolysis products could be expected to mainly comprise of light gases like CO, CH_4, H_2 and char (carbon) irrespective of the type of monomer. In order to prevent tar formation, gasification process is typically carried out at elevated temperatures (>900 °C). Alternatively, the use of catalysts permits the gasification process to be carried out at lower temperatures with significant reduction in tar formation. Thus, the feedstock is chemically and physically altered by the pyrolysis process so as to suit for the subsequent combustion process. As stated before, the main purpose of combustion is to generate the thermal energy necessary for the gasification reactions. Combustion is carried out using very small amount of oxygen (much less than the amount dictated by stoichiometry for complete combustion) to react with a fraction of the volatiles and char resulting from pyrolysis to form carbon dioxide, water and trace amounts of carbon monoxide. Finally, the hot gaseous products, along with the remaining char is subjected to a set of gasification reactions involving char, carbon dioxide and steam producing producer gas as the main product. Fig. 1 depicts a schematic representation of the chemical transformation of the fuel involved in a typical gasification process. The lines representing the zones are only imaginary, and thus do not necessarily isolate the physical process as depicted in Fig. 1. The list of chemical reactions involved in the gasification process is shown in Table 1. Only the major gasification reactions have been included along with the heat of reactions.

Co-gasification of plastics, biomass and coal has been extensively reported in literature in the recent past [8–14] with reference to generation of high calorific producer gas and an increase in the hydrogen content. This necessitated higher operating temperatures and usage of steam as a gasifying medium to reduce the formation of tars. In addition, the concentrations of tars and other hydrocarbons were lower when external oxidizing agents, like air or oxygen was employed due to partial oxidation. Although employing air as an oxidizing agent provides the energy for the gasification process, the presence of significant volumes of nitrogen reduces the calorific value of syngas. Alternatively use of pure oxygen for gasification renders the process economically unviable. This necessitated identification of materials with significant portion of oxygen as a co gasification agent. Some of the plastics such as polyethylene terephthalate (PET) contain large fraction of oxygen that can be effectively harnessed to promote the combustion reaction, releasing the necessary energy to promote the gasification reactions. Information pertaining to PE and PET co-gasification in the absence of external oxidizers has never been reported earlier in the literature and hence the primary objective of this work is to investigate the feasibility of co-gasification of PE and PET blends in the absence of any external oxidizers and to determine the proper blend to maximize conversion efficiency and calorific value of syngas. A comparative study of the mixed and virgin plastics with respect to syngas quality and cold gas efficiency is presented. A detailed sensitivity analysis on various operating parameters like temperature, equivalence ratio, and steam-to-fuel ratio has also been discussed.

Table 1
List of typical Gasification reactions.

No.	Reactions	Heat of reaction (kJ/mol) $T = 1000$ K, $P = P_o$	Type
1	$C + ½ O_2 \leftrightarrow CO$	−122	Reactions with oxygen
2	$CO + ½ O_2 \leftrightarrow CO_2$	−283	
3	$H_2 + ½ O_2 \leftrightarrow H_2O$	−248	
4	$C + H_2O \leftrightarrow CO + H_2$	136	Reactions with water
5	$CO + H_2O \leftrightarrow CO_2 + H_2$	−35	
6	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	206	
7	$C + CO_2 \leftrightarrow 2CO$	171	Boudouard reaction
8	$C + 2H_2 \leftrightarrow CH_4$	−74.8	Methanation reactions
9	$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	−225	
10	$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$	−190	

2. Model development

The gasifier in the current work has been modeled as an adiabatic Gibbs reactor with a heat duty of zero that represents a self-sustained reaction at the flame temperature of the fuel blend. The mixed plastics gasification has been detailed using a system of equilibrium reactions (Table 1) that result in products such as methane, hydrogen, carbon monoxide, carbon dioxide, water, sulphurous and nitrogen compounds. Any other high molecular weight hydrocarbons, such as tars and oils, are less likely to form under equilibrium conditions and hence are not included in the simulation. More importantly, the equilibrium condition that facilitates assessing the effect of feed composition on flue gas temperature, conversion efficiencies, syngas yield and product composition forms the basis of the present work neglecting the complexities of the gasifier hydrodynamics and reaction kinetics.

The following assumptions are made in developing the process model.

(1) All the chemical reactions were assumed to have reached equilibrium within the gasifier.
(2) The primary components of char are only carbon and ash.
(3) Only methane, hydrogen, carbon monoxide, carbon dioxide, oxygen, nitrogen, H_2S, C, COS, C, and water were considered to be present in the product stream.
(4) Tars and other heavy hydrocarbons are assumed to form only under non-equilibrium conditions.