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Thermodynamic modelling and evaluation of a two-stage thermal process for waste gasification

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HIGHLIGHTS

- This paper compares single and multiple stages gasification technologies.
- A model is developed to predict efficiency and gas composition at each stage.
- The model is validated with experimental data taken from a demonstration plant.
- Carbon conversion and syngas yield are enhanced when using a two-stage process.
- Optimal oxidants ratio and energy demand depend on the aims of different projects.

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ABSTRACT

Tar generation and ash disposal represent the strongest barrier for use of fluid bed gasification for waste treatment, whereas sufficing for both is only possible with expensive cleaning systems and further processing. The use of plasma within an advanced two-stage thermal process is able to achieve efficient cracking of the complex organics to the primary syngas constituents whilst limiting the electric power demand. This study focused on the thermodynamic assets of using a two-stage thermal process over the conventional single-stage approach. These include, for example, the fact that the primary thermal waste decomposition is performed in conditions of optimal stoichiometric ratio for the gasification reactants. Furthermore, staging the oxidant injection in two separate intakes significantly improves the efficiency of the system, reducing the plasma power consumption. A flexible model capable of providing reliable quantitative predictions of product yield and composition after the two-stage process has been developed. The method has a systematic structure that embraces atom conservation principles and equilibrium calculation routines, considering all the conversion stages that lead from the initial waste feed to final products. The model was also validated with experimental data from a demonstration plant. The study effectively demonstrated that the two-stage gasification system significantly improves the gas yield of the system and the carbon conversion efficiency, which are crucial in other single stage systems, whilst maintaining high energy performances.

1. Introduction

Energy generation and waste disposal are two of the most difficult challenges facing the world today. As the world's fossil fuel resources are depleted, we are facing a mounting crisis of energy supply. At the same time, global population growth and rising living standards increase the energy demand, and the resulting amount of waste material produced is dramatically higher than ever before. Waste-to-Energy (WtE) technologies have an important role to play in resetting this balance. In this context, there is considerable interest in new ways to dispose of waste using thermal conversion technologies, particularly gasification and pyrolysis. Waste gasification, latest addition to Waste-to-Energy technologies, converts solid wastes into green electricity or clean gaseous fuel known as synthesis gas (or syngas). This promising technology has received increasing attention in the past two decades due to the growing demand for clean fuels and chemical feedstocks, as well as the need for reducing dependency on fossil fuels, lowering green house gas emissions and disposing of existing wastes. In general all the advanced thermal conversion technologies, which include gasification and pyrolysis, are increasingly being preferred to incineration and combustion in waste to energy

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Nomenclature

n_i	molar flowrate of gaseous species *i*, kmol/h
b_j	total number of atoms of the *j*th element
a_{ij}	number of atoms of the *j*th element present in a molecule of chemical species *i*
f_i	fugacity of species *i*, bar
P	pressure, bar
R	universal gas constant, 8.314 kJ/kmol K
T	temperature, K
P_i	partial pressure of species *i*, bar
ϕ	fugacity coefficient
y_i	mole fraction of gas species *i*
$\Delta\overline{G}^0_{f,i}$	standard Gibbs free energy of formation of species *i*, kJ/kmol
$\Delta\overline{H}^0_{f,i}$	standard enthalpy of formation of species *i*, kJ/kmol
$\Delta\overline{S}^0_{f,i}$	standard entropy of formation of species *i*, kJ/kmol K
G^{tot}	total Gibbs free energy of the system, kJ/h
$\overline{C}_P$	heat capacity at constant pressure, kJ/kmol K
ΔH	net enthalpy rate, kJ/h
Q_{loss}	heat loss, kJ/h
W_{power}	electric power from plasma, kJ/h
$\sum H$	total stream enthalpy rate, kJ/h
$\dot{m}$	mass flowrate, kg/h

Abbreviations

WtE	waste to energy
FBG	fluidized bed gasifier
PCBs	polychlorinated biphenyls
RDF	refuse derived fuel
PAHs	polycyclic aromatic hydrocarbons
IGCC	integrated gasification combined cycle
SR	stoichiometric ratio
MSW	municipal solid waste
TOC	total organic carbon
SOFC	solid oxide fuel cell
GHV	gross heating value, MJ/kg
LHV	lower heating value, kJ/kmol

Superscripts

′	stage one
″	stage two
°	standard reference state

Subscripts

r	reactant
p	product
i	*i*th gas species
j, k	*j*th, *k*th chemical element
IN	flux in
OUT	flux out
comp	component
(g)	gas phase
(s)	solid phase
(v)	vapour phase

Greek letters

ν_i	stoichiometric coefficient of species *i*
α,β	char conversion splitting factors
μ_i	chemical potential of species *i*, kJ/kmol
GRG	generalized reduced gradient
FTIR	Fourier transform infrared spectroscopy
VBA	visual basic for applications
ASR	automotive shredder residue
C&I	commercial and industrial
VOC	volatile organic carbon
CGE	cold gas efficiency
OPR	oxygen partition ratio
NEE	net electrical efficiency
SNG	synthetic natural gas

applications. The advantages include higher recycling rates, lower emissions, higher energy efficiencies, lower costs, smaller footprints and reduced visual impact [1].

Most of the gasification systems from waste are based on high-temperature techniques that use oxygen as a source of heat or as partial oxidation agent. On this regard, there are numerous advanced oxygen-blown gasifiers that are at various stages of development [2–4]. Among all waste gasification technologies, fluidized bed reactors are the most promising, for a number of reasons [5]. In particular, the enhanced flow mixing between reactants, the nearly constant temperature and the great operating flexibility of fluidized bed reactors make it possible to utilize different types of feedstock, including biomass and solid wastes. These gasifiers usually work as "partial combustors", and a portion of the carbon present in the fuel is combusted to support pyrolysis and gasification reactions. Because of the relatively low temperature used to prevent agglomeration and sintering of bed material, the gas that is produced by a standard fluid bed gasifier (FBG) has tars and other condensable organic species that are technically difficult and costly to remove. Furthermore, the bottom ash/char that is generated in the gasifier or pyrolysis fluid bed reactor may contain high levels of carbon, heavy metals and organic pollutants which lower the conversion efficiency of the process and limit any secondary usage. The ash/char residue can be up to 20% of the weight of the incoming material and must be further processed before being landfilled [6]. Tar generation and ash disposal represent the strongest barrier for use of FBG for waste treatment, whereas sufficing for both is only possible with expensive cleaning systems and further processing.

The use of plasma systems has increasingly been applied with thermal waste treatment for its ability to completely decompose the input waste material into a tar-free synthetic gas and an inert, environmentally stable, vitreous material known as slag. The principal advantages that plasma offers to thermal conversion processes, besides the already mentioned tar/ash related issues absence, are a smaller installation size for a given waste throughput, and the use of electricity as energy source, characteristics which permit the technology to treat a wide range of low calorific value materials including liquids and solids. Because of these potential advantages, plasma technologies have been developed for the destruction and removal of various hazardous waste, such as PCBs [7], medical waste [8], metallurgical wastes, incineration fly ash [9], and low-level radioactive wastes. Its efficient application in the treatment of general waste is still under debate though, due to the power required to convert the solid waste to a gas. Only additions of combustion heat supplied by the waste feedstock or a fuel additive make the process suited to large waste streams. Examples of technology development include InEnTec in USA and Alter NRG, in Japan [10].

In applying the plasma technology to the gaseous products from a thermal gasifier, an advanced two-stage thermal process is able to achieve efficient cracking of the complex organics to the primary syngas constituents whilst limiting the electrical energy demand of the process. Forerunners in this approach are Advanced Plasma