INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–12

Available online at www.sciencedirect.com

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Performance assessment of plasma gasification for waste to energy conversion: A methodology for thermodynamic analysis

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form
7 August 2017
Accepted 22 August 2017
Available online xxx

Keywords:
Plasma gasification
Thermodynamic analysis
Content conversion efficiency
Hydrogen quality
First – Second law efficiency
Mass – Power scale parameter

ABSTRACT

Performance assessment of plasma gasification for solid waste disposal is the main concern of the study. As an extensive review on the manner; the current terminology, definitions and the available theoretical background for thermodynamic analysis are outlined. Thermodynamic analysis is provided in terms of energy and mass conservation giving attention to the calculation routes as a basic contribution to the state of art. The defined first law and second law efficiency terms, $\eta_{ES}, \eta_{EP}, \eta_{EXS}, \eta_{EXP}$ content conversion efficiency parameters, CCE and hydrogen quality H_q are referred through the so-called process and system descriptions in this respect. The proposed methodology is presented using the available experimental data of Tang et al. [1] and Hong et al. [2] as sample cases for the verification of the study. It seems that the variation of first and second law efficiency terms, CCE, H_q as a function of plasma input power, W besides the defined mass and power scale parameters of S_m and S_w can be referred for the performance assessment of a plasma gasification system (under the influence of solid waste–fuel properties).

Introduction

Plasma is a high temperature ionized matter that includes electrons, neutral particles besides ions. It is usually defined as the fourth state of matter which can be regarded electrically neutral [3]. Temperature of plasma is the major parameter controlling the degree of ionization. Plasma has been used for the acetylene extraction from natural gas since the 19th century. However the current technology is primarily based upon the studies of NASA [4]. The industrial applications have a wide range in the fields of coating, thin film production, gasification, flow control and sterilization. Gasification is a thermochemical conversion of an organic compound to a gaseous mixture which is consisting of carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), and methane (CH_4) [5]. Gasification can be defined as auto-thermal or allo-thermal depending on the nature of energy input for the process. The part of combusted fuel provides the energy to sustain the gasification in the first while the second necessitates an external heat supply continuously. The relevant terms of combustion and pyrolysis are also referred herein. Combustion is an oxidizing reaction with an amount of oxidant which is in excess of the stoichiometric amount in a temperature range of 850–1200 °C. Pyrolysis is a thermal decomposition in the absence of an oxidant in a temperature range of 400–950 °C [6]. The so called – fuel may be any of the possible organic compound (from biomass, waste to coal). The

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http://dx.doi.org/10.1016/j.ijhydene.2017.08.147
0360-3199/

Table of symbols

η_E	Overall theoretical system efficiency
η_{EP}	First law efficiency of process
η_{ES}	First law efficiency of system
η_{EXP}	Second law efficiency of the process
η_{EXS}	Second law efficiency of system
η_{HG}	Hot gas efficiency
$\overline{c_p}\left(kJ/kmol\cdot K\right)$	Molar specific heat at constant pressure
$c_{p(syn)}\left(kJ/kg\cdot K\right)$	Specific heat of syngas at constant pressure
CCE	Content conversion efficiency
CCE_{H_2}	Hydrogen content conversion efficiency
CCE_{ash}	Ash content conversion efficiency
CCE_{syn}	Syngas content conversion efficiency
CCE_{system}	System content conversion efficiency
e_0	Standard chemical exergy
$Ex_{ch}\left(kJ/kg\right)$	Chemical exergy
$Ex_{fuel}\left(kJ/kg\right)$	Total exergy of solid fuel
$Ex_{ph(i)}\left(kJ/kg\right)$	Physical exergy of gas mixture component
$Ex_{ph}\left(kJ/kg\right)$	Physical exergy
$Ex_{plasma}\left(kJ/kg\right)$	Total exergy of plasma
$Ex_{syn}\left(kJ/kg\right)$	Total exergy of syngas
$Ex_{tot}\left(kJ/kg\right)$	Total exergy
$Ex_{fuel}\left(kJ/kg\right)$	Fuel exergy
$Ex_{syngas}\left(kJ/kg\right)$	Syngas exergy
H_q	Hydrogen quality of syngas
$h\left(kJ/kg\right)$	Enthalpy at operation conditions
$h_0\left(kJ/kg\right)$	Reference enthalpy
$HHV_{ash}\left(kJ/kg\right)$	Higher heating value of ash
$HHV_{fuel}\left(kJ/kg\right)$	Higher heating value of fuel
$HHV_{syn}\left(kJ/kg\right)$	Higher heating value of syngas
$LHV\left(kJ/kg\right)$	Lower heating value
$LHV_{fuel}\left(kJ/kg\right)$	Lower heating value of fuel
$\dot{m}_{H_2}\left(kg/s\right)$	Hydrogen mass flow rate
$\dot{m}_{ash}\left(kg/s\right)$	Ash mass flow rate
$\dot{m}_{fuel}\left(kg/s\right)$	Solid fuel flow rate
$\dot{m}_{input}\left(kg/s\right)$	input mass flow rate
$\dot{m}_{output}\left(kg/s\right)$	Output mass flow rate
$\dot{m}_{plasma}\left(kg/s\right)$	Plasma gases mass flow rate
$\dot{m}_{syn}\left(kg/s\right)$	Syngas mass flow rate
$\dot{n}_i\left(kmol/s\right)$	Molar flow rate
$P(kPa)$	Pressure
$R\left(kJ/kmol.K\right)$	Universal gas constant
S_m	Mass scale parameter
$S_w\left(kJ/kg\right)$	Power scale parameter
$s\left(kJ/kg\cdot K\right)$	Entropy at operation conditions
$s_0\left(kJ/kg\cdot K\right)$	Reference entropy
$T\ (K)$	Temperature
$T_o\ (K)$	Ambient temperature
$T_{syn}\ (K)$	Syngas temperature
$W_{plasma}(kW)$	Power for plasma generation
x_i	Fraction of gas species in the mixture

gasification products of fuel are the so-called synthesis gas (syngas) and ash.

In reference to the type of energy input; it is apparent that the type of plasma governs the electrochemical conversion. The characteristics of the fuel are also of primary importance. However the following basic classification can be proposed although each class has an interrelation with the others [7].

1) **Plasma – generation – energy input:** electrical, thermal, ultraviolet light, electromagnetic radiation etc.
2) **Plasma gasification-principle of operation:** characteristics of the process in combination with fuel characteristics (ranges of temperature, pressure, capacity, life time, etc.) DC: direct current, RF: radio frequency, MCw: Microwave plasma. Plasma environment gases; air, oxygen, nitrogen, carbon dioxide, argon, steam, helium and etc.
3) **System hardware characteristics**: a variety of design possibilities on the system components and processes (Plasma fixed/moving reactor, plasma entrained-flow bed reactor, plasma spout/spout-fluid bed reactor etc.)

Tang et al. [1], classified thermal plasma gasification systems depending on the generation method, reactor structure and plasma suppliers. Thermal plasma is generated by direct current (DC) [8–11], radio frequency (RF) [12–15] or microwave (MCw) plasma [2,16–23] in literature. In the case of DC plasma, the applied high voltage to electrodes create an arc. Supplied gas is forwarded to arc which causes the ionization of gas and plasma formation. In the case of RF plasma, the electrode

Please cite this article in press as: Ozdinc Carpinlioglu M, Sanlisoy A, Performance assessment of plasma gasification for waste to energy conversion: A methodology for thermodynamic analysis, International Journal of Hydrogen Energy (2017), http://dx.doi.org/10.1016/j.ijhydene.2017.08.147