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System development and self-sustainability analysis for upgrading human waste to power

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ABSTRACT

This paper presents a system to upgrade faecal matter in an environmentally friendly way by the deployment of plasma gasification and SOFC (solid oxide fuel cells). The entire system chain, including a dryer, a microwave-assisted plasma gasifier, a gas processing system and an SOFC system, is studied to evaluate system performance and self-sustainability. The effects of gas processing approach, moisture content and oxidant-to-fuel ratio on system self-sustainability are studied in detail. The results show that the variables aforementioned strongly affect system performance. It is recommended to deploy the approach of adding air, a mild moisture content (30% by weight) and an intermediate oxidant to fuel ratio (1.05 kg kg^{-1}) to achieve enhanced system performance under the conditions studied.

1. Introduction

Sustainable development requires an efficient and environmentally friendly management of wastes. Conventional routes available for waste management are combustion, pyrolysis and gasification. Among these routes, gasification serves as a valuable process that transforms low value feedstock into valuable products and fuels. Unlike conventional gasification power plants, plasma gasification offers complete gasification even at a small scale due to the elevated operating temperature. Therefore, plasma gasification is considered as an environmentally sustainable technology for waste treatment. It is well known that fuel cells, particularly SOFCs (solid oxide fuel cells) possess an enhanced fuel-to-electricity efficiency due to the direct conversion of chemical energy to electricity, and SOFCs can potentially use multiple fuels including syngas from plasma gasification. Thus, power plants based on plasma gasifiers and SOFCs are likely to be highly efficient in upgrading wastes to green electricity.

Compared to conventional biomass gasification technology such as air-blown down-draft fixed-bed gasifiers, plasma gasification technology is still at an early developing stage. Conventionally, plasmatron uses an electric arc which is formed by applying a high potential difference to two electrodes to ionize the passing gas and to generate a high temperature that is particularly effective for the gasification of various fuels. By contrast, an innovative approach to generate plasma is using microwaves, which is less energy-intensive, more economic viable and relatively more efficient [3]. Depending on the design, the conversion efficiency of electricity-to-microwave can be as high as 100% [4]. Both kinds of plasmatrons have been applied and studied in experiments; for example, Ray et al. [5] presented an advanced gasification technology that combines a fluidized bed gasifier and a plasma gasifier enabling to treat various wastes, and reported a high carbon and energy conversion efficiency. Yoon and Lee [6] studied the variation in the syngas composition and the microwave-driven plasma gasification efficiency when various plasma gases and feedstock were used. Particularly, they looked into the effects of oxygen-to-fuel ratio on the syngas composition and the gasification efficiency. Hong et al. [1] employed 2.45 GHz microwave energy for coal plasma gasification in oxygen/air plasma and steam/air plasma. With the oxygen/air plasma, further increasing coal flow rate above 2.0 kg h^{-1} does not significantly affect the syngas concentration, whereas with the steam/air plasma, the syngas concentration becomes relatively stable when the mass ratio between coal and steam is above 0.45 (kg kg^{-1}). The authors also suggest SOFCs coupled with plasma gasification would be interesting for highly efficient power generation in the future. Wang et al. [2] studied the effects of microwave power, processing time, water content and biomass size on microwave torrefaction of rice husk and sugarcane. The results suggest that microwave power of the order of 250–300 W favors the syngas production with a relatively fine biomass size. They

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Nomenclature

E	energy, kW
E_x	exergy, kW
F	Faraday constant, C mol^{-1}
I	current density, mA cm^{-2}
M	molecular weight, kg mol^{-1}
P	pressure, Pa
R	the universal gas constant, J mol^{-1} K^{-1}
R_{eq}	equivalent resistance, Ω cm^2
T	temperature, K
U_F	fuel utilization, %
$V_{rev,x}$	reversible cell voltage, V
Y_i	molar fraction of species, i

Greek letters

η	efficiency, %
Φ	flow rate, kg s^{-1}

Superscripts and subscripts

an	anode
aux	auxiliary
ele	electricity
in	inlet
out	outlet

Abbreviations

AC	alternating current
AP	auxiliary power, kW
APD	air preheating duty, kW
CHP	combined heat and power
CPOX	catalytic partial oxidation
DC	direct current
EFP	electricity for plasmatron, kW
FCP	fuel cell power, kW
FPD	fuel preheating duty, kW
GDC	gadolinia doped ceria
HHV	higher heating value, kJ kg^{-1}
LHV	lower heating value, kJ kg^{-1}
LSM	lanthanum strontium manganese oxide
NE	net electricity, kW
NEE	net electrical efficiency, %
OTFR	oxidant-to-fuel ratio
SOFC	solid oxide fuel cell
YSZ	yttria stabilized zirconia

conclude that microwave-induced torrefaction enhances the caloric value, increases the carbon content, and decreases the oxygen content of torrefied solid products efficiently and economically in comparison with conventional torrefaction.

Literature survey shows that current efforts mainly focus on plasma gasification, and studies on the system development based on plasma gasification and SOFCs are very limited. This work attempts to fill this gap and to achieve suitable operating regime for the development of such a power plant. Detailed studies on system self-sustainability under various operating patterns are analyzed.

2. System layout

The system layout is shown in Fig. 1 which includes fuel pretreatment, a dryer, a plasma-assisted gasifier, a gas cleaning and processing system and an SOFC system. The electricity generated from the SOFC system is expected to overcome the power consumed by the microwave generator and other auxiliary components like blowers and pumps, whereas heat generated by combustion using unreacted electrode off-gas in the SOFC system is utilized for drying, fuel and air preheating, and/or steam generation.

2.1. Fuel pretreatment

Human faecal matter is selected as the fuel for the plasma gasification. The pre-dried matter contains high moisture content (70–80% by weight) and requires being reduced to a certain range for the operation of the plasma furnace. In addition to the water reduction, depending on the design of the feeding, the faecal matter may need to be milled before feeding it into the furnace.

2.2. Plasma gasification

The plasma gasification system studied includes a microwave generator with 2.45 GHz frequency, air and fuel feeding and control parts, a reactor as well as temperature, gas composition and tar measuring/analysis equipment. A schematic drawing of the plasma setup is shown in Fig. 2.

As analyzed by Rutberg et al. [8], the use of air as plasma gas is relatively simple and promising for the development of plasma gasification technology. Therefore, in this work air is the plasma gas in the studies.

2.3. Gas cleaning and gas processing

Plasma gasification inevitably generates a certain amount of trace species which, without proper cleaning, may degrade SOFC performance. The type and the amount of the trace species can vary substantially depending upon the fuel types and operating conditions applied. In this study, a gas cleaning system is being developed to deal with the potential trace species, including particulates, alkali compounds, heavy metals, acid gases (HCl and H_2S) and tars. This preliminarily design shown in Fig. 3 is believed to result in

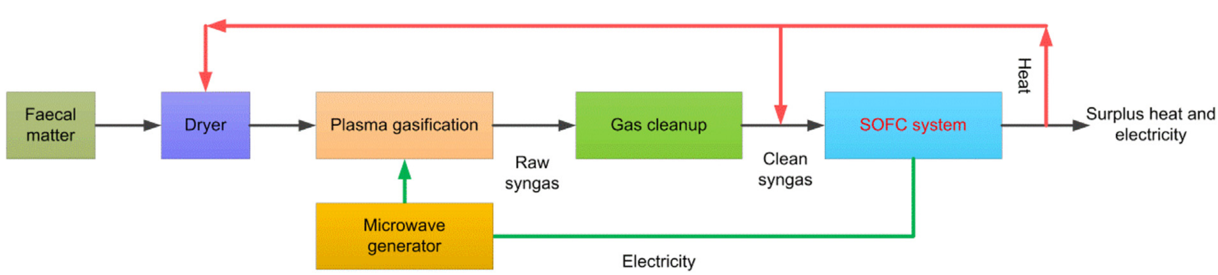

Fig. 1. The main flow scheme of the integrated plasma gasifier–SOFC system.