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Renewed sanitation technology: A highly efficient faecal-sludge gasification–solid oxide fuel cell power plant

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HIGHLIGHTS

- High recovery of energy by a faecal sludge power plant.
- High efficiency not limited by moisture content of faecal sludge.
- Heat management with gasifier-Solid Oxide Fuel Cell system.
- Optimised design conditions for high efficiency operation.

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ABSTRACT

Sustainable development goals for 2030 aim at the extensive reduction of the global sanitation breach; this might be achieved by renewed sanitation technologies and while providing sanitation recover valuable products such as energy. Consequently, this work presents a gasification–solid oxide fuel cell (SOFC) power plant that was configured for high-efficiency energy recovery from faecal sludge. The main limitations of faecal sludge gasification are the production of impurities, such as tar, and the high energy requirements for both the endothermic gasification process and removing the high moisture content in the feedstock. However, results from this work indicate that a superheated steam dryer combined with an indirectly heated multistage gasifier and a gas-cleaning unit can overcome the mentioned limitations. The external heat for the gasifier is supplied by the process heat available and a microwave plasma torch, and there is sufficient heat to drive a micro steam turbine. Thermodynamic calculations indicated that the plant could reach a net electrical efficiency of the order of 65%. As a result, a gasification–SOFC power plant is more suitable for energy recovery than any other process such as biochar production by pyrolysis; hence, it might become a technology that is financially feasible and can be used globally for sanitation purposes.

1. Introduction

1.1. Towards a new-generation sanitation process

Sanitation is a system in which human excreta and wastewater are successively collected, stored, transported and transformed [1]. It has multiple benefits not only in health and ecosystem but also in food security, business growth, and energy. In sustainable development, sanitation is a key element [2]. However, nowadays a global gap exists in terms of sanitation. Rijsberman et al. [3] stated that there are 2.4 billion people, one-third of the world population, without access to basic sanitation, and there are more than one billion people that defecate in the open. Approximately 90% of the wastewater is discharged untreated. Further, sewage sludge generated during wastewater treatment demands huge areas of land for its disposal.

Sustainable development goals for 2030 focus on ensuring that every person has access to adequate and equitable sanitation and hygiene, and open defecation is eliminated. However, these goals may be achieved effectively by radical innovations in sanitation, and sanitation must include safe recovery and reuse of water, nutrients, organic matter, energy, and minerals [4].

As a result, the development of innovative sanitation technologies is encouraged; for example, the Bill & Melinda Gates Foundation — Reinvent The Toilet Challenge (RTC) program funded sanitation technologies that provide affordable sanitation, recover valuable resources, operate off the grid and are economically viable [5]. To recover energy from human sludge, thermochemical, electrochemical and biological processes were tested in the RTC program and as with any new

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technology, a thorough understanding of the fundamental physics and chemical reactions of these processes is required. Such technologies can process organic matter to produce several types of biofuels such as syngas, biochar, and bio-oil. The quality that can be obtained for the syngas produced depends on the conversion process used and the chemical composition of the biomass. Fresh human faeces have a lower heating value (LHV) of approximately 20 MJ/kg on dry bases, which is comparable to wood; however, the moisture content (MC) is approximately 70–82%, and the ash content is 3–6 wt.% [6].

As far as thermochemical processes are concerned, pyrolysis and gasification have the main advantage that the conversion of the feedstock into fuel requires seconds or hours, in contrast to biological treatment that takes days or months. In terms of gas emissions, gasification and pyrolysis processes are more environmentally friendly than combustion and incineration [7]. The high process temperatures destroy pathogens, and it is possible to design a continuous process with compact reactors [8].

Some demonstration plants funded by the RTC program comprise the production of hydrochar by hydrothermal carbonization and this method appropriately treats biomass with high moisture content. However, there are engineering limitations, which cause low conversion efficiencies [9]. A real human waste electrolysis cell coupled with molecular hydrogen was developed by Cho et al. [10]. Its energy efficiency is very low compared to ideal electrolysis units. Direct pyrolysis of faecal sludge was utilized to produce biochar [5], which is a promising method in terms of thermal management [11]. However, information on the physical properties of biochar obtained from faecal sludge for further use as a carbon-neutral fuel is not available.

1.2. *Gasification as energy recovery technology*

Gasification is a technology currently applied at an industrial level; however, the produced gas is of low quality and has high amounts of impurities (tar, particles, HCl, and H_2S). Among these impurities, tar can be reduced by proper gasifier design, which positively influences the conversion efficiency. For energy recovery, the undesirable substances may be removed from the gas produced.

Furthermore, gasification requires a significant amount of energy owing to the endothermic nature of the reactions and for dewatering high-moisture feedstock. The heat can be supplied either by combustion of part of the gas produced with oxygen from air or by an external source of heat (allothermal gasification) [12]. Therefore, the thermal efficiency and the design of a gasifier dependent on the energy consumption during the gasification and drying processes, which is the main limitation of this technology.

To achieve the highest energetic efficiency, biomass gasification plants generally operate to produce electricity in combined heat and power (CHP) configuration; in Europe, the biomass gasification plants in CHP configurations have capacities lower than 1 MWe. In addition, allothermal gasification avoids combustion of gas products, so it maintains the heating value of the syngas, and produces syngas without nitrogen dilution [13].

Table 1 compares the operating conditions and efficiencies of several biomass thermal power plants. The LHV of biomass was calculated according to [13] from the elemental composition.

Thermodynamic calculations for a human-sludge plasma-gasification–SOFC power plant indicate that the η_{el} of the system is negatively influenced by the high moisture content (MC) of the feedstock and high electricity demand of a plasma gasifier. In the system model by Liu et al. [14], the η_{el} barely reaches 5.4%, while in Mountouris et al. [15], the η_{el} had a value of 10%.

According to experimental investigations, the η_{el} is higher with relative dry wood as feedstock. The integration of plasma gasification and a steam turbine by Rutberg et al. [16] yielded an η_{el} of 33%. The combination of allothermal steam gasification and an SOFC in a study by Panopoulos et al. [17] produced an η_{el} equal to 35.5%.

Table 1
Performance of different gasification-based combined system power plants.

	Liu et al. [14]	Mountouris et al. [15]	Rutberg et al. [16]	Panopoulos et al. [17]	Bang et al. [18]	Facchinetti et al. [20]	Santhanam et al. [21]	Sadhukhan et al. [22]	Hermann et al. [23]
Gasification process	Plasma	Plasma	Plasma	Allother.	Hybrid-Allother. two stage	CSCWG	Allother.	Two FBG	Allother.
Results base on	Model	Exper.	Exper.	Exper.	Exper.	Model	Model	Model	Model
Biomass	Faecal matter	Sewage sludge	Wood	Wood	Wood	Wood	Casuarina	Straw slurry	Wood
Moisture content wt. (%)	80	68	20	10	32.2	80	15	8.5	50
Feed (kg/s)	0.0008	2.89	1	0.025	0.043	NA	2.2	0,064	0.41
Feed LHV (kJ/kg)	16,841	15,351	18,437	19,301	18,183	18,600	15,500	14,600	19,301
Reactor temperature (°C)	> 800	1000	900–1200	790–890	> 800	400	800	950	850
Reactor pressure (bar)	Atm.	Atm.	Atm.	Atm.	Atm.	300	9	Atm.	Atm.
System net electrical efficiency LHV (%)	6.4	10	33	35.4	48	63	73.6	64	61
System net electrical efficiency HHV (%)	5.94	5.95	23	27	30	NA	70	62	57
Electricity generator	SOFC	Gas engine	Brayton and steam cycle	SOFC	SOFC	SOFC-Rankine cycle-GT-Fuel processing	SOFC-GT	SOFC	SOFC-Steam turbine