



Thermo-economic analysis of solid oxide fuel cell using human waste as a source of fuel



A.E. Afolabi^a, K. Sunday^a, A.S. Abdulkareem^{a,b,*}, Y.O. Abdulsalam^a, A.S. Kovo^a, P. Oladijo^b

^aChemical Engineering Department, School of Infrastructure, Process Engineering and Technology, Federal University of Technology, PMB 065, Gidan Kwano, Minna, Niger State Nigeria

^bDepartment of Chemical, Material and Metallurgical Engineering, College of Engineering and Technology, Botswana University of Science and Technology, Private Bag, 16, Palapye, Botswana

ARTICLE INFO

Article history:

Received 5 July 2021

Revised 14 October 2021

Accepted 19 October 2021

Editor: DR B Gyampoh

Keywords:

Biogas

Bio-digester

ATR

Shift reactor

SOFC

ABSTRACT

The production of fuel cell technology for commercial purposes is hindered by limited durability and cost. Hence, we focused on the thermo-economic analysis of solid oxide fuel cell (SOFC) that is fuelled with hydrogen produced from human waste to generate 200 kW power. This was achieved through computer simulation using Thermolib 5.4 version (a MATLAB/Simulink's software). Two configurations were adopted for biomass production and are based on gasification and slow pyrolysis. The results obtained revealed that producer gas from gasification and slow pyrolysis have a thermal efficiency of 82.2 % and 34.69 respectively. Lower heating value (LHV) of 113.14 kJ/mole and 466.37 kJ/mole accounted for the variation. Additional energy requirements of 571.50 kW for gasification and 353.04 kW for slow pyrolysis would be needed to achieve the set power output. Exergy analysis further showed that producer gas (slow pyrolysis) had the highest exergy input of 11848.86 kW and corresponding output of 11160.91 kW which was far higher than that of producer gas (gasification) with exergy input as 5,992.17 kW, and exergy output of 5698.44 kW. The difference was due to the presence of ethane which had the highest standard exergy of 1437.2 kJ/mole in addition to the methane content of the gas. The exergy efficiency indicated that auto-thermal reformer (ATR) had an efficiency of 99.71% and 99.6% for gasification and slow pyrolysis respectively. The SOFC from producer gas gasification had an efficiency of 57.59 % with the reformat stream having a mole fraction of 0.3543 and 0.0028 for hydrogen and carbon monoxide respectively whereas producer gas from slow pyrolysis had 72.50% exergy efficiency with mole fractions of 0.5194 of hydrogen and 0.1288 of carbon monoxide in the reformat. The cost analysis indicated that the total annual cost for producer gas from slow pyrolysis configuration was \$190,380.70, which is higher than that of producer gas from gasification configuration by 52.66%. Exergy and economic performance favoured the choice of gasification configuration as the preferred route to produce hydrogen gas for Solid Oxide Fuel Cell configuration. We concluded that fuelling of Solid Oxide Fuel Cell with producer gas from human waste is viable, efficient, and highly economical.

© 2021 The Author(s). Published by Elsevier B.V. on behalf of African Institute of Mathematical Sciences / Next Einstein Initiative.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

* Corresponding author.

E-mail address: kasaka2003@futminna.edu.ng (A.S. Abdulkareem).

Introduction

Hydrogen is a candidate fuel that is gradually replacing the traditional fossil fuel. It is making energy systems more reliable, cleaner, and effective, thereby engendering energy security and environmental sustainability. Hydrogen is generated from partial oxidation, auto-thermal reforming, and steam reforming [2,30]. High reactivity of hydrogen at the electrochemical anode usually triggers the oxidation reaction of hydrogen to yield water as a by-product which is more suitable than carbon dioxide [12]. Hydrogen production, however, has suffered some setbacks. These include energy density, high cost of production, storage, and transportation [19]. Nevertheless, hydrogen for electricity remains the leading energy carrier for future sustainable energy supply thereby motivating the search for pathways for generating hydrogen from readily available sources [19]. The inadequate supply of electricity in Africa, especially the sub-Saharan Africa is compounded by high loss and inefficiency of overly centralized grid system resulting in unaffordable high energy cost in Africa. The per capital of electrical energy consumption in Africa compared to the rest part of the world is not encouraging. The fossil fuel which is the main source of hydrogen for electricity generation is depleting because of the growing demand for energy and the rising challenges posed by ecological solution created from release of greenhouse gases into the environment from burning of fossil fuel has raised significant concern. Results of this research will contribute goal number 7 priority areas number 1 of Africa Union agenda 2063, which focus on environmentally and climate resilient economies and communities, with biodiversity, conservative and sustainable resource management.

Among the hydrocarbon sources, biomass is a natural resource that is readily available for hydrogen gas production and remains the major fuel for fuel cell operation. It is classified as the third energy source after coal and oil. The renewability and neutrality of biomass with respect to carbon dioxide and ease of exploitation could ameliorate the effect of carbon emission and fossil fuel depletion associated with global energy consumption. However, the extent of hydrogen gas from biomass depends on the economic and available technology [3,22]. Utilization of biomass - derived fuel as a source of fuel in a fuel cell technology led to lower cost of operation and availability of fuel cell technology for commercial application [22].

Human faeces have been proven to be a feasible source of energy [11]. Faeces can be converted into energy primarily through thermal and biochemical method [21]. Human faeces, on dry basis, is made up of carbon (27.16%), hydrogen (4.62%), nitrogen (4.91%), oxygen (22.37%) and sulphur (1%) [17].

Thermodynamics is the science of thermal engineering and energy concerned with making the best use of accessible energy resource. It is established on two fundamental laws and principles. The first law provides the concept of an energy (or enthalpy) balance in terms of thermodynamic quantity applied to a system [4] and it is called the conservation of energy principle [7]. The second states that energy has both thermodynamic quality and quantity, with processes occurring in the path of decreased value of energy [7]. The quality of a fuel is a measure of the heating value which is the amount of energy content per unit mass. Heating value is expressed in MJ/kg. It is of two forms for solid fuel; the lower heating value (LHV) and the higher heating value (HHV) [17]. The heating values of the gas obtained from human waste can be calculated based on the combustible content of the gas. However, a report [32] indicated that human faeces, based on the experimental elemental composition, has a heating value of 19.31 MJ/kg.

Energy analysis, on the one hand, is a thermodynamic technique that allows the assessment of heat loss (enthalpy). However, such analysis does not give information about the ideal conversion of energy [4]. Exergy analysis on the other hand, is based on the second law of thermodynamics providing insight into different ways of evaluating and comparing processes and systems with their efficiency yield which is a true measure of how close a real performance approaches the ideal. This analysis gives a clear reason and locations of thermodynamic losses and effect for the established environment in relation to the natural existing environment [14].

Consequently, with exergy analysis, designs can be improved and optimized. Exergy can be transferred to a system via mass, heat, and work [14]. According to Meyer et al. [20], and Lee [16]; exergo-economic methodology is applied in design of energy conversion systems to estimate the cost of the final products and the exergy destroyed within each system component. This information is essential to detect cost-ineffective processes and identify technical options which could improve the cost efficiency of the overall energy conversion system. Solid Oxide Fuel Cell (SOFC) converts energy by transforming fuel in the form of chemical energy into electrical energy with the aid of an oxide ion conductor known as an electrolyte [25]. These cells present a pure technology with little pollution and the ability to electrochemically produce electricity at elevated efficiencies not restricted by the Carnot cycle limit of heat engines [27]. SOFCs have remarkable advantages over conventional energy conversion systems and these advantages include high efficiency, dependability, modularity, fuel flexibility, and exceptionally low-level emission of nitrate and sulphur oxides [27]. Solid oxide fuel cells operate in a silent vibration-free mode which removes the sound associated with conventional power generation systems [15,27].

Galvagno et al. [10] from their simulation model revealed that heat that could be recovered from SOFC unit was 135 kW with a net efficiency of 70%. Abdulkareem et al. [1] showed that the SOFC stacked in methane configuration had better performance with economic and exergetic efficiency. The thermo-economic modelling and parametric study of hybrid solid oxide fuel cell-gas turbine-steam power plants developed by Arsalis [5] indicated that cost was modelled to include procurement, operating, capital and total cost per annum. Producer gases were generated from human faeces through simulation using Aspen plus [23] and experimentally reported [32]. Onabanjo et al. [23] used Aspen Plus to develop a thermo-

dynamic equilibrium of the gasification scheme. The group also investigated the sustainability of human faces involving a non-stoichiometric as a feedstock for gasification process. Results of their findings indicated that human faces are a suitable valuable source of energy recovery. From the various literature reviewed, it is obvious that producer gas has been generated from human faces-derived solid through gasification and slow pyrolysis processes. Though the thermo-economic analysis of the processes has not been carried out by Onabanjo et al. [23], however, gasification process was simulated using data extracted from the work of [23].

This present study focused on the development of model that simulate solid oxide fuel cell fuelled with hydrogen produced from human waste through gasification and slow pyrolysis. The process consisted of gasification, slow pyrolysis plant and a solid oxide fuel cell. Each of the process was simulated individually or collectively. The potential design issues can be identified through the simulation of the model. The works developed by Dincer and Ratlamwala, [8], Querol et al. [24], Vosough et al. [33], Soeno et al. [29], Gundersn (2009) [37] and Lee [16] give the basis for the exergy calculations. [36] carried out the optimization of SOFC fuelled with biogas using a thermodynamic mathematical simulation model in which the effect of hydrogen optimization was ascertained to impact SOFC performance. Galvagno et al. [10] reported analysis of integrated agro-waste gasification and 120 kW solid fuel cell combined heat and power (CHP) system with modelling and experimental investigation. The group used Aspen Plus software to carry out the viability of energy generation from citrus peel air/steam gasification coupled with a 120 kW SOFC unit. Results of their findings revealed that 135 kW of heat could be recovered from the SOFC with net efficiency of 70%. Ay et al. (2006) reported exergetic performance analysis for a proton exchange membrane fuel cell. Influence of operating temperature and pressure on the efficiency and irreversibility's was reported and the results of their findings revealed that exergetic efficiency of proton exchange membrane fuel cell is reduced with increase in the thickness of membrane and current density, while at the same membrane thickness, increase in operating pressure and reduction in current resulted to lowered efficiency.

From the reports reviewed, trade-off between the most efficient and economic route for the generation of Hydrogen from Human waste for SOFC application has not been fully explored and the application of thermo-economic analysis of a SOFC is required for the selection of the best route for generating a rich hydrogen stream from producer gas. However, human faeces as raw material for producer gas – derived hydrogen to produce 200 kW electricity has not been fully investigated. Also, the application of Thermolib software for the selected configurations is yet to be explored in the literature. This current study considered optimizing hydrogen production through auto-thermal reforming of hydrocarbon contents of producer gas from human wastes. The thermo-economic analysis of the SOFC fuelled with the reformat stream was equally carried out. Considering the huge quantity of waste generated by human activities and concept of waste utilization as a viable and efficient alternative resource for green energy production which is the key to the development of a sustainable global energy mix for the future and high cost of production of hydrogen from hydrocarbon source for fuel cell system which hinder the availability of fuel cell at commercial scale. The novelty of this research is therefore on simulation of hydrogen rich gas from human waste as a fuel for solid fuel cell to generate 200 kW of electricity. This was achieved through optimization of hydrogen production by auto-thermal reforming of hydrocarbon contents of producer gas from human waste.

Materials and methodology

The main material used for the simulation work is the producer gas derived from sample of human faeces. Simulation was carried out with the help of Thermodynamic Library software (Thermolib). The adopted producer gases (syngas) were obtained by simulation at 979K [23] and experimentally at 723K [32]. The modified form of the configuration from the work of Suzuki et al. [31] was adopted for simulation process using the SOFC Demo and Reforming process found in the Thermolib 5.4 a. (MATLAB/Simulink's toolbox one-month trial version was downloaded from www.eutech-scientific.de). TableSM1 shows adopted compositions for the simulation while the parameters that were used for simulation and cost analysis are presented in Table SM2.

Simulation and thermo-economic analysis

Description of process

FigureSM1 represents a summary of the entire simulation configuration for this work. Figs. 1 and 2 were obtained from the Thermolib software during simulation of each process. Thermolib model simulation for the gasification and slow pyrolysis configurations comprised of a reforming process coupled with a solid oxide fuel cell, fuelled with a rich hydrogen stream of producer gas from human waste. The producer gas (fuel) was compressed and mixed with steam from a water source and channelled to heat exchanger 1 to raise the temperature and preheat the fuel mixture before being pumped to a reformer operated at 1,173 K. At the reformer, conversion of the hydrocarbons took place yielding a high fraction of hydrogen as fuel and lower carbon monoxide alongside non-combustible element within the reformat gas and the increased CO₂ diluents. The reformat gas was channelled to anode inlet port of SOFC operated at 973 K where the hydrogen gas, carbon monoxide

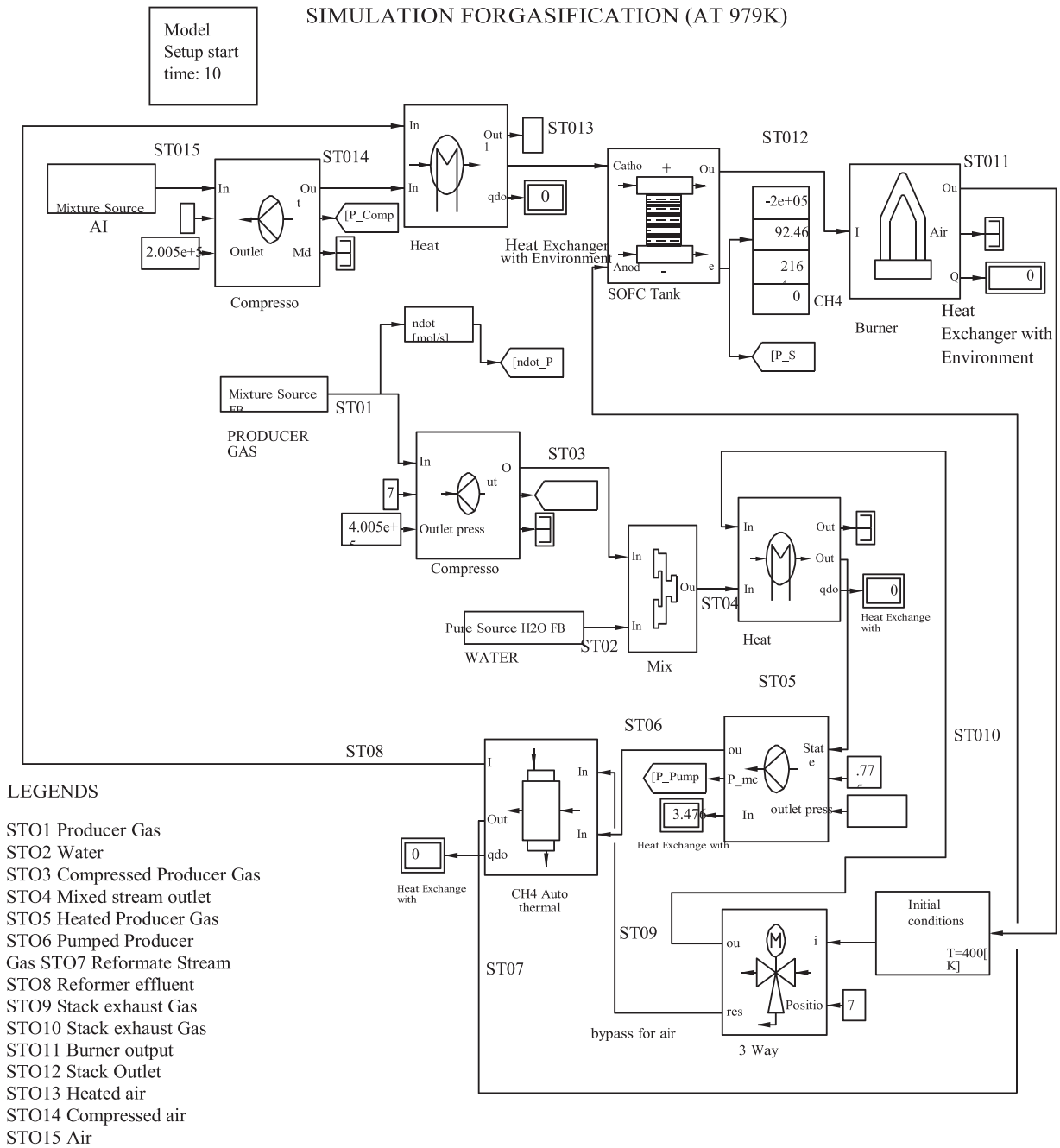


Fig. 1. Configuration for simulated producer gas (Gasification) at 979K.

and trace of methane were oxidized, while the oxygen from air (reduction process) produced is used to yield electricity and water as by products.

However, before the electrochemical process took place, preheated air from heat exchanger 2 comprising of 79% nitrogen and 21% oxygen was fed to the cathode inlet port. Afterwards, both reactions took place in the electrolyte of the stack. Waste heat from the solid oxide fuel cell exhaust stack outlet was recycled back to the system through a three-way valve that split the afterburner exhaust gas stream into two equal parts. These exhaust streams were channelled back to the heat exchangers 1 and 2 where heat was extracted to preheat the air stream supplied to the cathode side of the SOFC and provide additional heat for the mixed feed stream. Various lower heating values of the gases were also calculated based on the combustible gases as adopted from Onabanjo et al. [23] and Tesfayohanes et al. [32].

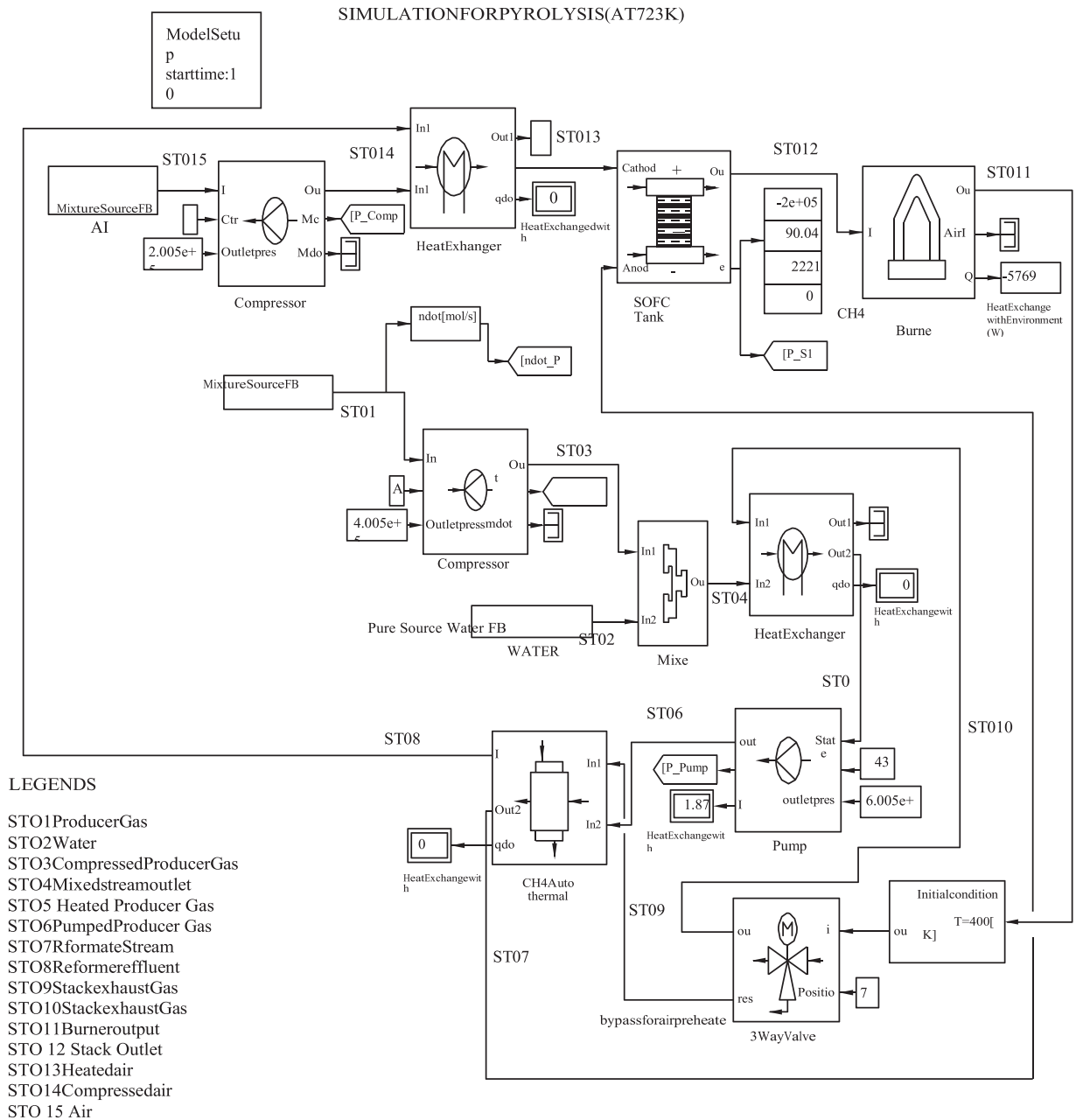


Fig. 2. Configuration for simulated producer gas (slow pyrolysis) at 723K.

Exergy calculation

The following assumptions were relied upon to obtain these model equations:

1. The potential and kinetic exergies were considered negligible; this is because the effect of kinetic and potential exergy is insignificant to the result (i.e. No moving part)
2. The reaction process was adiabatic.
3. Air source mixture comprised 79 % nitrogen and 21% oxygen; because the air is filtered, and other composition of air are insignificant.
4. Simulation was carried out on a steady state basis; the software is incapable of dynamic system because a trial version was installed.
5. All gases were assumed to have ideal gas behaviour to simplify the simulation.

6. No leakage of gas as this could reduce the pressure significantly in reality.
7. The lower heating value (LHV) of the producer gas was calculated and used based on the combustible gases.
8. The reaction was free of char and tar.
9. These assumptions were made to simplify the simulation and get results that are close to reality.

The following equations were used for the calculation of exergy:

For a system, the physical exergy is given by the relationship presented in Eq. 1 (Suleiman et al., 2016):

$$b_{phy} = c_p \left[(T - T_o) - T_o \ln \left(\frac{T}{T_o} \right) \right] + RT_o \ln \left(\frac{P}{P_o} \right) \quad (1)$$

The basic exergy expression for a steady flow stream is presented in Eq. 2 (Suleiman et al., 2016):

$$\varepsilon(T, p, x) = [H(T, p) - H_o(T_o, p^\circ)] - T_o [S(T, p) - S_o(T_o, p^\circ)] \quad (2)$$

The environmental parameters were assumed as:

$p^\circ = 101.325$ kPa and $T_o = 298.15$ K. The exergy of a stream (specified temperature T , pressure p , and composition x) (Suleiman et al., 2016):

For a mixture, the chemical exergy is represented by Eq. 3.

$$b_{ch} = \sum_{i=1}^n x_i b_{ch, i} \quad (3)$$

While the exergy efficiency (ψ) calculation is represented by Eq. 4:

$$\psi = \frac{\text{Exergy in product}}{\text{Total exergy input}} \quad (4)$$

Cost analysis

To carry out the thermo-economic analysis of the adopted designs to be used for the configurations, the cost components must be expressed to include:

- Procurement cost for all components.
- Capital cost per annum.
- Operating cost per annum; and
- Total cost per annum [5].

The component of cost model is presented in Table SM3

Where the efficiency correction factor is given as

$$f(\eta) = 1 + \left(1 - \frac{0.8}{1} - \eta(\text{pump}) \right) \quad (5)$$

Result and discussion

This paper covers the thermodynamic and economic analysis of a solid oxide fuel cell that is fuelled with hydrogen carbon monoxide. These were generated from producer gas obtained from human faeces via simulation of gasification and slow pyrolysis process routes configurations. The parameters considered included the physical and chemical exergy, the lost exergy (work), energy flow and the economic performance of the fuel cell. The paper sought to simulate two configurations representing the two routes using Thermolib software. This involved generation of more hydrogen from the gases via auto-thermal reforming to target 200 kW worth of electricity with the aid of a SOFC. Gasification route targeted at generating producer gas in the presence of a gasifying agent (oxygen enriched air) was compared to the performance of the producer gas trapped as a gaseous product from slow pyrolysis even though slow pyrolysis is known to produce more char. Therefore, from the data obtained, thermo-economic analysis of both configurations was carried out to ascertain which of the processes was economical. The thermodynamics was also calculated to find out the energy and exergy value for both configurations. The obtained simulated results on the energy and exergy analysis for the producer gas are presented in Tables 1 and 2 respectively.

From Tables 1 and 2, the energy analysis for both simulations indicated that the energy flows (in terms of enthalpy) from the equipment were negative except for streams through which compressed air flowed in, having their energy flow as positive. The negative values indicated that the equipment in which the reactions took place lost energy to the environment. This implies that the reactants energy was higher than that of the product which resulted to an exothermic reaction. There was an exception from the SOFC and compressor 1 where the output energy was higher. For the positive values, endothermic reaction took place with energy gained into the system. Thus, with increased output energy flow for an exothermic reaction, energy was produced and required for a decreased output energy flow.

Table 1

Energy analysis for producer gas (gasification at 979 K).

Equipment	Energy ratein (kW)	Energy rateout (kW)	Energy rate Absorbed (kW)	Energy rateproduced (kW)
Compressor1	-92.01	-463.74	-	-371.73
Mixer	-923.66	-923.66	-	-
Heat Exchanger1	-1073.71	-734.16	339.55	-
Pump	-734.16	-197.31	536.85	-
ATR	-297.34	-297.13	0.21	-
SOFC	-48.14	-248.15	-	-200.01
Lambda burner	-248.15	-249.39	-	-1.24
3 Way valve	-250.08	-250.08	-	-
Heat Exchanger2	-89.41	148.96	238.37	-
CompressorTotal	12.03	10.62	-1,114.98	-1.41

Table 2

Exergy analysis for producer gas (Slow pyrolysis at 723 K).

Equipment	Energy ratein (kW)	Energy rateout (kW)	Energy rate Absorbed (kW)	Energy rateproduced (kW)
Compressor1	-131.88	-674.11	-	-542.23
Mixer	-1070.66	-1070.66	-	-
Heat Exchanger1	-1295.34	-998.10	297.25	-
Pump	-998.10	-212.70	785.40	-
ATR	-276.08	-275.97	0.11	-
SOFC	-82.12	-282.14	-	-200.02
Lambda burner	-282.14	-287.91	-	-5.77
3 Way valve	-288.05	-288.05	-	-
Heat Exchanger2	-11.58	11.40	22.98	-
CompressorTotal	72.90	68.23	-1,105.74	-4.67

The results also indicated that among the equipment, both pumps required high energy of 536.85 and 785.40kW respectively while that of slow pyrolysis is higher and followed by heat exchanger. The conservation of energy of the procedure involved in the heat exchanger states that the energy detached from the gas line must be equal to that absorbed by the airline [3]. Thus, from the results, the heat exchangers 1 of gasification and slow pyrolysis configuration required additional heat of 339.55 and 297.25 kW respectively. Furthermore, energy required for heat exchanger 1 to preheat the feed composition to raise its temperature was higher compared to heat exchanger 2 used for preheating air alone. ATR energy flow indicated that the reformers needed negligible amount of energy of 0.21 and 0.11 kW as shown in the tables, which are attested to by the slight increase in molar output flow rate of the streams compared to what was reported by Skerbergene [28] that ATR does not require additional heat (energy). However, compressor1 used for the feed compression for both simulations produced a higher energy with that of pyrolysis of producer gas having the higher value of 542.23 kW because of the presence of heavier hydrocarbon content (C_2H_6) whose compression yielded more energy. The compressor energy input represents the power required to compress the feed and air up to the desired level before entering the next equipment [28]. The lambda burner was required for the conversion of the chemical energy of the unreacted moles of fuel in the stack to generate more thermal energy [3] of 1.24 and 5.77 kW respectively.

Hence, based on the energy balance, the energy requirement for the two configurations were 1,114.98 and 1,105.74 kW for PG gasification and PG slow pyrolysis respectively while the energy produced by the fuels were 574.39 and 752.69 kW respectively, thus, making the PG gasification the most energy requiring process and PG slow pyrolysis the most energy producing process with four equipment generating energy to both configurations namely; compressor1, SOFC, lambda burner and compressor (air). Table SM4 gives the overall energy efficiency for the two configurations.

From Table SM4, the overall energy efficiency presented was obtained as part of data from the software but can be calculated using Eq. (4). The result indicated that the producer gas (gasification) showed a better energy efficiency of 82.2 % due to the producer gas lower heating value (LHV) content of 113,141.4 J/mole for a 200kW power output generation having methane as its only hydrocarbon content (a hydrocarbon with a single carbon) that efficiently combusted as fuel. For slow pyrolysis however, the energy efficiency was low due to its lower heating value of 466,372.52 J/mole which was four times higher than that of producer gas from gasification. The former process had more capacity and fuel quality for generating more power output higher than 200 kW which was the targeted power generation for the simulation. When the producer gas from slow pyrolysis was combusted, more heat was generated due to the presence of a heavier hydrocarbon ethane with high standard chemical exergy value because of the two carbon atoms in its gas composition. This is in addition to the methane content simulated to generate the same 200 kW power output. From the simulated result, it can be deduced that the generation of hydrogen from hydrocarbons at high temperature of above 1000 K and pressure of 6 bars had a negative impact on the thermal efficiency though with higher yield of hydrogen for the set power output.

Exergy analysis

Presented in Tables SM5 and SM6 are the simulated exergy analysis for the producer gas generated through gasification and slow pyrolysis respectively.

From Table SM5, the exergy result indicated that the following equipment had high exergies coming into them. The heat exchanger 1 had the highest as 1,405.42 kW, followed by the pump and mixer which had the exergies of 1,348.26 and 1,238.77 kW respectively. The compressor for air had the least value of 25.66 kW, the heat exchanger 1 had the highest exergy input of 3,051.58 kW, mixer 2,591.15 kW and pump 2,650.44 kW respectively. Also, the air compressor had the least exergy of 55.04 kW because the compressor stream had only air as its content with a high physical exergy. The high exergies showed that the irreversibility of the equipment came along with the corresponding high entropy due to the mixing of reactants, temperature difference, chemical reaction, and fluid friction in the equipment [7]. For the heat exchanger1, the obtained exergy was from the high chemical exergy coming into the equipment and the lost exergy between the hot and the cold fluid streams. The heat exchangers can transfer energy but not exergy. Therefore, the higher the temperature and the exergy value of the hydrocarbon content of a stream, the higher its corresponding total exergy value obtainable [34]. Furthermore, the high exergy lost in the heat exchanger agrees with the theoretical statement that in thermodynamics, majority of the exergy loss are found in this type of equipment [13,26].

For the SOFC of both configurations, it can be observed that the PG gasification had an exergy inlet of 502.05 kW and an output of 289.15 kW with 212.90 kW lost while that of slow pyrolysis had an input exergy of 807.24 kW and an output of 585.23 kW with a higher exergy destroyed of 222.01 kW. This is an indication of lost exergy due to the irreversibility of the electrochemical reaction taking place at the electrolyte and heat loss in the solid oxide fuel cell stack [16]. The ATR from the simulated result indicated that there was less exergy lost basically due to the slight increase in the flow rate of the reformat stream having high hydrogen converted and significantly simulated temperature range of an output expected of an ATR reformer as reported in the literature [18].

For the compressor 1, PG (gasification) and PG (slow pyrolysis) had the exergy output value of 1,199.77 kW and 2,509.48 kW respectively higher than the incoming exergy values of 238.00 kW and 490.81 kW respectively. This is because of the increase in the molar flow rate of the output stream with higher chemical exergy. The three-way valve, also known as a splitter, that has the function of splitting the stack exhaust stream into two equal halves for recycling back into the system, for both processes indicated that there was negligible difference between the total exergy in and total exergy out. Also, both chemical exergies were approximately equal, indicating that there was no reaction taking place in the equipment. This is not the case for the mixer, as there was a mixing reaction taking place.

For the lambda burner, it was observed that due to its function required in the conversion of unreacted fuel to yield more thermal energy there was a slight decrease in the chemical exergy of the input stream to the output stream. Thus, for the exergy analysis, the PG gasification configuration had a total exergy input of 5,992.14 kW and output exergy of 5,698.44 kW respectively. The PG slow pyrolysis had a total exergy input of 11,848.85 kW and 11,160.92 kW total exergy output. Therefore, the high standard exergy for methane and ethane accounted for the high chemical exergy of the system attributed to the mole fractions of these hydrocarbon contents of the streams.

The lost work analysis (Tables SM7 and SM8) showed that the highest irreversibility occurred in compressor1 due to the increased molar flow rate of the output stream. This resulted in lower efficiencies in both configurations and when compared to the efficiency of other equipment.

The efficiencies of the SOFC simulated were higher than those reported by Zhang, [35] which was in a range of 45-55 % and the power output of 200 kW. The simulated SOFC indicated that the equipment was independent of size as they were both operated at different areas but the same temperature [35]. Also, from the reformat stream fed to the anode side of the SOFC, it was observed from the gas composition that PG gasification had the mole % of 0.28 for CO and 35.43% of H₂ with an efficiency of 57.20% compared to that of slow pyrolysis having the mole % of 12.88 of CO and 51.94 % of H₂ with an efficiency of 72.50 %. This proved the fact that CO is also a fuel for SOFC. The ATR, mixer and lambda burner had negligible losses while the three-way valve had no loss at all. The listed equipment had high efficiencies of 99.71, 99.48, 99.31 and 100 % respectively for gasification configuration and 99.64, 99.17, 98.40 and 99.93 % respectively for slow pyrolysis configuration. Furthermore, the exergetic performance indicated that the efficiency of the heat exchanger 1 for gasification configuration had a higher efficiency of 95.95% compared to that of slow pyrolysis with 86.23%.

From Table SM9, it can be noted that five equipment had an improvement as compared to exergetic performance of the equipment that made up the configuration of the work of Emordi et al. [9] while others had exergetic efficiency less than that in the previous work.

Gas composition

Tables SM10 and SM11 present mole % for the feed composition and reformat from ATR for both configurations.

From Tables SM10 and SM11, the PG from the pyrolysis had hydrogen increase of 38.14 mole % in addition to the existing hydrogen that came in with the feed giving a total of 51.94 mole % of hydrogen generated via reforming. This was due to the ethane content of the gas - an additional hydrocarbon. That of gasification was 16.03 mole % of hydrogen, making a total of 35.43 mole % of hydrogen.

Furthermore, the inlet temperature at which each stream came into the ATR despite both being operated at 1,173K, indicated that the higher the inlet temperature, the higher the hydrogen yield (Hagh, 2004). Also, the optimum hydrogen was observed at the ATR operated temperature of 1,173 K for both configurations after which it remained constant which was in close range to 1,100 K reactor's temperature [6]. It was therefore noted that the ATR reaction space (area) was independent of the conversion, temperature, and pressure. The inlet stream temperature of the ATR for the two configurations were as follows: PG (gasification) 1,075.65 and 1,288.97 K while that of pyrolysis was 1,454.42 and 1,666.12 K respectively.

Meanwhile it can be observed that at these temperature ranges, the hydrocarbon content of the feeds reduced drastically along with the CO content of the producer gas as seen in the reformat stream. The reformat stream of the gasification (producer gas) had the least of CO content of 0.28 moles % and that of the pyrolysis had 12.88 moles % respectively. This represented an increase yield of carbon-dioxide in both configurations. Thus, the contribution of carbon monoxide to the electricity generation in SOFC stack was of low significance in PG gasification configuration compared to that of PG pyrolysis configuration. This is because the available carbon monoxide had been consumed to yield more hydrogen gas in the water gas reaction that occurred alongside other reactions in the ATR [36]. This is evidently seen in the exergetic efficiency of the stacks.

Therefore, the overall exergetic performance (Table SM12) indicated that the producer gas from gasification had a better irreversibility (useful work) for 200 kW power generation. Both energy and exergetic efficiencies also indicated that the PG gasification configuration had a higher efficiency. This was attributed to the size of the solid oxide fuel cell used for the simulation [5].

Cost estimation

Table SM 13 and SM14 list out the cost component for the two-producer gas configuration, while Table SM13 shows the total cost analysis of the two configurations. From the result (Table SM15), the PG slow pyrolysis had the highest equipment, operating and corresponding total annual cost of \$235,334, \$162,658.70, and \$190,380.70 compared to PG gasification configuration that cost \$219,347, \$98,866.13, and \$124,706.13 respectively. This makes the reforming process of slow pyrolysis more expensive. Furthermore, considering the size of the SOFC stacks employed for the various configurations and the equipment cost, the PG gasification with a larger area had a higher cost price. With respect to the size of SOFC, the configurations equipped with a smaller SOFC had a total cost lower than those with the larger SOFC as expected. Considering complexity of these costs in Naira worth, the profitability analysis was carried out on dollar basis.

Profitability analysis

Presented in Table SM16 is the result of profitability analysis of the two configurations. Although, the results as presented indicated that the two proposed configurations are viable to produce hydrogen rich gas from human waste as a fuel for SOFC, the cost of configuration of slow pyrolysis is higher than that of the gasification configuration. The rate of return which determine how well a project, investment or capital expenditure perform with respect to time was also simulated for these configurations. Results obtained (Table SM1), indicated that the rate of return on gasification and slow pyrolysis configurations are viable for production of hydrogen rich gas from human waste. However, the cost of slow pyrolysis configuration is higher than that of the gasification configuration.

Conclusions

In this work, two configurations namely, gasification and slow pyrolysis routes were selected and simulated with a Thermolib software to obtain values which were used for the calculations of the thermo-economic analysis. This was to ascertain the energy and exergy efficiencies of both configurations as well as the cost analysis, resulting in the following deduction:

1. Based on the results obtained from energy analysis, the higher the volume of the heavier hydrocarbon content of a producer gas, the more the energy needed to compress the feed. Also, the higher the hydrocarbon content, the lower the heating value obtained. This implies that such producer gas can generate more electricity when combusted as observed with the energy analysis of the PG slow pyrolysis where the thermal efficiency was low considering set power output of 200 kW. The energy analysis for the configuration routes also indicated that gasification required more energy while slow pyrolysis produced more energy. Producer gas (gasification) configuration provided a better thermal efficiency of 82.2 %.
2. From the exergy analysis point of view, the choice of reformer (ATR) to achieve the set objective of hydrogen generation worked out with both efficiencies of 99.7092 % and 99.645% for gasification and slow pyrolysis respectively. The SOFC exergy efficiencies were 57.20% for gasification and 75.50% respectively. The overall exergetic efficiency also indicated that PG gasification had a better irreversibility occurrence in the process.
3. The economic analysis indicates that the configuration of PG slow pyrolysis had the higher cost estimated for its equipment, operating and total cost when compared to that of PG gasification. This makes the configuration more expensive. In terms of the profitability analysis, both criteria used indicated that both configurations were viable options. This is because if payback period is considered, project investors consider five years to be an acceptable period.

Funding Statement

This research did not receive any grant from funding agency (Eq. 5).

Declaration of Competing Interest

None.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2021.e01024.

References

- [1] A.S. Abdulkareem, S. Bilyaminu, A.S. Afolabi, K.C. Yenkw, Exergy and economic analyses of hybrid solid oxide fuel cell by computer simulation, in: Proceedings of the World Congress on Engineering, II, 2015, pp. 785–790. http://www.iaeng.org/publication/WCE2015/WCE2015_pp785-790.pdf. Retrieved from.
- [2] Y.O. Abdulsalam, A.S. Abdulkareem, H. Uthman, A.E. Afolabi, G.A. Olugbenga, Thermo-Economic Analysis of PEM fuel cell fuelled with Biomethane obtained from Human Waste by computer simulation (2020) 2276-2468/© 2020 Published by Elsevier, doi:10.1016/j.sciaf.2020.e00485.
- [3] G.A. Abuadala, Investigation of sustainable hydrogen production from steam biomass gasification, Canada 27 (42) (2010) 1–3, 64-75. Retrieved from <https://ir.library.utoronto.ca/bitstream/1807/101177/0957650917693483>.
- [4] S.R. Allent, G.P. Hammond, R.C. McKenna, The thermodynamic implications of electricity end use for heat and power, Proc. Inst. Mech. Eng. Part A 231 (6) (2017) 508–525 <http://doi.org/10.1177/0957650917693483>.
- [5] A. Arsalis, Thermo-Economic Modelling and Parametric Study of Hybrid Solid Oxide Fuel Cell-Gas Turbine-Steam Turbine Power Plants ranging from 1.5MWe to 10MWe A Thesis, Virginia, 78-80, 2007, pp. 123–127.
- [6] Dey, M., Mann, B., Anshu, A. & Mannan, M. (2014). Activation of protein kinase PKR requires dimerization-induced cis-phosphorylation within the activation loop. DOI:<https://doi.org/10.1074/jbc.M113.527796>
- [7] I. Dincer, Y.A. Cengel, Energy, entropy and exergy concepts and their role in thermal engineering, Entropy 3 (3) (2001) 116–149 10.33901e3030116.
- [8] I. Dincer, T.A.H. Ratlamwala, Importance of exergy for analysis, improvement, design and assessment, Wires Energy Environ 2 (2013) 335–338, doi:10.1002/wene.63.
- [9] C.O. Emordi, A.S. Abdulkareem, O.S. Azeze, S. Afolabi, Exergy and energy analysis of solid oxide fuel cell fuelled using methanol, propane and butane, IOP Conf. Series 173 (2018) 1–15 10/1088/1755-1315/173/1/012010.
- [10] A. Galvagno, M. Prestipino, G. Zafarana, V. Chiodo, 71st Conference of the Italian Thermal Machines Engineering Association, Energy Procedia 101 (2016) 528–535.
- [11] D.P. Hanak, J.K. Athanasios, O. Tosin, T.W. Stuart, P. Kunar, F. Beatriz, M. Vasilije, M. Ewan, P. Alison, W. Leon, T. Sean, C. Elise, Conceptual energy and water recovery system for self-sustained nano membrane toilet, Energy Convers. Manag. 126 (2016) 352–361, doi:10.1016/j.enconma.2016.07.083.
- [12] S. Hussain, in: A Numerical Evaluation of the Design of an Auto thermal Reformer for the On-board Production of Hydrogen from Iso-octane, Department of Mechanical and Materials Engineering, Queen's University Canada, 2009, pp. 3–8.
- [13] M. Juan, L. Montelongo, A.Y. Brent, Y.S. William, An Open Source Exergy Calculator tool, Chem. Asia Pac. J. Chem Eng. 2 (2009) 431–437 Retrieved from <https://onlinelibrary.wiley.com/doi/abs/10.1002/ce.1001>.
- [14] M. Kanoglu, Y.A. Cengel, I. Dincer, in: Efficiency Evaluation of Exergy Systems, 9, Springer, 2012, p. 24, doi:10.1007/978-1-4614-2242-6-2. Briefs in Energy.
- [15] N. Laosiripojana, W. Wiyaratn, W. Kiatkittipong, A. Arpornwichanop, A. Soothitawat, S. Assabunrungrat, Reviews on solid fuel cell technology, Eng. J. 13 (2009) 65–81, doi:10.4186/ej.2009.13.65.
- [16] Y.D. Lee, Thermodynamic, Economic and Environmental Evaluation of Solid Oxide Fuel Cell Hybrid Power –Generation Systems 26 (2015) 81 Retrieved from <http://www.semanticscholars.org/>.
- [17] N. Loveldi, Development of a Solid Human Waste Semi Gasifier Burner for use in Developing Countries MSc. Thesis, University of Colorado, 2014.
- [18] V.H. Manacas, H.A. Matos, S. Spatenka, Advanced Steady-State Modelling and Optimization of Natural Gas Reforming Reactors (2013) United Kingdom 3. Retrieved from http://www.fenix.tecnico.ulisboa.pt/downloadfile/.../Extended_Abstract.pdf.
- [19] H. McKinnon, Improved Hydrogen Production from Biomass Gasification in a Dual Fluidized Bed Reactor M.Sc Thesis, Improved Hydrogen Production from Biomass Gasification in a Dual Fluidized Bed Reactor, 4, University of Canterbury, 2006.
- [20] L. Meyer, R. Castillo, J. Buchgeister, G. Tsatsaronis, Application of exergo-economic and exergo-environmental analysis to an SOFC system with an auto thermal biomass gasifier. Berlin, Int. J. Thermodyn. 12 (4) (2009) 177–186 www.icatweb.org/journal.htm. published in the ECOS08 proceedings.
- [21] J.D. Mori, Faeces Conversion Processes submitted as coursework for PH240 Standard University (2011) Retrieved from <http://large.stanford.edu/courses/2011/ph240/demori2/>.
- [22] G. Nahar, V. Dupont, Recent Advances in hydrogen production via auto-thermal reforming process (ATR). A review of patents and research articles, Recent Patents Chem. Eng. 6 (1) (2012) 8–421, doi:10.2174/2211334711306010003.
- [23] T. Onabanjo, K. Patchigolla, S.T. Wagland, B. Fidalgo, A. Kolios, P.A. McAdam, L. Williams, S. Tyrrel, E. Cartmell, Energy recovery from human faeces via gasification: a thermodynamic equilibrium modelling approach, Energy Convers. Manag. 118 (2016) 364–376, doi:10.1016/j.enconman.2016.04.005.
- [24] E. Querol, B. Gonzalez – Regueral, J.L. Perez – Benedilo, Practical approach to exergy and thermo-economic analyses of industrial processes, in: Springer Brief in Energy. XIV, 84, 2013, p. 19, doi:10.1007/978-1-4471-4622-3-2. <http://www.springer.com/978-1-4471-4621-6>. Retrieved from.
- [25] F.M. Ramadhani, A. Hussain, H. Mokhlis, S. Hajimolana, Optimization strategies of solid oxide fuel cell (SOFC) application, Renew. Sustain. Energy Rev. 76 (2017) 460–484, doi:10.1016/j.rser.2014.03.052.
- [26] A.B. Rian, W.S. Ertesvag, Exergy analysis of a steam production and distribution system including alternatives to throttling and single pressure steam production. Norway, Energy Convers. Manag. 52 (2010) 703–712, doi:10.1016/j.enconman.2010.07.049.
- [27] S.C. Singhal, Solid Oxide Fuel Cells, the Electrochemical Society Interface (2007) 41–42 Retrieved from <http://www.Electrochem.org/dl/interface/wr/07/wtr071....>
- [28] K. Skerbergene, in: New Technologies for the Purification and Carbon Capture in Hydrogen Production from Natural Gas, Norwegian University of Science and Technology, 2015, pp. 10–12.
- [29] Y. Soeno, H. Tsulno, K. Siratori, K. Halada, Exergy analysis to evaluate integrated environmental impacts. Special issue on growth of eco-materials as a key to eco-society, Jpn. Inst. Metals 44 (7) (2013) 1244–1250 Materials Transactions.
- [30] B. Suleiman, A.S. Abdulkareem, U. Musa, I.A. Mohammed, M.A. Olutoye, V.I. Abdullahi, Thermo-economic analysis of proton exchange membrane fuel cell, Energy Convers. Manag. 117 (2016) 228–244, doi:10.1016/j.enconman-2016.03.033.
- [31] T. Suzuki, K. Miyamoto, S. Kobayashi, N. Aratani, T. Yogo, R and D on hydrogen production by auto-thermal reforming, Petrol. Energy Centre (2002) 2. Retrieved from <http://www.pecj.or.jp/japanese/report/e-report/02sin23e.pdf>.

- [32] W. Tesfayohanes, R.F. Yacob, G.L. Karl, W.W. Alan, Pyrolysis of human faeces: gas yield analysis and kinetic modelling, *Waste Manag.* 79 (2018) 214–222, doi:[10.1016/j.wasman.2018.07.020](https://doi.org/10.1016/j.wasman.2018.07.020).
- [33] A. Vosough, N. Aminreza, G. Mohammed, Y. Sadagh, Exergy concept and its characteristic, *Int. J. Multidiscip. Sci. Eng.* 2 (4) (2011) 49–51 ISSN: 2045-7057. Retrieved from www.ijmse.org.
- [34] G. Wall, M. Gong, Exergy analysis versus pinch technology, in: *Proceedings of the Efficiency, Costs, Optimization, Simulation and Environmental Aspects of Energy Systems*, 451, Stockholm, Sweden, 2009, p. 455. www.exergy.se/ftp/exergetics.pdf.
- [35] W. Zhang, *Simulation of Solid Oxide Fuel Cell-Based Power Generation Processes with CO2 Capture 12 (2006) 49 Thesis*.
- [36] G.N. Prodrondis, F.A. Coutelieres, *Exergetic Optimization on Solid Oxide Fuel Cell Systems*, World Academy of Science, Engineering and Technology (2016).
- [37] Gundersen, T, *Introduction to Concept of Exergy and Energy Quality*. Energy and Process Engineering. Norway. 3. Retrieved from <https://www.semanticscholar.org/>.