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A Hybrid Biomass Hydrothermal Gasification- Solid Oxide Fuel Cell System Combined with Improved CHP Plant for Sustainable Power Generation

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Abstract

The most popular technique, so far, for biomass waste to energy conversion has been incineration, but this technique has raised a lot of objection among nature activists due to the release of particulate matter and pollutants like nitrogen oxides (NOx) into the atmosphere. However, advanced non-incineration conversion methods like pyrolysis, thermal gasification, and plasma-arc gasification are providing ways of generating energy from waste that avoid many of the pollution concerns around incineration, and may provide better economics for waste-to-energy as well. This paper describes a combined hydrothermal gasification of biomass in sub or supercritical water, integrated with a solid oxide fuel cell which can be fuelled with both constituents of the syngas (Carbon monoxide and hydrogen). Full analysis of the hybrid cycle and expected improvements in efficiency are presented, together with elaborate discussion of the technological and strategic pros and cons.

Peer-review under responsibility of the organizing committee of the international conference on Sustainable Solutions for Energy and Environment 2016

*Keywords:*nitrogen oxides (NOx);biomass hydrothermal gasification; Municipal Solid Waste (MSW); Supercritical water (SCW) gasification; Syngas

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1. Introduction

Demand for energy is increasing at an unprecedented rate due to increasing human population, emerging industries and rising standards of living. At the same time, resources of fossil fuels are becoming more expensive and finite, nuclear sources are becoming less secure and concerns over harmful emissions and greenhouse gases are mounting, which motivate the search for more sustainable and environment friendly energy sources.

Nomenclature

SCW	Supercritical water gasification
CHP	Combined Heat and Power Cycle
SOFC	Solid Oxide Fuel Cell
BHG	Biomass Hydrothermal Gasification
MGT	Micro Gas Turbine

Hydrogen as a clean fuel has been considered significantly in recent years. However, hydrogen can be produced from either fossil fuels or renewable resources. Current hydrogen production methods are producing greenhouse gases as much as fossil fuel systems do. Thus, to consider hydrogen as a clean energy resource, it is essential that hydrogen be supplied from carbon neutral sources [1]. In order to address these issues, new approaches in the utilization of energy sources should be adopted.

One important source of energy is biomass, which has the potential to provide 14% of the world's energy needs and at the same time, reduce the increase of carbon dioxide in the atmosphere[2][3], this way addressing three sets of environmental issues at one stroke: providing a valuable and sustainable source of energy, reducing land use and pollution from landfills, and mitigating the well-known environmental jeopardy of fossil fuels. Climatic conventions such as (Kyoto, Buenos Aires and Paris) and the European Union's white paper demand a substantial increase in the use of biomass, which can be achieved only if new applications for the use of biomass, such as electric power generation from biomass, are developed[4].

As far as bio-waste is concerned, the most popular technique, so far, for waste to energy conversion has been incineration, but this technique has raised a lot of objections among nature activists due to the release of particulate matter and pollutants like nitrogen oxides (NO_x) into the atmosphere. However, advanced non-incineration conversion methods like pyrolysis, thermal gasification, and plasma-arc gasification are providing ways of generating energy from waste that avoid many of the pollution concerns around incineration, and may provide better economics for waste-to-energy as well[5]. Furthermore, Waste-to-energy systems could provide a more sustainable solution if waste-to-energy systems, like thermal gasification-based waste conversion plants,were fitted with direct Hydrogen/Syngas generation, hence enabling other clean technologies like fuel cells, which have the capability of operating using hydrogen or carbon monoxide as the input fuel. Between all types of fuel calls, solid oxide fuel cells (SOFC) are more promising; due to their high working temperature range (800–1000 °C), type of electrolyte (ceramic), and compatibility with different types of fuels. Another advantage of the SOFC is the fact that its efficiency rises when pressurized under high temperatures, which also enables them to be used as a heat source for a gas turbine[1].

It is observed that research and development efforts are moving towards efficient and sustainable small scale Combined Heat and Power (CHP) systems incorporating biomass gasification, SOFCs and MGTs, although, small scale CHP plants present lower electrical efficiency in comparison to large scale ones, particularly when biomass fuels are used[6]. Research shows that the gasification/SOFC cycle has a higher efficiency than the gasification/MGT system. Also it was concluded that 50% efficiency is achievable from gasification/SOFC/MGT hybrid cycle [7] .

In this work a combined hydrothermal gasification of biomass in sub or supercritical water, integrated with a gas turbine and a high temperature solid oxide fuel cell, which can be fueled with both constituents of the syngas (Carbon monoxide and hydrogen) is described. This configuration offers a viable power supply solution for medium sized communities at urban and suburban locations.

The electrical output of the fuel cell is utilized directly through the electrical grid, while the thermal output of the fuel cell is used in a Combined Heat and Power (CHP) cycle to produce more electrical energy in a gas turbine driving a generator. So as to improve the efficiency of the gas turbine, excess heat in the system is also used to drive an absorption cycle to provide pre-cooling for the working fluid in the gas turbine, hence improving the efficiency of the GT. Excess heat can be used further in the hydrothermal gasification process, which is carried out at a relatively low temperature (about 400 °C) and occurs more rapidly when compared to the fermentation processes[8]. Furthermore, hydrothermal gasification is carried out in supercritical fluid water, in other words, liquid water under pressure at temperatures much higher than the evaporation temperature. This enables processing of wet biomass without the necessity for a drying process, as water is required in the process as a gasification agent and solvent, while the conventional thermal gasification demands dry biomass in the process which leads to excessive energy being consumed in the process for drying wet biomass[9][10]. This process is therefore more suitable for bio-wastes with high water content, such as food wastes and animal dungs, than the conventional thermal gasification process that requires additional energy to overcome the latent heat of water[11].

This paper presents a description of the concept with basic analysis of the hybrid cycle. Justifications of anticipated improvements in efficiency are presented, together with a brief discussion of the technological and strategic pros and cons.

2. Products of biomass gasification

Gasification is a thermo-chemical process taking place at high temperatures typically >700°C to convert carbonaceous materials including biomass, fossil fuels, plastics, and coal into syngas, which is a mixture of H_2,CH_4, CO, and CO_2. A limited amount of oxygen and/or steam is used as the gasifying agent and as a heat carrier agent.

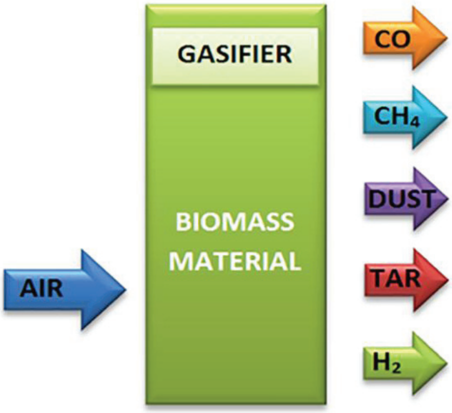

Fig. 1. Schematic of the products of a gasification plant

The reaction taking place in the gasifier can be summarized as indicated below:

Partial oxidation:

$$C + 1/2\ O_2 \longleftrightarrow CO \qquad dH = -268 MJ/kg\ mol$$

Complete oxidation:

$$C + O_2 \longleftrightarrow CO2 \qquad dH = -406 MJ/kg\ mol$$

Water gas phase reaction:

$$C + H_2O \longleftrightarrow CO + H_2 \qquad dH = 118 MJ/kg\ mol$$

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$$C + CO_2 \longleftrightarrow 2CO \qquad dH = 170.7 MJ/kg\ mol$$

The heats of reaction for the three processes show that the greatest energy release is derived from the complete oxidation of carbon to carbon dioxide, i.e. combustion, while the partial oxidation of carbon monoxide accounts for only about 65% of the energy released during complete oxidation. Unlike combustion that produces only a hot gas product, carbon monoxide, hydrogen and steam can undergo further reactions during gasification as follows:

Water gas shift reaction:

$$CO + H_2O \longleftrightarrow CO_2 + H_2 \qquad dH = -42\ MJ/Kg\ mol$$

Methane formation:

$$CO + 3H_2 \longleftrightarrow CH_4 + H_2O \qquad dH = -88 MJ/kg\ mol$$

The arrows indicate that the reactions are in equilibrium and can proceed in either direction, depending on the temperature, pressure and concentration of the reaction species. It follows that the product gas from gasification consists of a mixture of carbon monoxide, carbon dioxide, hydrogen and water vapour.

In general, the overall Steam reforming reaction of any oxygenated organic compound can be presented as follows:

$$CH_xO_y + (1-y)H_20 \longrightarrow CO + (1-y+x/2)\ H_2$$

It can be derived from the steam reforming reaction above that the maximum (stoichiometric) yield of hydrogen is
(1-y+x/2) moles per mole of carbon in feed.

Energy from biomass has many advantages; it provides a valuable and sustainable source of energy, reduces land use and pollution from landfills and mitigates the well-known environmental jeopardy of fossil fuels. Nonetheless, based on the current situation, it can be noticed that the efficiency of current gasification processes is low, which renders biomass gasification economically unviable from the energy efficiency point of view, although this could be argued considering the necessity to treat bio-waste, which normally incurs a cost for treatment that can be traded for the low efficiency of the system. Furthermore, we need to consider that the row material for gasification in the case of bio-waste comes from a free source. One more disadvantage of gasification of biomass is the technical problem pertaining to the quality of the produced gas and tar cracking [12].

3. Why Supercritical water gasification of biomass?

A large portion of biomass waste is wet biomass containing up to 95% water, this wet biomass results in high drying cost in classical gas phase gasification or liquefaction process. This can be advantageously avoided by using a gasification or liquefaction in near critical and supercritical water.

Liquid water at standard conditions (25 °C and 0.1 MPa) is an excellent polar solvent due to its high dielectric constant. It has a high solubility for many compounds and electrolytes; however, it is poorly miscible with hydrocarbons and gases. When water enters its supercritical phase, the dielectric constant drastically decreases. Water thus starts to behave like an organic, non-polar solvent which results in poor solubility for inorganic, and complete miscibility with gases and many hydrocarbons. Due to its miscibility, phase boundaries do not exist anymore. This absence leads to fast and complete homogeneous reactions of water with organic compounds.[13]

When water in supercritical conditions is used as the gasifying agent, biomass is almost completely gasified as it decomposes rapidly into small molecules or gases. Consequently, neither char nor tar occurs, so Hydrogen's volumetric ratio of greater than 50% is easily achieved[14], and the product gas usually contains H_2 and CO_2 mainly with a very small portion of CH_4 and CO.

Moreover, SCW gasification requires only one reactor unlike the conventional biomass gasification process which needs two reactors, this makes the SCW a simple and more concise process.

4. Proposed plant configuration

The proposed CHP system flowchart consists of a SCW biomass gasification unit, a steam reformation unit, a water-gas shift reaction unit, a product gas cleaning train, a high temperature SOFC, an air blower compressor, MGT, two heat exchangers and a heat recovery steam-generating absorption cycle. The gasifier produces syngas that is fed into the SOFC to generate electricity, while the SOFC cooling liquid enters the first heat exchanger, where it is utilized to generate high-temperature flow of compressed air that drives the gas turbine and produces electricity with little or no fuel combustion needed, while further heat dissipation takes place in the second heat exchanger to heat up the product syngas before it is fed into the SOFC.

The steam generator, which is driven by the absorption cycle, produces the steam needed to sustain the gasification process in the SCW biomass gasification unit, significantly reducing the need for any external source of heat to generate steam. The conceptual system is shown schematically in Figure 2.

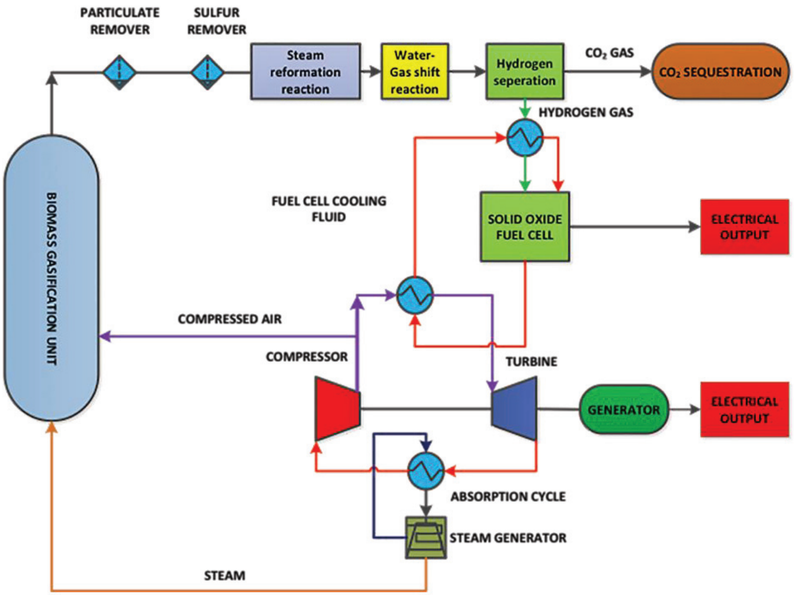

Fig. 2. Schematic of the conceptual Hybrid Biomass Hydrothermal Gasification- SOFC System Combined with Improved CHP Plant

5. Conclusions

In order to assess the whole system, each component of the system must be studied separately and its impact on other systems assessed. For example, with regards to the fuel cell, the required number of cells for the specified stack power is determined by the cell operating voltage, current density and fuel utilization factors. Also, the suitability of SOFC to run with synthesis gas coming from gasification of waste must be assessed, in addition to the effect of SOFC inlet stream temperatures on SOFC, gasifier and system performances. A sensitivity study of the operating conditions of the absorption cycle and its contribution to the system is important to assess the overall efficiency improvement.

The electrical output of the fuel cell is utilized directly while the thermal output of the fuel cell is used in a CHP cycle to produce more electricity through the MGT. this configuration optimises the performance of the system and reduces losses to the minimum and hence reduces harmful emissions.

Gasification is carried out in SCW, which is more suitable for wet biomass and saves energy consumed for drying. However, the sustainability of the system on the one hand significantly depends on the constant and reliable supplies of biomass, and on the other hand, it depends on the local laws and conditions where the system is operating, such as high fuel costs and high feed-in tariffs of electricity.

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References

[1] M. Aghaie, M. Mehrpooya and F. Pourfayaz, "Introducing an integrated chemical looping hydrogen production, inherent carbon capture and solid oxide fuel cell biomass fueledpowerplant process configuration," Energy Conversion and Management, vol. 124, pp. 141-154, 2016.

[2] Levin, D.B., et al., "Potential for hydrogen and methane production from biomass residues in Canada.," Bioresource Technology, vol. 1, pp. 654-660, 2007.

[3] Kong, L., et al.,, "Hydrogen production from biomass wastes by hydrothermal gasification," Energy Sources Part A, pp. 1166-1178, 2008.

[4] M. Bolhar-Nordenkampf, H. Hofbauer, R. Rauch and C. Aichernig, "Biomass CHP Plant Güssing – Using Gasification for Power Generation," Phuket, 2003.

[5] L. Research, "Waste to Energy, in The Cleantech Report," Lux Research Inc., 2007.

[6] A. M. Pantaleo, S. Camporeale and B. Fortunato, "Small scale biomass CHP: techno-economic performance of steam vs gas turbines with bottoming ORC," in ATI 2015 - 70th Conference of the ATI Engineering Association, 2015.

[7] M. Borji, K. Atashkari, S. Ghorbani and N. Nariman-Zadeh, "Parametric analysis and Pareto optimization of an integrated autothermal biomass gasification, solid oxide fuel cell and micro gas turbine CHP system," international journal of hydrogen energy, vol. 40, pp. 14202-14223, 2015.

[8] Matsumura, Y., et al.,, "Biomass gasification in near- and super-critical water: Status and prospects (Review)," Biomass and Bioenergy, vol. 1, pp. 269-292, 2005.

[9] Momirlana, M. and T.N. Veziroglu, "The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet," International Journal of Hydrogen Energy Sources Part A, pp. 795-802., 2005.

[10] A. Kruse, "Hydrothermal biomass gasification," J. of Supercritical Fluids, pp. 391-399, 2009.

[11] Bircan, S.Y., K. Matsumoto, and K. Kitagawa, , "Environmental Impacts of Hydrogen Production by Hydrothermal Gasification of a Real Biowaste," in Gasification for Practical Applications, © 2012 Bircan et al, licensee InTech. , 2012, pp. 211-224.

[12] A. M. Radwan, "An overview on gasification of biomass for production of hydrogen rich gas," 2012.

[13] O. Yakaboylu, J. Harinck, K. G. Smit and W. de Jong, "Supercritical Water Gasification of Biomass: A Literature and Technology Overview," 2015.

[14] J. Zhang, "Hydrogen Production by Biomass gasification in Supercritical Water," vol. 19, no. 6, 2008.