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Process simulation of biomass gasification integrated with a solid oxide fuel cell stack

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HIGHLIGHTS

- A cathode recycle or electric heater for syngas preheating is not attractive.
- Thermal integration between the gasifier and fuel cell is desirable.
- Lowering the syngas preheat temperature is highly recommended.
- High temperature syngas cleaning reduces plant complexity and improves performance.
- Gasification air preheating is more attractive than gasification steam superheating.

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ABSTRACT

Biomass gasification-solid oxide fuel cell (BG-SOFC) combined heat and power (CHP) systems are of major interest in the context of climate change mitigation, energy security and increasing energy efficiency. Aspen Plus is employed to simulate various BG-SOFC CHP systems. The aim of the research work is to investigate the technical feasibility of these systems and to study the influence of important operating parameters and examine integration options. Systems based on dual fluidised bed steam gasification and tubular SOFC technologies are modelled. The cathode recycle and electric heater integration options are not attractive in comparison to the base case anode recycle system. Thermal integration, i.e. using SOFC flue gas as gasifier oxidant, is desirable. Lowering the syngas preheat temperature (prior to SOFC anodes) is highly recommended and is more practical than lowering the cathode air preheat temperature. Results of the parametric study indicate that: steam to carbon ratio and biomass moisture content should be as low as possible; fuel utilisation factor can change the mode of operation of the plant (focus on electricity or heat); high temperature syngas cleaning is very attractive; gasification air preheating is more attractive than gasification steam superheating. High efficiencies are predicted, proving the technical feasibility of BG-SOFC CHP systems.

1. Introduction

The efficient utilisation of biomass resources is of utmost importance if it is to replace a significant proportion of fossil fuels. Traditional biomass combustion based technologies achieve low electrical efficiencies at small scale (20–25%) and therefore cannot compete with fossil fuels. Scale is limited by biomass supply logistics. The systems examined in this research work are at a relatively small scale of 120 kW DC power output (see Section 2.2 for additional details). Biomass gasification coupled with solid oxide fuel cells (BG-SOFC) offer much higher efficiencies. These systems offer highly efficient renewable energy, are modular in nature making them ideal for decentralised combined heat and power (CHP) applications and as a result have recently gained much attention [1–9]. For a comprehensive list and description of research on BG-SOFC systems, refer to Nagel [4] and Doherty [10]. Biomass gasification and SOFCs are well matched as they are thermally compatible (similar operating temperatures ~800 to 1000 °C) and thus offer many integration options. Fig. 1 displays a simplified block diagram of a BG-SOFC CHP system. These plants are still being developed and there is a need for accurate process

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Nomenclature

Roman letters

BG-SOFC	biomass gasification-solid oxide fuel cell
CGE	cold gas efficiency
CHP	combined heat and power
c_p	specific heat capacity, kJ kg^{-1} K^{-1}
CZ	combustion zone
db	dry basis
DFB	dual fluidised bed
FICFB	fast internally circulating fluidised bed
GZ	gasification zone
HHV	higher heating value, MJ m^{-3} or kJ kg^{-1}
j	current density, A m^{-2} or mA cm^{-2}
LHV	lower heating value, kJ kg^{-1}
$\dot{m}$	mass flow rate, kg s^{-1}
$P_{biomass}$	biomass input power, kW
$P_{el,AC}$	electrical AC power, kW
pp	percentage points
$P_{parasitic}$	total parasitic power, kW
ppmv	volumetric parts per million
Q	maximum recoverable heat, kW
STBR	steam to biomass ratio
STCR	steam to carbon ratio
T_g	gasification temperature, °C
U_a	air utilisation factor
U_f	fuel utilisation factor
wb	wet basis
ZnO	zinc oxide

Greek letters

ΔT	temperature difference
$\eta_{CHP,net}$	plant net AC CHP efficiency (LHV basis)
$\eta_{el,net}$	plant net AC electrical efficiency (LHV basis)
η_{SOFC}	SOFC AC efficiency (LHV basis)

Subscripts

biomass	biomass input fuel
fuel	input gaseous fuel to SOFC stack
gas	syngas

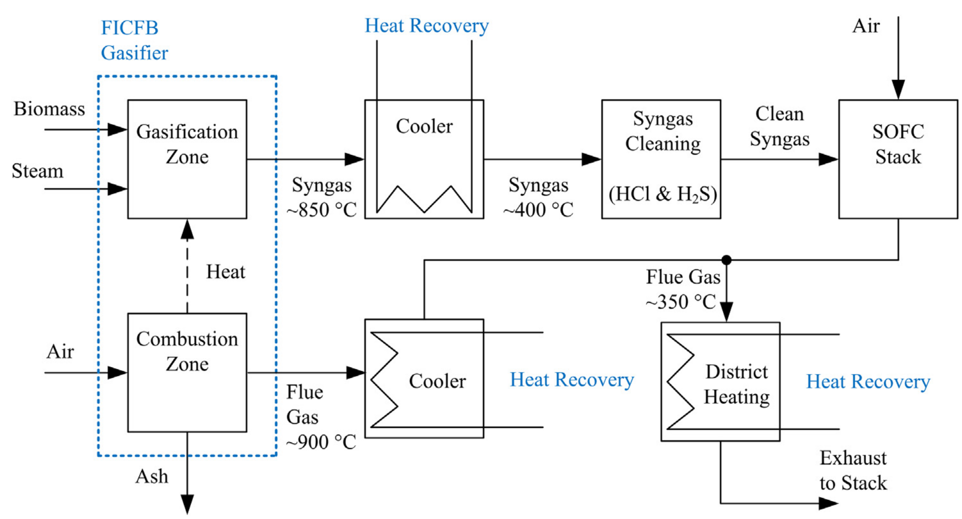

Fig. 1. Simplified block diagram of a BG-SOFC CHP system.

simulation models that can aid in the design and understanding of these systems.

Gasification is a thermochemical process in which a carbonaceous fuel is converted to a combustible gas. This combustible gas is known as syngas (from synthetic or synthesis gas) and consists of hydrogen (H_2), carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2), water vapour (H_2O), nitrogen (N_2), higher hydrocarbons and impurities such as tars, ammonia (NH_3), hydrogen sulphide (H_2S) and hydrogen chloride (HCl). The process occurs when a controlled amount of oxidant (e.g. pure O_2, air, steam) is reacted at high temperatures with available carbon in a fuel within a gasifier. Air gasification produces a syngas with low energy content, around 4–7 MJ m^{-3} higher heating value (HHV), while pure O_2 and steam blown processes result in a syngas with a heating value in the range of 10–18 MJ m^{-3} (HHV) [11].

A fuel cell consists of two electrodes separated by an ion conducting electrolyte. Fuel is supplied to the negative electrode (anode) and oxidant to the positive electrode (cathode). Fuel cells convert the chemical energy contained in a fuel directly to electrical energy via electrochemical reactions, making them a highly efficient energy conversion device. SOFCs can utilise a wide spectrum of fuels (natural gas, coal and biomass syngas, liquid fuels including methanol and kerosene) due to their high operating temperature.

The aim of this research work is to investigate the technical feasibility of BG-SOFC CHP systems and to study the influence of important operating parameters and examine integration options. This aim is accomplished through the development of zero-dimensional process simulation models using Aspen Plus. The models are isothermal, steady state and based on Gibbs free energy minimisation (temperature approach method employed to adjust the gasifier output syngas composition, i.e. restricted equilibrium model type).