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Thermal modeling and efficiency assessment of an integrated biomass gasification and solid oxide fuel cell system

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ABSTRACT

Performance assessment of a novel energy system integrating both biomass gasification and fuel cell systems is performed thermodynamically through energy and exergy efficiencies. Steam gasification for rich hydrogen gas production as a useful gasification output is considered. Energy and exergy thermodynamics model of the gasification process is introduced. A thermal model of bubbling fluidized bed gasifier, operating at atmospheric pressure, is also considered to investigate the temperature profile through the gasifier. Direct internal reforming solid oxide fuel cell model is introduced and it is integrated with the system for power production. The presented models are validated, and the effects of different operating parameters on the system performance are studied under various conditions. Different values of gasification operating temperature and moisture content of the supplied fuel are also considered in parametric studies. The results show that steam biomass ratio has a significant effect on the hydrogen production efficiency and optimal value of 0.677 is calculated for maximum exergy efficiency at the base case condition.

Introduction

One of the most promising alternatives of multi-generation energy systems is integrated gasification and solid oxide fuel cell (SOFC) technology. This technology is more attractive when utilizing indigenous biomass driven fuel for the gasification process. Biomass can be considered green and renewable source of sustainable hydrogen production rich gas through gasification process [1,2].

In the open literature, numerous studies are performed on biomass gasification applications and their potential use for cogeneration and hydrogen production [3–5]. Abuadala and Dincer [3] conducted a review study on the potential of hydrogen production through biomass gasification. They performed some parametric studies to investigate the

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operating conditions of gasification on the system performance. An extensive parametric study is conducted by Schuster et al. [5] on a dual steam gasifier for combined heat and power (CHP) generation. They investigated effects of gasification temperature, fluidization agent and water content on the performance of the system. Song et al. [6] carried out a thermodynamic assessment based on exergy efficiency for biomass steam gasification process. They considered interconnected fluidized bed in their analysis. Brau and Morandin [7] designed two concepts for biomass to hydrogen systems using indirect atmospheric steam gasification and pressurized direct oxygen-steam blown gasification. SOFC is considered the most suitable for integration with biomass gasifiers. This is assisted by its relatively high operating temperature, high energy conversion efficiency, and relative insensitivity tolerance to fuel contaminants. Thermodynamic and optimization analyses are conducted by Athanasiou et al. [8] to study the performance of integrated gasification and SOFC system. Fryda et al. [9] performed exergy analysis on an integrated biomass gasification and SOFC with heat pipes for CHP. They reported overall exergy efficiency of 34%. Colpan et al. [10] reported electric and exergy efficiencies of 41.8% and 39.1% when studying steam as gasification agent among other options for biomass gasification and SOFC systems. Ozcan and Dincer [11] investigated the performance of SOFC integrated system for trigeneration application. Wongchanapai et al. [12] investigated the effect of different operating parameters on the performance of a small scale integrated biomass gasification and SOFC system. An electric efficiency of 58.2% is reported by Bang-Møller et al. [13] for biomass gasification, SOFC and micro gas turbine integrated system. Bang-Møller et al. [14] investigated the potential of increasing electric efficiency of two stage biomass gasification and SOFC integrated system.

In this study, we aim to integrate both biomass gasification and direct internal reforming SOFC systems in a novel manner and assess thermodynamic efficiencies energetically and exergetically. The system components are modeled using a potential computational tool, so-called: Engineering Equation Solver (EES) [15]. In the gasification process, steam is considered as drying and gasification agent. The effects of changing several operating parameters on system performance are investigated through parametric studies. A model of atmospheric bubbling fluidized bed is presented, considering hydrodynamics relations, to predict the axial temperature profile through the gasifier.

System description

The proposed integrated system is schematically shown in Fig. 1. The model considers steam as the gasification and drying medium for the provided biomass fuel. Dry biomass is assumed to go through the gasification process at 10–30% of moisture content. Steam is supplied through the heat recovery steam generator which utilizes the flue gases out of the burner as heat source. Air is provided to the fuel cell after being heater by the gasification produced gas. Air supply to the gasifier can be tuned to maintain the desired operating temperature of the gasifier through partial oxidation. Generally, gasification produced gas would contain some tar and sulfur among other contaminants that may affect the fuel cell performance. Hot gas cleaning can be considered using Barium oxide as experimentally investigated by Stemmler et al. [16]. In the current study, cleaning process is not considered in analysis. There are several studies in the literature that discussed chemical hot gas cleaning for removal of H_2S and if there are HCl or ammonia as contaminates [17–21]. High temperature gas cleaning works by passing the produced gas through ceramic or sintered metal hot gas filter, then through high temperature (800 °C) packed bed catalyzer for tar cracking. In case of hydrogen production, reformer is utilized to reduce the light hydrocarbons and sulfur can be handled through zinc oxide packed bed [1,22]. The syngas produced from the process is cooled to the inlet condition of the fuel cell. Its heat is utilized to heat the supplied air. A certain percentage of the produced syngas is directed for hydrogen production unit which is cooled down, providing its heat to the supplied air. The SOFC model is introduced as direct internal reforming solid oxide fuel cell (DIR-SOFC), where methane is internally reformed into hydrogen. The amount of syngas directed to the SOFC is controlled based on the power desired from the system. The flow exiting from the SOFC is burned where the flue gas heat is directed to the HRSG after passing through the gasifier to support the biomass drying process and provide heat to the gasification process. The burner is assumed to operate under complete combustion condition where adiabatic flame temperature model is adopted for the process.

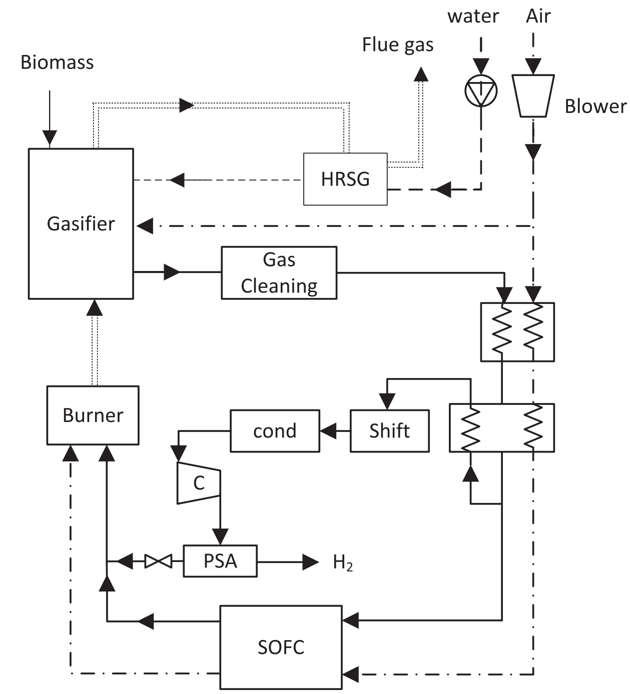

Fig. 1 – Schematic of the proposed integrated system.

Analysis

Thermodynamic analyses based on energy, exergy, chemical equilibrium, kinetics of gasification and SOFC analyses are