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Design of biomass and natural gas based IGFC using multi-objective optimization

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ABSTRACT

Integrated Gasification Combined Cycle (IGCC) and Integrated Gasification Fuel cell Cycle (IGFC) uses Syngas in fuel cells and gas turbines to produce power. Several designs have been studied and it is common to analyze different designs (one at a time) to understand which design is more efficient. In this work we propose a superstructure that has both fuel cell topping and fuel cell bottoming cycles and use multi-objective optimization (MOO) to obtain optimal designs. The capacity of the fuel cells and the gas turbines in the superstructure is a decision variable and this gives an opportunity to size the system more efficiently. Here, we use two objectives, one is the energy generated by fuel cells while the other is the energy generated by the gas turbines in MOO and the analysis of the Pareto front gives us many networks. We identified different networks that produce about the same amount of energy when biomass is the fuel. However, when natural gas is used as fuel, the fuel cell only network produces more energy than other networks. Further, it was observed that it is only possible to produce more energy in IGFCs when the combustion and gasification units are maintained at Gibbs equilibrium.

1. Introduction

Human population is constantly increasing. This combined with rapid economic growth and development around the world is leading to an ever-increasing demand for fuels. In view of this, alternative resources of energy are gaining importance. According to the International Energy Agency (IEA) [1], energy from biomass would constitute 23% of the total world energy use by 2050. The use of biomass would reach 3600 Mtoe/yr (Million Tons of Oil Equivalent per year) of which 700 Mtoe/yr would be used to produce liquid fuels for the transportation sector, 700 Mtoe/yr for the generation of power and 2200 Mtoe/yr for the production of biochemicals, district heating, cooking, and industrial steam. This translates to 15 Billion t/yr of biomass being transported to centralized locations. In order to minimize the energy used in the transportation of large amounts of biomass and also to minimize the transmission losses in the power sector, it may be worthwhile to produce power at decentralized locations that serve smaller communities. As a result, distributed energy systems (DES) are gaining importance [2].

The global energy demand was about 400 Quadrillion BTU in the year 2000 and is expected to increase to 1200 Quadrillion BTU by the year 2040 [3]. Energy savings through improved efficiencies have the potential to reduce this demand to 700 Quadrillion BTU. Furthermore, in view of the increasing awareness on climate change, the US Department of Energy (DOE) has set a target of 60% efficiency (higher heating value) for next generation coal fired power plants and it was observed that current designs have not achieved this goal [4]. Thus, further optimization to improve the design of IGCC/IGFC systems is necessary. This together with the advantages of operating a DES motivates us to focus on the optimal design of an IGFC system.

The process of production of syngas from biomass/coal for use in the generation of power is called an IGCC (integrated gasification combined cycle) and when the syngas is used in a fuel cell it is called as an IGFC (integrated gasification fuel cell cycle). The IGCC/IGFC systems also consist of gas cleaning systems, steam turbines, gas turbines and heat exchangers. Briefly, the biomass i.e., wood chips or plant stalks are processed and fed to the gasifier to produce syngas at a high temperature. The produced syngas is then cleaned to remove any particulate matter and toxic substances that may foul the fuel cell. The syngas may be passed through a water–gas shift reactor to increase the hydrogen content. The high

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temperature gas makes it an ideal fuel for high temperature fuel cells and improves the efficiency of the integrated system. The efficient design of a high temperature gas clean up system is critical for the practical implementation of the IGFC system. Alternatively, the syngas may be cooled and the gas clean up may be done at a lower temperature using more efficient gas clean up systems. If this is done, the cleaned syngas must be reheated, thus compromising the efficiency [5].

2. Literature review

In view of the rather limited availability of comprehensive review and models of all the three major components of IGFCs in one research paper, we first present a review of biomass gasification, fuel cells and gas turbines.

2.1. Biomass gasification

Biomass and coal gasification have been studied extensively over the past few decades. Gasification is a process wherein the biomass undergoes devolatilization at lower temperatures (about 300°C–400 °C) followed by tar cracking and gas phase reactions at higher temperatures (400–800 °C). In some instances the temperature of coal gasification can reach 1400 °C [6]. Some of the earliest gasification studies include those of Ergun [7], where coke gasification was studied extensively and the composition of syngas at various temperatures was obtained. Several studies on the combustion rate of carbon [8], the kinetics of char combustion in a fluidized bed [9], mathematical models for thermal decomposition of coal [10–14] and combustion and gasification kinetics of pyrolysis chars from waste and biomass [15] are presented in literature. All these studies focused on the devolatilization of biomass and change in weight of the initial biomass with temperature.

At above 800 °C, combustion is dominant if oxygen is present. However, in a gasification unit, drying, pyrolysis gasification and combustion all occur simultaneously [16]. Gasification is an endothermic process and the energy released from the combustion process is used to supply the energy required for gasification. This process leads to the evolution of tars, char and gases such as CO, CO_2, H_2O, H_2, CH_4 and higher hydrocarbons.

A comprehensive review on the process of biomass gasification in a fluidized bed gasifier was presented by Gomez-Barea and Leckner [17]. The overview can be divided into two parts. One, the process of biomass devolatilization, change in particle size of the biomass and the process of tar cracking and two, the gas phase reactions. They validated the models for the first part. In the second part, they compiled data from several sources and have given the values of the pre-exponential factors and the activation energy in the Arrhenius rate equation. They have shown in their compilation that these values vary widely, sometimes by a factor of 10^5. Vitasari and co-workers worked on exergy analysis of biomass to synthetic natural gas production via Syngas. They have observed that the largest losses occur in the Syngas Gasifier [18] and this is possibly due to the presence to steam for water–gas shift reaction.

Several reactions occur in a biomass gasification unit. Biomass devolatilization occurs as:

$$\text{Biomass} + O_2 + H_2O \rightarrow \text{Tar} + \text{Char} + CO + CO_2 + H_2 + H_2O + CH_4;$$

Tar is assumed to have a general formula CH_xO_y where $x = 8/6$ and $y = 1/6$ and Char is assumed to be C_s although in reality it is only about 95% carbon.

Partial combustion and complete combustion of Tar occurs as:

$$C_xH_yO_z + \frac{y/2 + x - z}{2} O_2 \rightarrow xCO + \frac{y}{2} H_2O$$

and

$$C_xH_yO_z + \frac{y/2 + 2x - z}{2} O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O$$

In addition to the above reactions, various other reactions occur in biomass gasification, however these are not presented here.

Perez-Fortes et al. [19] developed a gasifier model that is based on a series of experimental correlations and used the model in the simulation of an IGCC. Development of such correlations requires extensive availability of data. Schuster et al. [20] simulated the process of biomass gasification assuming that the products of the gasification process are in thermodynamic equilibrium. The same research group developed a model for biomass char combustion in a fluidized bed gasification unit [21]; however, this model was not validated with experimental results. In a later study [22], they presented a model for biomass gasification considering thermodynamic equilibrium, hydrodynamics in the fluidized bed, reaction kinetics and elemental balance and showed that their model fitted experimental results very well [20,23]. One of the important reactions in the process of biomass gasification is the water–gas shift reaction, where carbon monoxide is oxidized to carbon dioxide thereby reducing the water molecule to hydrogen and effectively increasing the concentration of hydrogen in the products. A study on the water–gas shift reaction kinetics and an equation for the equilibrium constant of the reaction was presented by Choi and Stenger [24]. This reaction is important for fuel cells such as the PEMFCs that do not tolerate carbon monoxide. Others [25] have studied the kinetics of the reaction of char with carbon dioxide and steam. In addition to these studies, several researchers have investigated the reaction kinetics of coal chars and other biomass using a thermo-gravimetric analyzer [26–30].

Neural networks were used by some researchers for simulating biomass gasification [31]. However, no information on the amount of data used in developing the neural network model was presented. Free energy minimization and Gibbs equilibrium are widely used by various researchers to study the product composition in a biomass reforming/gasification unit and a free energy minimization approach for carbon dioxide reforming of methane [32]. Both experimental and modelling analysis of a gasification/pyrolysis reactor was performed by Baggio et al. [33]. They used significant quantities of saw dust (up to 375 g) in a batch reactor. However, their model and comparison of the experimental and modelling results are limited only to changes in weight of biomass with temperature. Thus, their experimental results are limited and insufficient to convincingly validate the model.

2.2. Fuel cells and gas turbines

Researchers have developed different types of fuel cells and they are classified based on the electrolyte employed. Solid oxide fuel cells (SOFCs) and molten carbonate fuel cells (MCFCs) have a wide range of applications and can use CO as fuel. Hence they are suited for integration with biomass gasification units.

The National Fuel Cell Research Center (USA) has done considerable work in the control of (SOFC) – micro-gas turbine (MGT) hybrid system for the generation of power. In their work, they consider that the fuel of known composition is readily available for use in the hybrid system. They have presented cycles such as fuel cell (FC) topping, fuel cell bottoming, direct and indirect cycles. A detailed two dimensional planar SOFC system integrated with a gasification unit was studied and it was shown that the detailed