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An experimental evaluation of an integrated biomass gasification and power generation system for distributed power applications

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HIGHLIGHTS

- ▶ A study of a trailer-scale biomass to power system.
- ▶ System characteristics and performance evaluation determined.
- ▶ Using pine, red oak, horse manure and cardboard as feedstock.
- ▶ Integrated system efficiency in the range of 17.6–24.8%.
- ▶ Feasibility and viability demonstrated for distributed energy and rural applications.

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ABSTRACT

This paper presents the feasibility study of a sound scientific, engineering, and technological solution for converting lignocellulosic biomass to electrical power using a trailer-scale downdraft biomass gasification system coupled with a spark-ignited IC engine/electric generator set for portable power applications on agricultural farms and in rural areas.

The main objective of this study is to investigate the coupling and integration between the gasification unit and the power generation unit. Also it is intended to emphasize on the effectiveness of distributed power generation systems and demonstrate the feasibility of such integrated systems in real world scenarios, where the lignocellulosic biomass resources are widely available and distributed across the board. Four feedstock materials, pine, red oak, horse manure and cardboard that represent a wide spectrum of lignocellulosic biomass resources were chosen for the study. The efficiencies for individual components and the overall integrated system efficiencies were evaluated using experimental data and a thermal–chemical model for all four feedstocks.

1. Introduction

Greenhouse effects and global climate change have created controversial and critical issues that involve the energy industry, government policy making, and society at large [1,2]. Long-term sustainability of the power, transportation and manufacturing sectors of the economy requires a portfolio of renewable and sustainable energy resources [3–5]. Such energy sources should carry high specific energy contents coupled with carbon–neutrality and low greenhouse gas emission. The development and implementation of these resources should have minimum impacts on the food chain, water supply, land use, and environment. Biomass, nuclear, solar, geothermal and wind are all excellent energy sources since they can be considered carbon–neutral. Biomass is one of the most important primary, renewable energy resources in a projected renewable sustainable energy future. The current system would contribute to demonstrating the technology to convert lignocellulosic biomass resources to useful energy, from thermodynamic efficiency and system technology standpoints, as well as from emissions, environment and impact on resources such as water and food.

A trailer-scale biomass gasification to power system is a small process unit that converts distributed biomass energy to refined usable energy such as synthesis gases, mechanical power, and electricity. A biomass air-breathing gasification system produces synthesis gas through the thermal–chemical conversion which involves partial oxidation of feedstock in a reduced oxygen atmosphere [6]. Because the biomass is spread widely around the world, a small scale biomass conversion system would be more competitive than a larger plant due to portability and feedstock transportation costs [7].

The goal of the biomass gasification system is to convert the biomass feedstock into a useful energy form called syngas which

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mainly contains hydrogen (H_2), carbon monoxide (CO) and methane (CH_4). The syngas can be further converted to liquid fuels in a catalytic reactor [8–12] or it would be utilized for the fuel cell system [13]. It could also be burned directly in conventional internal combustion engines and a gas turbine [14], which is more efficient than the direct combustion of the feedstock since it combusts at higher temperatures. By integrating the gasifier with an engine/generator set, the overall system is capable of producing electrical power for the direct usage, for example, in a typical household that consumes an average of 15 kW_e electrical power.

Sharma [15] studied a 75 kW_{th}, downdraft biomass gasifier to obtain temperature profiles, gas compositions, calorific values and trends as a function of the pressure drop across the system. Olgun et al. [16] designed and operated a bench scale, fixed bed, and batch type downdraft gasifier with wood chips and hazelnut shells as the feedstock. They varied the air to fuel ratios to produce a syngas with a high heating value and low pollutants. By analyzing the gas compositions the authors were able to find the optimal system condition to obtain the syngas with the highest lower heating value, which is 0.35 ER or 5.5 MJ/Nm^3.

Martínez et al. [17] used a moving bed downdraft reactor with two-air supply stages to efficiently and economically reduce the tar content in the gasifier effluent. They controlled the air flow fed to the gasifier and the distribution of gasification air between the two stages, which are the fundamental parameters that control the biomass consumption rate and the superficial velocity, or the specific gasification rate and the equivalence ratio.

Biomass gasification coupled with an internal combustion engine has also been evaluated by researchers using modeling and simulation approaches. Also, some of the researchers tried to demonstrate the value of an engine application with their gasification systems which produce high quality syngas. Baratieri et al. [18] simulated the use of biomass syngas in an internal combustion engine and a combined cycle gas turbine (CCGT) plant to maximize heat and power production for several designs. The syngas production section was modeled with an equilibrium chemical reaction approach, and the rest of the system was optimized via the mass and energy balance. Sharma [15,19] performed a study using a 75 kW_{th} downdraft gasification system integrated with a 20 kW_e internal combustion engine to evaluate the feasibility of this combined operation. Pressure drop, temperature profile, output gas composition and calorific value with respect to the system mass flow rate were investigated. However, the actual experiment using the internal combustion engine was not performed.

Huang et al. [20] introduced a trigeneration system which consists of an internal combustion engine integrated with a biomass gasification unit. This system can offer a combined delivery of heat, electricity and cooling. Modeling and simulation were used to design a commercial building scale trigeneration plant fuelled by a biomass downdraft gasifier. Coronado et al. [21] also tried to increase the total system efficiency with a compact cogeneration system that produces electric energy, and hot and cold water from the wood gasifier. The energy and economic analysis was presented, which concluded that the global efficiency of the system could reach up to 51.42%.

Zabaniotou et al. [22] showed the advantage of a small-scale combined heat and power production system by the experimental result and the chemical equilibrium model analysis so that it could reduce the transportation cost of biomass and provide heat and power where and when a necessity appears. Centeno et al. [23] developed a mathematical model which consists of two separate submodels for the fixed bed downdraft gasifier and the spark ignition internal combustion engine, respectively. These models were validated by comparisons to published theoretical results and experimental data in terms of gas composition and engine power output.

Instead of integrating the gasifier with the engine directly, some researchers used synthesized gaseous mixtures from several pure gases to mimic the syngas to evaluate the possibilities of the conventional engine applications. Mustafi et al. [24] used ‘Powergas’ – a synthetic fuel consisting mainly of carbon monoxide and hydrogen to investigate the engine emission and performance. The results indicate that engine power levels were 20% and 30% lower than those burning natural gas and gasoline fuels, respectively, and the carbon dioxide and NO_x emissions were found to be higher than those using other fuels. Sahoo et al. [25] varied the chemical composition of the syngas supplied to a diesel engine to check the feasibility. They used two types of pure gases, hydrogen and carbon monoxide to simulate the real syngas, and did the second law analysis for different engine loads.

Finally, some researchers employed combined systems where the biomass gasification system and the internal combustion engine were integrated in series to generate the mechanical power or electricity from the gasification of biomass.

Lin [7] integrated an updraft fixed bed gasifier with a 25 kW Stirling engine, and they successfully generated the shaft power at 24.5 kW. The Stirling engine coupled with an induction generator converts the heat from the solid biomass into electrical energy that is directly sent to the grid. Shah et al. [26] focused on the engine performance and emission of a 5.5 kW spark-ignited engine operated by the syngas produced using a fixed bed, downdraft atmospheric pressure gasifier fed with hardwood chips. Syngas was collected and put in a storage cylinder at a high pressure before supplying it to the engine rather than directly piped to the engine. Results show that even though the power output when using the syngas was lower than that when the gasoline was used, the overall efficiency of the system at the maximum electrical power output on syngas was the same as that on gasoline.

According to Ruan et al. [27], currently large scale biomass energy production systems including cellulosic ethanol, gasification, and pyrolysis facilities experience technical and economic hurdles. Compared with these large scale systems, small decentralized and distributed biomass energy production systems could offer advantages including lower capital costs, lower feedstock costs, simplified transportation and logistics, and higher returns for biomass producers. These small-scale distributed energy systems can directly utilize regional biomass supplies that are practical and economically viable from energy saving consideration. Therefore, biomass has been recognized as an ideal energy resource for decentralized energy systems. The synthesis gas is the basic product of a gasification system and it is primarily a gaseous fuel that is not a convenient and ready to use form of energy. Therefore, we proposed a combined system by integrating the gasifier with a power generating engine/generator set to address this issue.

Based on the above review, the existing literature on the integrated gasification to power systems is very limited from both qualitative and quantitative aspects. The current work outlines a sound scientific, engineering, and technological solution for converting lignocellulosic biomass, as well as agricultural and forest residues to electrical power using a trailer-scale down draft biomass gasification system coupled with a spark-ignited IC engine and an electric generator for portable power applications in agricultural farms and rural areas. In addition to addressing the engineering and technology issues, four different feedstock materials that represent a wide spectrum of lignocellulosic biomass resources were used in this study to promote biomass utilizations.

This study is divided into two major parts. The first part focuses on the syngas generation from four representative types of biomass feedstock using thermal–chemical gasification which aims at producing clean and dense syngas by adopting an array of gas cleaning components in succession. The second part is devoted to the conversion of the syngas energy content to electrical power