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SYNGAS FROM BIOMASS GASIFICATION AS FUEL FOR GENERATOR

By

Ajay Shah

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Biological Engineering
in the Department of Agricultural and Biological Engineering

Mississippi State, Mississippi

December 2008

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SYNGAS FROM BIOMASS GASIFICATION AS FUEL FOR GENERATOR

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The emergence of biomass based energy warrants the evaluation of syngas from biomass gasification as a fuel for personal power systems. The objectives of this study were to determine the performance and exhaust emissions of a commercial 5.5 kW generator modified for operation with 100% syngas at different syngas flows and to compare the results with those obtained for gasoline operation at same electrical power. Maximum power output for gasoline operation was 2451 W and maximum power output for syngas operation was 1392 W. Overall efficiencies of the generator were same at maximum electrical power outputs for operation with both the fuels. At four different electrical power output categories, the exhaust concentrations of carbon monoxide and oxides of nitrogen were significantly lower while the carbon dioxide emissions were significantly higher for the syngas operation. The unit cost of electricity generation was $6.38/kWh for syngas operation and $0.56/kWh for gasoline operation.

Key words: alternative fuels, gasification, syngas, generator.

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DEDICATION

I would like to dedicate this work to my inspiration, my idol-my father Shital Prasad Shah and my mother Rama Shah. Although my father left me physically, he always is with me spiritually supporting me to excel in all the steps of my life.

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CHAPTER 1

INTRODUCTION

This chapter contains a brief introduction of the overall study. Section 1.1 contains a brief background on syngas and the potential uses of syngas. Sections 1.2 and 1.3 present the problem statement and the objectives of this study. Section 1.4 contains the justification and usefulness of this work and section 1.5 contains the overall organization of the thesis.

1.1 Background

Bio-energy is a renewable energy derived from biological sources (plant materials) in the forms of heat, electricity, or vehicle fuel. Biomass based fuels are among the most rapidly growing renewable energy technologies. Some of the main reasons for the interest towards bio-renewable fuels are the rising prices of fossil fuels and increased concern about emission of the greenhouse gases. Likewise, renewed attention has been directed towards biomass gasification. Gasification is the thermochemical conversion of solid carbonaceous materials, such as biomass and coal, using a controlled amount of oxygen at elevated temperature into carbon monoxide (CO) and hydrogen (H_2), which aretogether known as synthesis gas (syngas). Gasification is very important because it increases the value of low energy-value feedstocks by transforming them to

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comparatively high energy-value product, syngas. Syngas has several uses: Syngas can be used for heat and power production by direct combustion (Bridgwater, 1994), for hydrogen production using water gas shift reaction (Demirbas, 2002), for the production of ammonia, methanol and Fischer-Tropsch hydrocarbons (Ragauskas et al., 2006), for biofuels production by anaerobic fermentation (Ragauskas et al., 2006) and for synthesizing gasoline via dimethyl ether (Kolesnichenko et al., 2007). This study is focused on using syngas as an alternative engine fuel to operate a naturally-aspirated, single-cylinder, four-stroke, spark-ignited engine driven generator, originally designed to run on gasoline, for electrical energy generation.

1.2 Statement of the Problem

Syngas from biomass gasification has the potential of being used as an alternative engine fuel for operating generators to produce electricity. Previous studies (Mustafi et al., 2006; Sadykov et al., 2005; McMillian and Lawson, 2005; Shudo et al., 2003; Smith and Bartley, 2000) have explored using syngas generated from chemical means, other than biomass gasification, as alternative engine fuel. Syngas from biomass gasification can be a promising alternative engine fuel, so there exists a need for determining the feasibility of operating commercial generators on this. This study focuses on using syngas, produced from biomass gasification, to generate electricity by fueling generators that were originally designed to operate on gasoline, and on comparing the performance and emissions parameters of the generator on syngas and gasoline. Finally, an economic analysis has been performed to determine the cost of using syngas to generate electricity.

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1.3 Objectives of the Study

1. To assemble the system to supply and utilize syngas to operate the generator.

2. To determine the performance of the generator at different electrical power outputs using syngas and gasoline as fuel

3. To compare the emissions of the generator on syngas and gasoline at four different electrical power outputs.

4. To conduct the economic analysis for syngas and gasoline operation of the generator.

1.4 Justification and Usefulness of the Study

- To identify syngas as a potential long-term bio-renewable fuel for electricity generation.
- To contribute to the development of industrial markets in the field of bio-renewable engine fuels.
- To reduce environmental degradation by decreasing the usage of fossil fuels and reducing harmful emissions.
- To make a positive contribution towards limiting the effects of greenhouse gases.

1.5 Organization of the Thesis

This thesis has five chapters. Chapter 1 presents brief background, problem statement, objectives and justifications of this study. Chapter 2 contains a brief overview

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of bioenergy, biomass, different biomass conversion technologies and gasification process. Chapter 3 contains details of the performance and emissions study of the generator on syngas and gasoline. Chapter 4 contains the economic analysis of using syngas and gasoline for electricity generation. Chapter 5 presents the conclusion of this study and the recommendations for the future work.

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CHAPTER 2

LITERATURE REVIEW

This chapter provides a brief overview of bioenergy, biomass, different biomass conversion technologies and gasification process. Section 2.1 highlights the need and importance of biomass based energy. Sections 2.2 and 2.3 discuss literature related to various biomass conversion and gasification technologies, respectively.

2.1 Biomass and Bioenergy

Biomass is any cellulosic or ligno-cellulosic organic matter, which is available on a recurring and reusable, and hence renewable, basis. Biomass includes trees, plants and associated residues, plant fiber, animal wastes, industrial waste, and the paper component of municipal solid waste (REPP, 2008). Biomass is widely considered as an important potential fuel for the future. Biomass is an attractive fuel in regards to the protection of the environment because the carbon dioxide produced while combusting biomass is ultimately used up by the plants during photosynthesis process to produce oxygen. Any renewable energy or fuel derived from biomass is known as bioenergy. The biomass might be either directly used as fuel or might be processed into liquids and gases. Biomass has excellent potential in terms of fulfilling the energy needs. Biomass based energy has been used since early centuries all over the world. Previously all over (and

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even now in the rural communities of) the world, biomass based energy was used (and is being used), but in a very conventional manner, as burning biomass directly for cooking, warmth and light. The awareness towards biomass based energy started to grow over the centuries and people started exploiting energy contained in biomass in more improved ways. Biomass powered industries grew substantially in the United States (US) after enactment of the Public Utilities Regulatory Policy Act (PURPA) in 1978. Most of the installed biomass facilities in US primarily consist of direct combustion steam Rankine systems with an average size of 20 MW (largest being nearly 75 MW) with typical efficiencies of around 20%. (Williams, 2004)

The prominence of biomass based energy can be seen from the Table 2.1 (EIA, Renewable Energy Annual, 2006).

Table 2.1 Annual Total Energy, Total Renewable Energy and Total Bioenergy Consumption in the United States:

Year	Total Energy Consumption (Quadrillion Btu)	Total Renewable Energy Consumption (Quadrillion Btu)	Total Bioenergy Consumption (Quadrillion Btu)
2002	97.68	5.89	2.71
2003	97.97	6.15	2.82
2004	100.05	6.26	3.02
2005	100.16	6.44	3.15
2006	99.40	6.92	3.37

It is evident from the table 2.1 that the total renewable energy covers around 7% of total energy consumed in US and has an increasing trend. Biomass based energy

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shares around 50% of the total renewable energy consumed. This clearly demonstrates the growing importance of biomass based energy.

2.2 Biomass Conversion Technologies

In most rural communities of the world, biomass is commonly used in small boilers or furnaces to fulfill the household energy requirements, such as cooking and farm heating. These are the simplest and the cheapest methods of the conversion of biomass, but they are inefficient and unsuitable for extensive energy production. For the most efficient biomass conversion, broadly three technologies, viz., thermochemical, biochemical and chemical, are used. Thermochemical technologies use heat to decompose feedstock into the usable form of energy products. These include gasification and pyrolysis processes. Biochemical technologies use biological agents such as enzymes and bacteria to decompose feedstock into usable form of energy products. These include technologies for fermentation of starch and sugar (from sugarcane and corn) to fuel ethanol; lignocellulosic fermentation to fuel ethanol; anaerobic digestion; landfill gas collection and aerobic digestion. Chemical conversion technologies convert biomass into useful form of energy with the use of chemical agents. Transesterification is a principal chemical conversion technology for the production of biodiesel. (EPA, 2007) The most common and commercialized technologies for bioenergy production are fuel ethanol production from corn and biodiesel production from oils/fats. For all of these techniques, first the biomass harvested or collected needs to be pretreated and made ready for processing. After pretreatment, biomass is converted to the useful form of energy.

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Among various conversion technologies, this study is focused on the utilization of syngas, which is the useful product generated as a result of gasification process.

2.3 Gasification Technology

Gasification is a thermochemical conversion of a carbonaceous feedstock such as biomass or coal by partial oxidation at elevated temperature into a gaseous mixture commonly known as syngas. Syngas mainly consists of carbon monoxide, carbon dioxide, hydrogen, nitrogen (if air is used as the oxidizing agent), methane, trace amounts of higher hydrocarbons such as ethane and ethene, water, and contaminants such as small char particles, ash, tars and oils. Air, oxygen, steam or a mixture of these can be used as the partially oxidizing agent. The heating value of syngas is mainly influenced by factors such as inert gas (nitrogen) content and CO/H_2 ratio. Gasification using air as oxidizing agent produces a low quality syngas in terms of higher heating value (HHV) (4-7 MJ/Nm^3 HHV) due to the presence of around 50% of inert N_2. Syngas from air gasification is mainly suitable for boiler, engine and turbine operation. Gasification using oxygen as oxidizing agent produces a better quality syngas (10-18 MJ/Nm^3 HHV) suitable for limited pipeline distribution and for use to convert into methanol, gasoline, etc. Pyrolytic or steam gasification can also be used to produce syngas of this quality, generally by supplying process energy from combustion of by-product char. (Bridgwater, 1995) The most widely used gasification technology is air gasification as this avoids the costs associated with oxygen production in oxygen gasification, and the complexities and costs associated with multiple reactors in steam or pyrolytic gasification. (Bridgwater, 1995)

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2.3.1 Principles of Gasification

Drying, pyrolysis, oxidation and reduction thermochemical processes occur in every gasifier in all types and constructions (Bridgwater, 1995).

Drying of biomass occurs at temperatures above 100°C in first zone of the gasifier reactor utilizing the heat from other reaction zones. Part of water vapor obtained as the result of drying process is converted to hydrogen and the remaining appears as moisture content in syngas (Brigdwater, 1995; Wei, 2005).

Pyrolysis, thermal breakdown of feedstock in the absence of oxygen, takes place in the temperature ranging between 200 to 600°C, producing solid char, liquid tar and a mixture of gases having relatively lower heating value. Although details of pyrolysis reactions are not known, it is believed that the large molecules of cellulose, hemi-cellulose and lignin break down into medium-size molecules and char (carbon). For longer residence time in this zone, the medium sized molecules and char will break down into even smaller molecules of CO, CO_2, H_2, CH_4, ethane, ethylene and many more compounds. For shorter residence time or lower temperature, medium sized molecules can escape and condense as tars or oils. (Brigdwater, 1995; Wei, 2005)

The products formed as a result of pyrolysis reaction enter the oxidation zone, where air (for air gasification), steam (for steam gasification) or oxygen (for oxygen gasification) is introduced and exothermic reaction occurs raising the temperature upto 1500°C. Medium-sized molecules are cracked into smaller-sized molecules like CO, H_2, CH_4, etc. For air gasification, nitrogen content in the syngas is high as air contains around 79% nitrogen by volume. Nitrogen is considered to be non-reactive with fuel constituents

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at relatively lower pressures and temperatures. However, this problem is eliminated with the use of steam or pure oxygen. (Brigdwater, 1995; Wei, 2005)

Products of oxidation zone, hot gases and glowing char enter the reduction zone, where there is insufficient oxygen for oxidation to occur. Thus, reduction reactions between hot gases (CO, H_2O, CO_2 and H_2) and char take place to produce CO, H_2 and other constituent gases and traces of impurities, combinedly known as syngas. The sensible heat of the gases and char is converted as much as possible into the stored chemical energy in syngas. (Brigdwater, 1995; Wei, 2005)

2.3.2 Types of Gasifiers

Gasifiers can be broadly categorized as fixed bed, fluidized bed and "novel" designs (EPA, 2007).

2.3.2.1 Fixed Bed Gasifier

Several variations in design based on the direction of flow of the generated syngas relative to the feed direction of biomass to the fixed grate for this type includes downdraft co-current, updraft co-current, updraft counter-current, cross-draft and open core or stratified fixed bed gasifier types, (Bridgwater, 1995; EPA, 2007); some variations in design are shown in figure 2.1.

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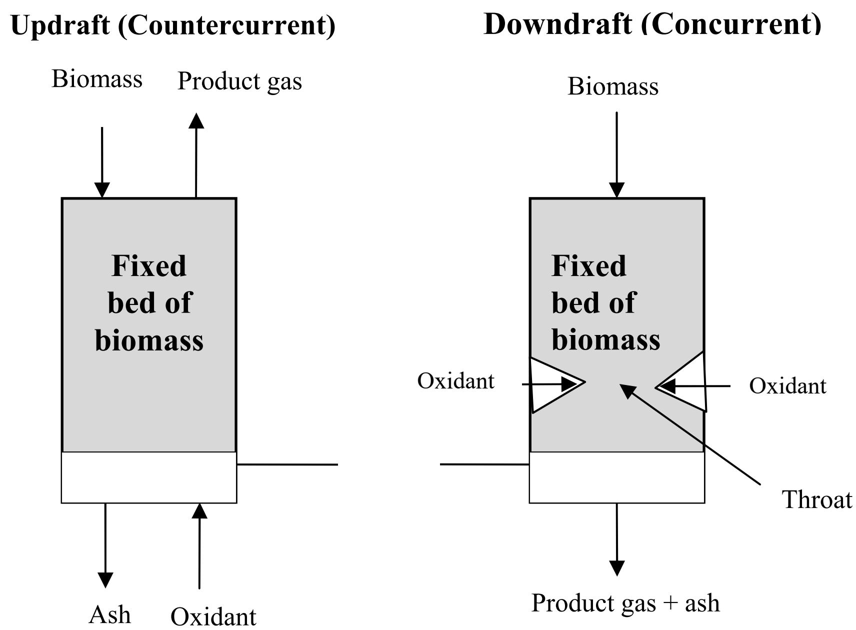

Figure 2.1 Some Typical Fixed Bed Gasifiers (Bridgwater, 1995)

Some of the features of downdraft gasifier include its simplicity and reliable design. Further, relatively clean gas is produced and the carbon conversion rate as well as conversion efficiencies are high. There exists the possibility of ash fusion and clinker formation on grate. The residence time of the solids is high. Except for the flow direction of product gas and the feedstock, the main difference between the downdraft and updraft gasifier is that the syngas produced from updraft gasifier is dirty with high level of tars. (Bridgwater, 1995)

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2.3.2.2 Fluidized Bed Gasifier

Several variations in design in fluidized bed gasifier include single reactor, fast fluid bed, circulating bed, entrained bed and twin reactor fluidized bed gasifier (Bridgwater, 1995). Figure 2.2 shows some types of fluidized bed gasifiers.

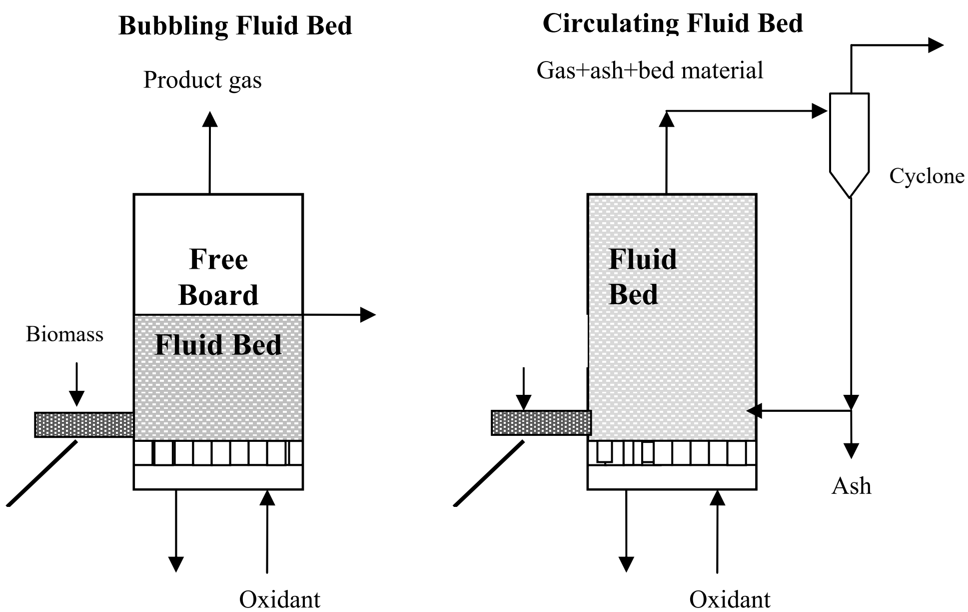

Figure 2.2 Some Typical Fluidized Bed Gasifiers (Bridgwater, 1995)

In this type, generated gas and solids (biomass feedstock to be gasified) are mixed intimately and thus, the reaction rates are quite high. These gasifiers have isothermal bed operation at the typical operation temperature of about 800-850°C. Silica sand is usually used as the fluidizing material. The conversion of feedstock to the product gas mostly takes place within the bed. Carbon conversion approaches 100% in most of the cases. The operation can be either pressurized or atmospheric. Some of the drawbacks of this type

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are the generation of syngas with relatively higher tar content and incomplete carbon conversion. (Bridgwater, 1995).

Apart from the fixed and fluidized gasifiers, there are other “novel” designs such as plasma arc gasification, 2-stage gasification, open-top gasification and aqueous phase reforming gasification (EPA, 2007).

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CHAPTER 3

PERFORMANCE AND EMISSIONS OF A SPARK-IGNITED ENGINE DRIVEN GENERATOR ON BIOMASS BASED SYNGAS

This chapter contains the performance and exhaust emissions of a spark-ignited engine driven generator on syngas from biomass gasification at four different electrical power outputs. Further, the results obtained for performances and exhaust emissions with syngas at four electrical power outputs were compared with those obtained with gasoline at the same electrical power outputs. Section 3.1 contains brief overview of some relevant works and the objectives of this study. Sections 3.2 and 3.3 present the procedures and results of this study. Finally, section 3.4 concludes this chapter.

3.1 Introduction

The need to have energy security and more environment friendly technologies necessitates the use of renewable fuels in internal combustion (IC) engines, to substitute or supplement gasoline and diesel. Many commercial spark and compression ignition engines are being converted to be fueled with propane, natural gas, hydrogen (H_2), liquefied petroleum gas (LPG), biogas or the mixture of the above gases for use in power generation, transportation and other applications (Thiagarajan et al., 1995; Yi et al., 1995;

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Das et al., 2000; Erol Kahraman et al., 2006; Mustafi et al., 2006; Papagiannakis et al., 2007).

A possible alternative fuel for the gasoline spark ignition (SI) engine, which is the subject of this study, is a synthetic gaseous fuel called 'syngas'. Syngas from biomass gasification is a potential renewable energy source for the future. Gasification is the conversion of carbonaceous materials, such as biomass and coal, using a controlled amount of oxygen at high temperature into carbon monoxide (CO) and H_2, which are together known as synthesis gas (syngas). The main constituents of syngas are CO, carbon dioxide (CO_2), H_2, methane (CH_4), water, nitrogen (N_2) and contaminants like tars, small char and ash particulates and other impurities (Wei et al., 2006).

The first attempt to use syngas to run IC engine was made around 1881 when it was referred to as 'suction gas' because the gas was sucked by the engine from the gasifier (Safari Seeds, 2008). During the period of 1901-1920, many gasifier-engine systems were commercially used for power and electricity generation. Subsequently, the availability of economical gasoline and diesel caused the decline in syngas production and utilization. But, a renewed interest has evolved for gasification technology and the use of syngas for power and electricity production due to the emergence of need for renewable energy.

Earlier studies (Papagiannakis et al., 2007; Mustafi et al., 2006; Sadykov et al., 2005; McMillian and Lawson, 2005; Shudo et al., 2003; Smith and Bartley, 2000) have explored the potential of syngas as an alternative engine fuel, but syngas in the studies was produced by methods other than gasification. Syngas in these earlier studies were produced by chemical conversion of natural gas, gasoline, diesel, etc. Mustafi et al.

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(2006) studied the use of syngas obtained from the processing of "Aqua–fuel" in a variable compression ratio "Ricardo E6" single cylinder gasoline SI engine. Mustafi et al. (2006) found that syngas produced about 20 and 30% lower engine power output than natural gas and gasoline, respectively. Regarding exhaust emissions, for syngas fueled engine in the study of Mustafi et al. (2006), concentrations of hydrocarbons (HC) and CO were negligible but CO_2 and oxides of nitrogen (NO_x) were found to be higher compared to the other fuels. Shudo et al. (2003) studied the use of low calorific flammable gases containing H_2 and CO generated by pyrolysis gasification from wastes such as shredder dust of automobiles, as engine fuel for single-cylinder, four-stroke SI engine to be used for stationary electric power generation. Shudo et al. (2003) studied the influences of heating values, CO/H_2 ratios and presence of different proportions of inert gas in engine fuel used on combustion and emissions from the engine. The most relevant findings of Shudo et al. (2003) in context to this study was that the NO_x emissions decreased upon increasing the amount of inert N_2, decreasing the heating value of fuel combusted and increasing the CO/H_2 ratio in the fuel. Sadykov et al. (2005) studied the use of syngas, synthesized from gasoline and natural gas in either axial type or radial type compact syngas generators, as engine fuel for four-cylinders, four-stroke "VAZ 2111" gasoline SI engine, four-cylinders, four-stroke "VAZ 2114" natural gas SI engine and water-cooled, four-cylinders, four-stroke "D-245.12" diesel compression ignition engine. Sadykov et al. (2005) found that there were substantial reductions in the NO_x, CO and HC emissions when syngas was used as fuel at stoichiometric levels of oxygen compared to gasoline. McMillian and Lawson (2005) developed a numerical model with experimental validation for the use of syngas, synthesized from partial oxidation of natural gas, as

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engine fuel in a SI partial oxidation engine to determine particulate emissions. McMillian and Lawson (2005) found that rich-burn particulate matter production was not more than that from typical lean-burn operation over the experimental range. Smith and Bartley (2000) studied the use of stoichiometric mixture of syngas that had been synthesized from a partial oxidation of methane, and natural gas as the fuel for a single cylinder "Caterpillar 1Y540" SI engine modified for natural gas operation with exhaust gas recirculation (EGR). Smith and Bartley (2000) compared the engine performance and exhaust emissions when the stoichiometric mixture of syngas and natural gas was used as fuel to that with natural gas used alone and found that the thermal efficiency increases with increasing EGR and the use of syngas with natural gas yielded 77 % reduction in raw NO_x emissions. Papagiannakis et al. (2007) studied the performances and exhaust emissions of a turbocharged, water-cooled, multi-cylinder (20 cylinders), four-stroke "GE-Jenbacher 320" natural gas SI engine fueled with syngas created from the gasification of biomass and compared the results with those for natural gas. Papagiannakis et al. (2007) found that nitric oxide (NO) and CO emissions were lower for natural gas compared to syngas. All these studies provide brief overview of the works related to using syngas as an alternative engine fuel.

Personal power systems, such as domestic commercial generators, could be a way of decentralized energy production and hence, could play a significant role in energy independence. Emission levels along with performance parameters play a vital role in the eventual deployment and implementation of such personal power systems. Personal power systems operating on alternative bio-renewable fuels like syngas can be a more promising alternative to fossil fuels operated power systems during natural disasters like

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hurricanes. The objectives of this study were to determine the performance and the exhaust gas emissions of a generator driven by a spark-ignited engine at different flow rates of syngas and compare the results with those for gasoline at the same electrical power outputs.

3.2 Materials and Methods

The syngas used in this study was produced using a fixed bed, down draft atmospheric pressure gasifier-"Renewable Fuel Gas Generator (RFGG)", purchased from Community Power Corporation, Littleton, Colorado. The capacity of the RFGG was 18 kW (electrical equivalent) with a gas flow rate output ranging from 30 to 60 Nm^3/h. A syngas purification unit was also embedded in RFGG gasifier unit. The feedstock used for gasification was hardwood chips, provided by Domtar Paper Co., LLC, Amory, Mississippi. The composition (v/v) of the generated syngas was 16.2-24.2 % CO, 13-19.4 % H_2, 1.2-6.4 % CH_4, 9.3-13.8 % CO_2 with N_2 balance (Wei et al., 2006). Some of the suggested properties required for the syngas to be of acceptable quality to be used as engine fuel (Stergarsek, 2004; Heesch et al., 1999; FAO, 1986; Tiedema et al., 1983) and the experimental values for those properties for the syngas generated from RFGG as obtained by Wei et al. (2006) are tabulated in Table 3.1. The syngas generated from RFGG was of acceptable quality to fuel an SI engine driven generator.

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Table 3.1 Average Properties of Syngas generated by RFGG and Allowable Limits for Use of Syngas as Engine Fuel:

Parameters	Unit	Average	Standard Deviation	Acceptable Syngas Quality for Engine Use
LHV	MJ/Nm^3	5.79	0.52	Greater than 4.2
Tars	mg/Nm^3	14.06	8.54	Lower than 50
Particulates	mg/Nm^3	3.05	1.79	Lower than 50

The generated syngas was stored in commercial 0.1 m^3 (25 gal) stainless steel LPG tanks (Worthington Cylinder Corporation, Columbus, OH) at 1500 kPa (220 psi). For storage, syngas was compressed using a two stage gas booster system (Model HIHPG2 – 20328, Hydraulics International Inc, Chatsworth, CA). The maximum air inlet and outlet pressures of the gas booster system were 1034 kPa (150 psi) and 13790 kPa (2000 psi), respectively. The schematic for the syngas compression and storage setup is shown in figure 3.1. The syngas generated from gasifier was diverted to the condenser through a bypass port with ball valve, connected between gasifier and gasifier flare. This was done to reduce the temperature of the generated syngas which was around 80°C (Wei et al., 2006). The excess syngas was burnt in a flare to prevent environment from being contaminated with CO. After reducing the temperature of the generated syngas, it was stored in the surge tank using a vacuum pump. The purpose of surge tank was to maintain constant pressure for intake to compressor. Finally, syngas is compressed with the hydraulic gas booster system and stored in the storage tanks at 1500 kPa (220 psi).

The stored syngas was then utilized as engine fuel to run a 5500 W overhead valve Elite Series Portable Generator (Model 01654-02, Briggs and Stratton Power

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Products Group LLC, Jefferson, WI). The generator was a naturally-aspirated, single-cylinder, four-stroke, spark-ignited engine driven, revolving field, alternating current (AC) generator, designed to operate electrical lighting, appliances, tools and motor loads (Owner's Manual No.:191958GS, Briggs & Stratton Power Products). The generator's armature was driven at 3,600 rpm (60 Hz) by the engine.

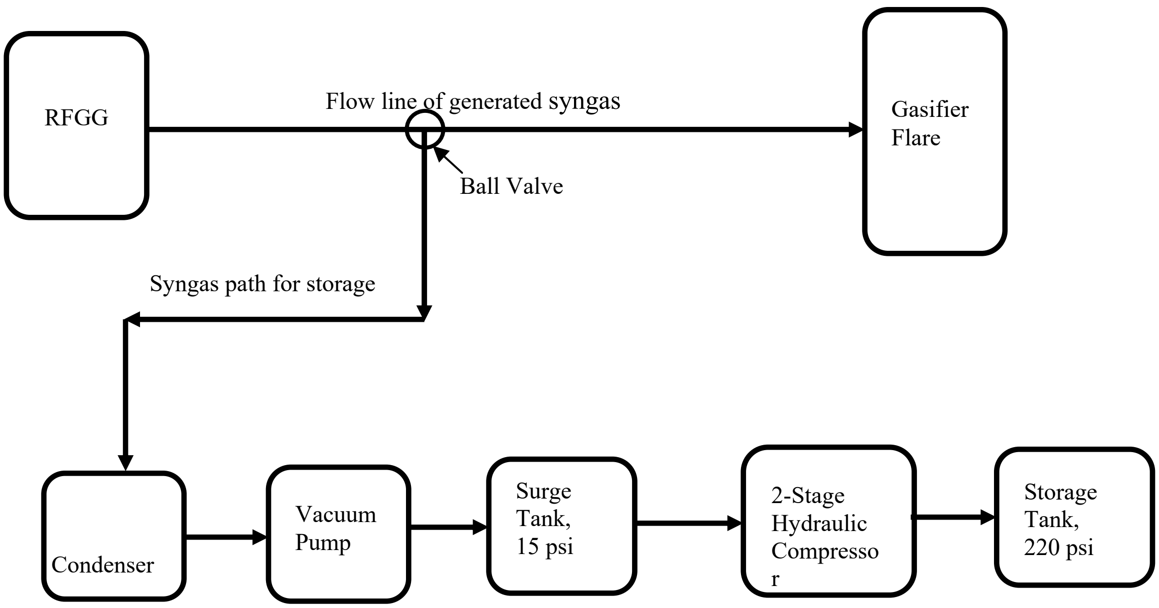

Figure 3.1 Schematic for Syngas Compression and Storage

The complete experimental setup is shown in figure 3.2. The generator was modified to run on syngas by the use of two air venturis in series, to establish the flow of syngas from the storage tank to the air intake manifold, where syngas mixed with air. Air venturis facilitated the continuous flow of air-syngas mixture to the carburetor and then to the cylinder of the engine. To regulate the flow of syngas from the storage tank, a

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pressure regulator (Model 44-2210-241, Tescom Corp., Elk River, MN) was used. The maximum inlet and outlet pressures of the pressure regulator were 12132 kPa (3500 psi) and 172 kPa (25 psi), respectively. A mass flow controller (Model FMA 544, Omega Engineering Inc, Stamford, CN) was installed to measure the flow of syngas from the cylinder to the generator. The range of the mass flow controller was 0-460 standard liters per minute (slm). The syngas was supplied to the engine through Accuflex 454-04 (25 mm) high pressure LPG hose. To run the engine on syngas, it was first cranked on gasoline and then the gasoline supply was turned off with the syngas supply being turned on simultaneously.

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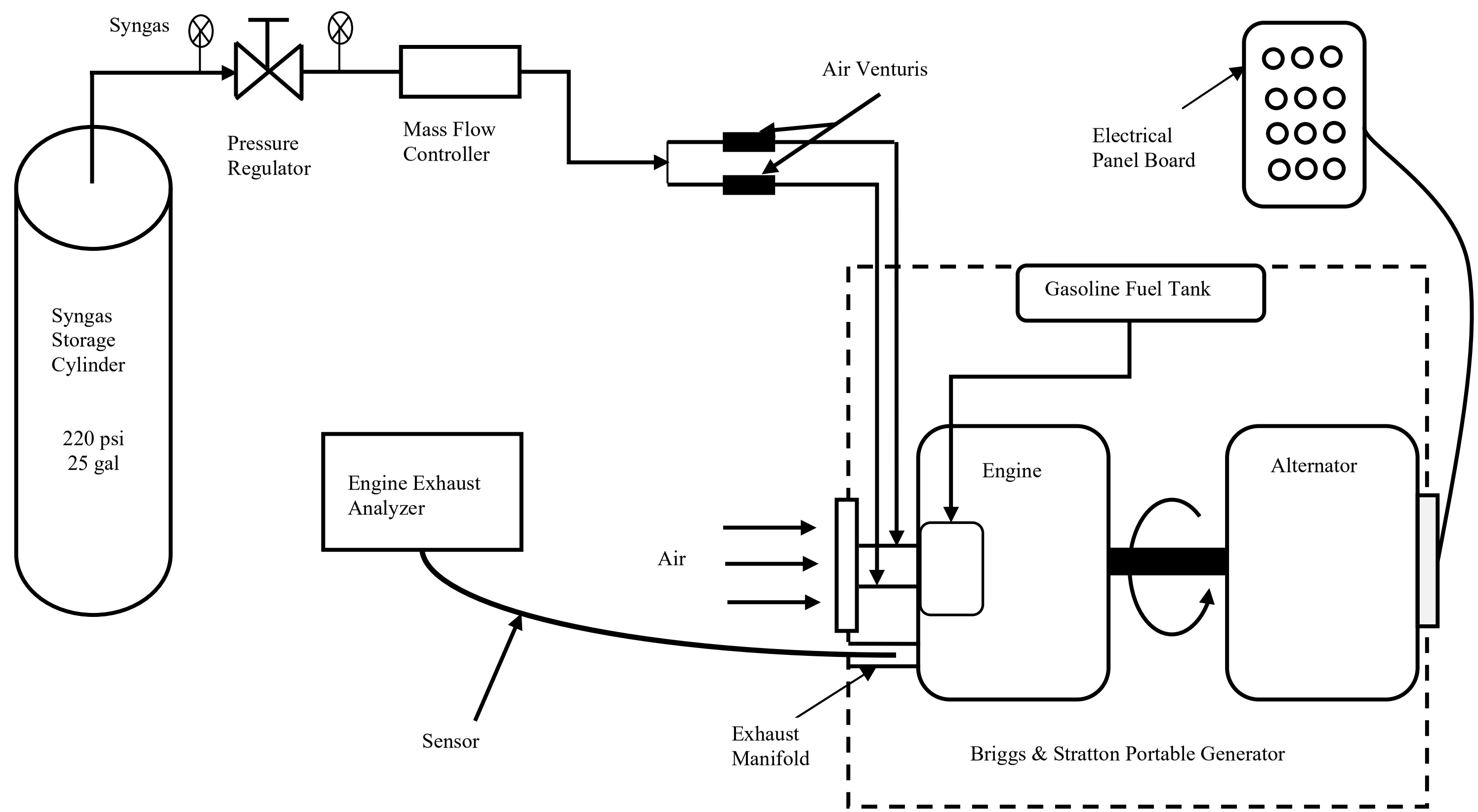

Figure 3.2 Schematic of Experimental Setup

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The engine performance parameters studied in this work were the electrical power output, overall efficiency and the run duration of the generator on syngas. The emissions studied were the concentrations of CO, CO_2, HC and NO_x (NO and nitrogen dioxide (NO_2)). For the experiments, four different flow rates of syngas, i.e., 50, 60, 80 and 90 slm, were chosen within the operating range of the generator. Power ratings 1, 2, 3 and 4 were designated for the electrical power outputs obtained for the ascending order of the chosen flow rates of syngas. In this study, power ratings 1, 2, 3 and 4 corresponded to the flow rates 50, 60, 80 and 90 slm respectively. For syngas operation, the load to the generator was adjusted such that the output voltage was around 90 V. This voltage, 90 V, has been considered as the practical minimum operating voltage of the generator in this study. For gasoline operation, required electrical power outputs for each power rating were obtained by adjusting the electrical loads to match with the electrical power outputs obtained for syngas operation and the output voltages for the gasoline operation were in the range from 104 V to 111 V.

A collection of incadescent light bulbs ranging in wattage from 25 W to 300 W were used to provide the appropriate resistive loads to the engine. The generator had two single-phase 120 V AC outlets and the circuits were also merged together to form a single two (240 V) phase AC circuit. In this study, the single phase circuits were used to measure the actual electrical power output of the generator to the loads. Equal wattage loads were connected to both of the outlets and the AC current and AC voltage were measured across those circuits using multimeters (Model 61-746, Ideal Industries Inc., Sycamore, IL). Total electrical power output was obtained as the arithmetic sum of the product of current and voltage in each line.

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The input to the generator was the energy contained in the engine fuels used and the final output was the electrical power output. The LHV of syngas generated from gasifier was 5.79 MJ/Nm^3 (Wei et al., 2006) and that of gasoline was 32.2 MJ/l. The total energy input to the generator for each power rating was quantified as the product of flow rate and the LHV of respective fuels. Thus, the overall efficiency of the generator was determined for each power rating for each fuel using relation (3.1).

$$\textbf{Overall Efficiency} = \frac{\textbf{Electrical Power Output}}{\textbf{Lower Heating Value of Fuel} * \textbf{Flow Rate of Fuel}} \tag{3.1}$$

For emissions study, the original tail pipe of the generator was extended using a 0.61 m (2-ft) long and 0.05 m (2-inch) internal diameter stainless steel pipe to facilitate easy inserting of the sensor for emissions determination and to have a bypass port for the sample collection. Portable engine exhaust analyzer (Model 7466LSK, Nova Analytical Systems Inc, Niagara Falls, NY) was used to quantify the concentrations of HC, NO and NO_2 in the generator exhaust. The data from the engine exhaust analyzer was acquired using the serial port communication at intervals of 5 sec. For the determination of the concentrations of CO and CO_2, two samples of generator exhaust per replication for each power rating were collected into Tedlar bags of 1 liter capacity each. Each collected sample was analyzed three times using a gas chromatograph unit (Model GC6890, Agilent Technologies Inc., Palo Alto, CA) and the concentrations of CO and CO_2 were reported as the arithmetic mean of 18 values for each power rating. The concentrations of NO and NO_2 were presented combinedly as NO_x in this study.

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For the determination of the flow rate of gasoline, original fuel tank of the generator was replaced with a calibrated vessel of 14 liters capacity. Flow rate of gasoline was determined by measuring the change in volume of gasoline for specific duration at each power rating.

For the multiple comparison procedures of the analyzed performance and emissions data at 95% confidence interval, SAS 9.1.3 (SAS Institute Inc., Cary, NC) was used. All the results reported in this study are the arithmetic average of the three replications.

3.3 Results and Discussion

3.3.1 Performance: Electrical Power Output, Overall Efficiency and Run Duration

The maximum electrical power output for syngas operation was 1392 W, which was obtained at flow rate of 80 slm. The overall efficiency was 19.1%. The output voltages for this electrical power output were 89.0 V and 89.3 V respectively in lines 1 and 2 of the generator circuit. For gasoline operation, the maximum electrical power output as obtained at the gasoline flow rate of 1.42 lph was 2451 W. The overall efficiency was 19.3%. The output voltages were 88.9 V and 88.6 V, respectively in lines 1 and 2 of the generator electrical circuit for gasoline operation. Thus, the overall efficiency for gasoline and syngas operation were similar at their respective maximum electrical power outputs. The maximum electrical power output for syngas operation was lower because the LHV of syngas (5.179 MJ/kg) is lower compared to the LHV of gasoline (44.4 MJ/kg).

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The electrical power outputs of the generator at syngas flow rates of 50, 60, 80 and 90 slm were 739 W, 915 W, 1392 W and 1135 W respectively, which were designated as power ratings 1, 2, 3 and 4, respectively (Figure 3.3). The notation 'PR' stands for power rating in the figures 3.3-3.7. For power rating 4, although syngas flow rate was the highest, the generator's electrical power output was not the highest. For the comparison, performances and emissions data were collected at these four power ratings with syngas and gasoline. At the point of maximum electrical power output of the generator on gasoline, comparison with syngas could not be made due to the incapability of the generator to generate 2451 W with syngas.

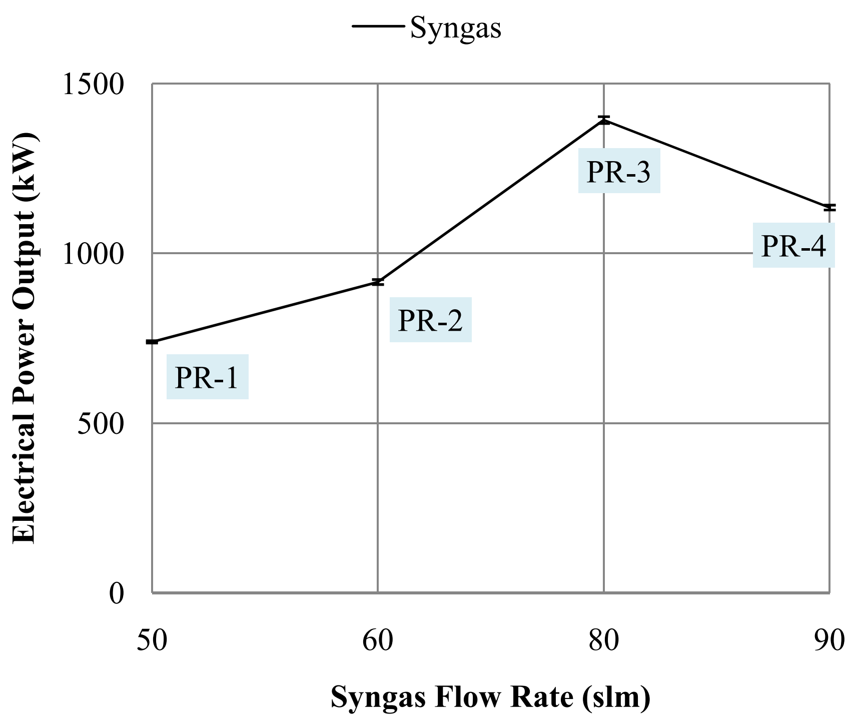

Figure 3.3 Electrical Power Outputs of the Generator (Syngas Operation) at different Syngas Flow

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Within the operating range for syngas, the maximum overall efficiencies of the generator were found to be 19.1% and 11.4% on syngas and gasoline respectively, both at power rating 3. Figure 3.4 shows the overall efficiencies of the generator on gasoline and syngas at all the four power ratings and the maximum electrical power output of the generator on gasoline. Further, the percentage change for overall efficiency for the syngas operation compared to the gasoline operation for each power rating is plotted as up-down bar in figure 3.4. The notation 'GPR-Max' in the figure 3.4 stands for the maximum electrical power output on gasoline.

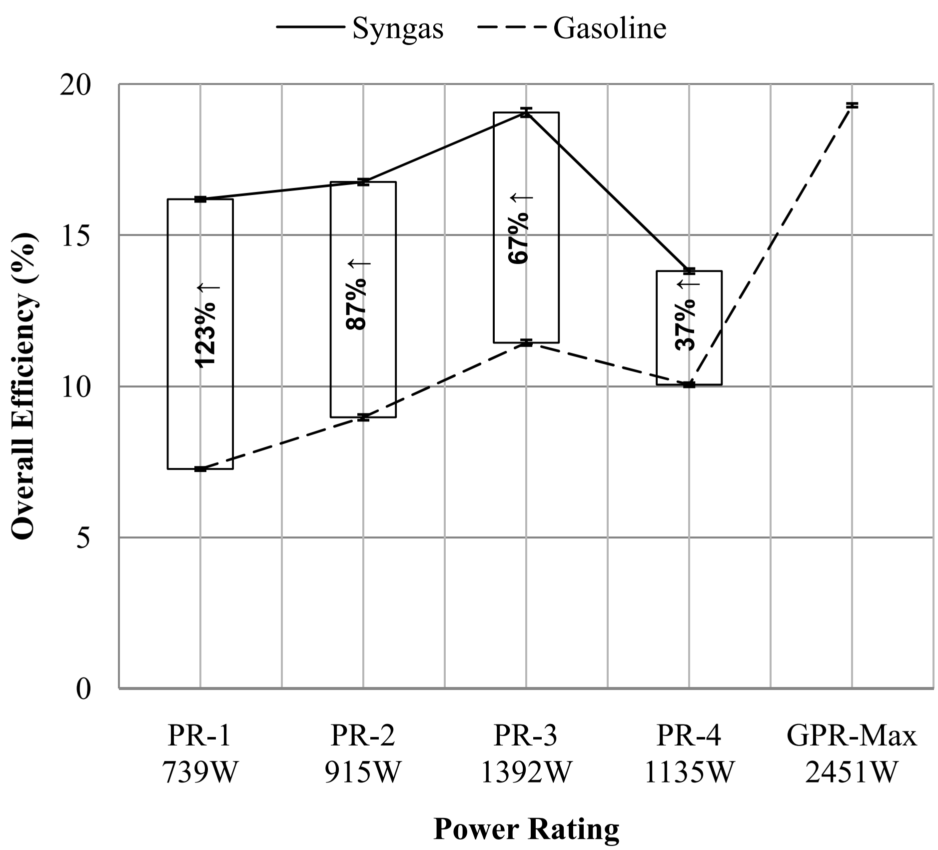

Figure 3.4 Overall Efficiencies of the Generator at different Power Ratings.

Note: Maximum electrical power outputs from syngas and gasoline were 1392 W and 2451 W respectively. Efficiencies at maximum power outputs are similar

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For both the syngas and gasoline operations, the overall efficiencies and the electrical power outputs of the generator increased from the power rating 1 to 3 and then decreased for the power rating 4. For syngas operation, the overall efficiency was the least for the power rating 4 despite feeding the highest flow rate of syngas to the generator. This can be attributed to the reason that the generator not being able to utilize all the syngas fed to it. The trends and values obtained for electrical power outputs for syngas and gasoline operations are almost the same for all four power ratings. This validates one of the objectives of this study; to compare different emissions parameters at the same electrical power outputs. At each power rating, the overall efficiency for syngas operation was significantly higher by 37-123% than that for gasoline operation. This might be due to the reason that the lower heating value (LHV) of gasoline is higher than that of syngas, so during gasoline operation the equivalent electrical power outputs as obtained with syngas operation were attained even at lower overall efficiencies. The overall efficiencies for gasoline operation was lower further due to the reason that the required electrical power outputs for each power rating were attained at the output voltages in the range of 104-111 V in both the lines whereas for syngas the electrical power outputs were attained at output voltages in the range 86 to 92 V.

For syngas operation, the syngas flow could not be maintained below 690 kPa (100 psi) at higher flow rates (80 and 90 slm) and hence, pressure drops of 1380 kPa (200 psi) could not be attained at the higher syngas flow rates. For easy comparison, the run durations are reported for equivalent pressure drop of 1380 kPa (200 psi) for all four syngas flow rates. For pressure drop of 1380 kPa (200 psi), the run durations obtained on an average with syngas as engine fuel for the power ratings 1, 2, 3 and 4 were 22 min, 20

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min, 16 min and 14 min respectively. The low run duration warrants the need for further research to store syngas in higher capacity cylinders and higher pressures in order to be able to run the generator for the extended durations. The flow rate of gasoline increased for the power ratings 1 through 3 and then decreased for the power rating 4. It was in the range of 1.14 to 1.37 lph. The flow rate of gasoline was the maximum for the maximum electrical power output of the generator on gasoline.

3.3.2 Emissions Results

Figures 3.5, 3.6 and 3.7 show the exhaust emissions, CO, CO_2 and NO_x respectively from the generator on syngas and gasoline at different power ratings. These plots also show the percentage change of the respective emissions for syngas operation as compared to the gasoline operation at each power rating. CO emissions were significantly lower by 30-96% for syngas operation compared to gasoline operation, perhaps because of better combustion of syngas in the engine cylinder within the experimental range. For gasoline operation, the higher content of CO might be due to the incomplete oxidation of the carbon in gasoline as it is high carbon compound. Further, it might be due to the rich operation (lower air to fuel ratio) of the engine (Heywood, 1988). For syngas operation, CO emissions were in the range of 1,148 to 8,693 ppm, except for the power rating 4 (27,135 ppm). For power rating 4, despite feeding the highest flow of syngas to the generator, the generator's electrical power output and the overall efficiency were not the highest, perhaps due to the incomplete combustion. For syngas operation, CO emissions show the increasing trend with increasing syngas flow as it increased from the power rating 1 to 2 and there was no significant change between power ratings 2 and 3. For the

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power rating 4, it again increased significantly (figure 3.4). For gasoline operation, the exhaust CO concentrations increased with increasing electrical power outputs from the power ratings 1 to 3 and then decreased for the power rating 4, as electrical power output for the power rating 4 was less than that for 3. For gasoline operation, this advocates the dependence of CO emissions upon electrical power outputs of a generator. CO emissions were in the range 30,563 to 48,954 ppm for gasoline operation. The substantial decrease in CO emissions with the use of syngas as engine fuel reinforces its importance as low concentrations of CO would decrease the risk of suffocation caused by the strong adherence of CO to haemoglobin (Abdel-Rahman, 1998).

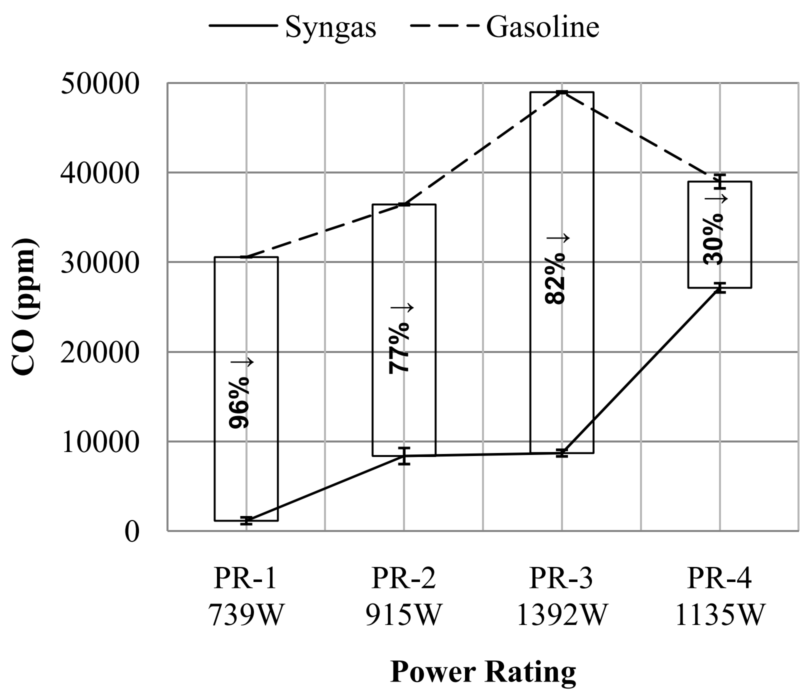

Figure 3.5 Exhaust Emissions Concentrations of CO

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CO_2 concentrations in the exhaust emissions of the generator were significantly higher by 33-167% for the syngas operation compared to the gasoline operation (Figure 3.5). The increase in the CO_2 concentration in the generator exhaust while operating on syngas compared to the gasoline operation at every power rating was due to the presence of CO_2 in syngas used in this study and the conversion of CO in the syngas to CO_2 upon combustion. For the syngas operation, CO_2 emissions show the increasing trend with the increasing syngas flow. With the increase in syngas flow, the exhaust CO_2 concentrations increased from the power rating 1 to 2 and then remained statistically constant without any significant change. The concentrations of exhaust CO_2 were 10.6-13.1% for syngas operation and 4.9-8.1% for gasoline operation. For the gasoline operation, CO_2 emissions had decreasing trend with respect to increasing electrical power output as the concentrations of CO_2 emissions remained statistically similar for the power ratings 1 and 2 and then decreased significantly for the power ratings 3 and then 4.

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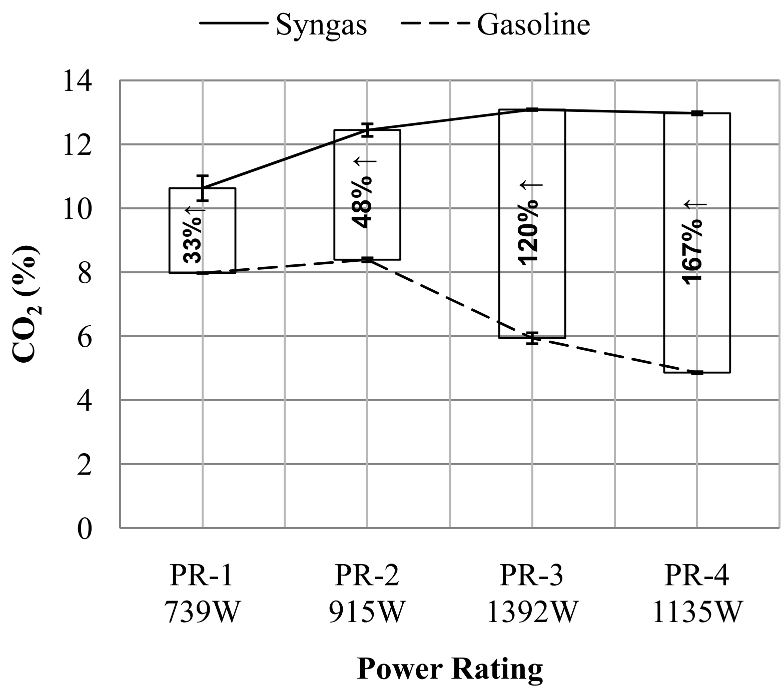

Figure 3.6 Exhaust Emissions Concentrations of CO_2

The concentrations of exhaust HC were found to be less than 40 ppm for almost all the 4 power ratings for syngas operation. This can be considered as negligible. Further, no trend was observed for HC emissions in this study. This may be due to the presence of very less HC (1.2-6.4 %) in the syngas used in this study.

For each power rating, NO_x emissions were lower by 54-84% for the syngas operation (31-94 ppm) compared to the gasoline operation (166-215 ppm) as shown in figure 3.6. NO_x are formed from the oxygen and nitrogen at high temperatures in a reaction separate from combustion by Zeldovich mechanism (Sadykov et al., 2005). This signifies the dependence of NO_x on temperature. The lower NO_x emissions for syngas operation might have occurred due to the lower temperatures in the engine cylinder due to lower LHV of syngas resulting in lesser reaction between nitrogen and oxygen. For

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syngas operation, NO_x increased from the power rating 1 upto 3 and decreased for the power rating 4. This shows the dependence of NO_x formation on the electrical power output of the generator. Higher the electrical power output, higher the temperature generated in engine cylinder and hence higher the formation of NO_x. Both electrical power output and NO_x in the exhaust emissions were the highest for the power rating 3. For gasoline operation, there was no specific trend for NO_x emissions. However it was found to be the highest for the power rating 3. The substantial reduction in NO_x emissions adds to the value of syngas as engine fuel as NO_x causes lung irritation, impairment of functions of the lungs, tissue damage and irritation of mucous membranes. Further, NO_x increases the risk of nitric acid formation. (Abdel-Rahman, 1998)

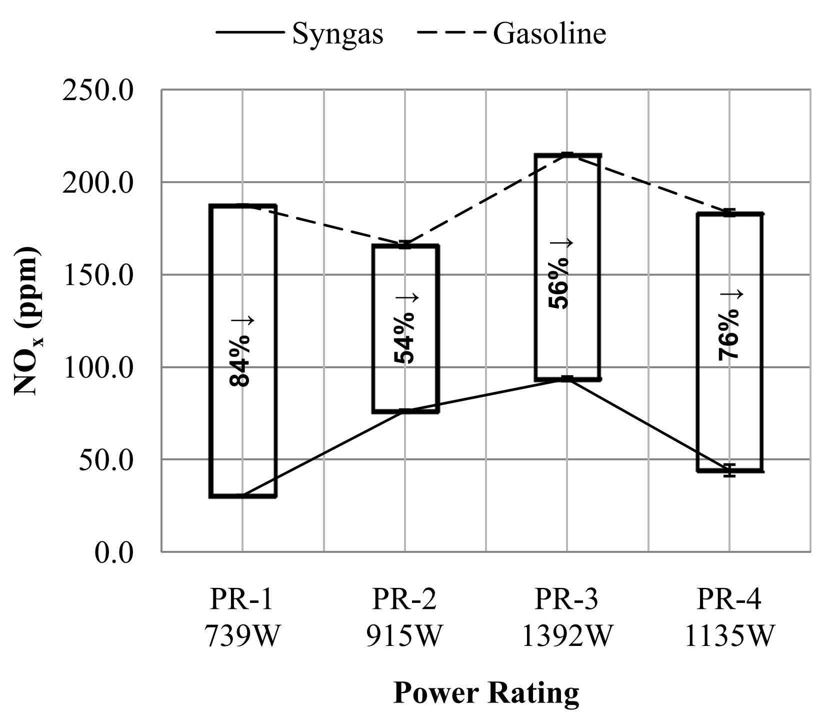

Figure 3.7 Exhaust Emissions Concentrations of NO_x

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The trend of the results for emissions obtained in this study were similar to that obtained by the study of Mustafi et al. (2006), except the NO_x emissions. In the study of Mustafi et al.(2006) NO_x was higher for syngas operation compared to the gasoline operation due to the generation of higher temperature in the engine cylinder and the relatively shorter combustion duration as the fuel used in the study did not contained the inert N_2 and contained 52% CO and 44% H_2, both having relatively high flame speed and flame temperature. The trends for CO and NO_x emissions results were same as found by Sadykov et al. (2005).

3.4 Conclusion

A system to supply and utilize syngas in a naturally-aspirated, four-stroke, single-cylinder, spark-ignited engine driven generator was assembled and run successfully. The generator was operated at syngas flow rates of 50, 60, 80 and 90 slm and the electrical power outputs were 739 W (power rating 1), 915 W (power rating 2), 1392 W (power rating 3) and 1135 W (power rating 4) respectively. The maximum electrical power output of the generator on gasoline was found to be 2451 W. The overall efficiency of the generator at maximum electrical power output on syngas and gasoline was same. The run durations of the generator on syngas for a pressure drop of 1380 kPa (200 psi) were in the range of 14-22 min. To achieve the desired electrical power outputs, flow rates of gasoline were in the range of 1.14-1.37 lph. The amounts of CO in generator exhaust emissions were statistically significantly lower by around 30-96% for syngas operation (1,148-27,135 ppm) compared to the gasoline operation (30,563-48,954 ppm) for every power rating. However, CO_2 emissions in the generator exhaust were always statistically

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significantly higher by around 33-167% for syngas operation (10.6-13.1%) compared to the gasoline operation (4.9-8.4%). NO_x emissions were always statistically significantly lower by around 54-84% for the syngas operation (31-94 ppm) compared to the gasoline operation (166-215 ppm).

Although the maximum attainable electrical power for the syngas operation was lower, CO and NO_x emissions decreased significantly for the syngas operation. The increase in CO_2 emissions during syngas operation would not contribute significantly towards environmental degradation as syngas is generated from biomass and hence, it is considered CO_2 neutral. Increase in electrical power output of generator, increase in run duration by increasing storage pressure/volume of syngas and exhaust heat recovery would be important steps towards making feasible syngas operated personal power systems.

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CHAPTER 4

ECONOMIC ANALYSIS

This chapter presents the economic analysis of using syngas as engine fuel in the generator during emergency situations. Further, the results of economic analysis obtained for the syngas operation are compared with those obtained for gasoline operation. Section 4.1 presents the introduction of this chapter. Section 4.2 explains the methodology for the calculations of unit cost of syngas available for utilization in terms of energy value and the unit cost for electricity generation from syngas and gasoline. Section 4.3 presents the results of the economic analysis and section 4.4 presents the conclusion of this chapter.

4.1 Introduction

The intensity of natural disasters and their consequences can never be predicted accurately. There exists a need to be proactive to tackle the possible consequences of natural disasters as these are unavoidable. Some of the probable consequences of such emergency circumstances are the discontinuity of grid connected electric power supplies, lack of fossil fuel supplies, etc. In such adverse circumstances, there is a need for emergency power systems running on alternative sources of energy like wind, solar, biomass, etc. One of the potential alternative sources of emergency power can be a system comprising a generator to operate on syngas and a gasifier-compressor

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arrangement to supply stored syngas. For the ultimate deployment of such a system, economic analysis needs to be performed in order to assess its financial viability. For economic analysis, the cost incurred per kWh of electricity generation from such systems should be determined. The gasifier-compressor-engine system at Mississippi State University (MSU) was taken as the basis for this study. The main objective of this study was to determine the unit cost of electricity generation from such systems during emergencies.

The typical facility installed at MSU includes:

- a gasifier, having syngas generation capacity of 60 Nm^3/h,
- a two stage gas booster system having capacity of compressing syngas upto 13,790 kPa (2,000 psi),
- syngas storage tanks, which are commercial 0.1 m^3 (25 gal) stainless steel liquefied petroleum gas (LPG) tanks having capacity to store syngas upto 1,724 kPa (250 psi) and
- a 10 hp naturally-aspirated, single-cylinder, four-stroke, spark-ignited engine driven generator, originally designed to operate on gasoline but with modification, converted to operate on 100% syngas.

A possible variation in the existing system is also considered in this economic analysis; using a single high-pressure high-capacity cylinder instead of using the multiple low-capacity low-pressure cylinders for storage. The maximum electrical power outputs and run durations of the generator and flow rates of the fuel for syngas and gasoline

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operation are obtained from chapter 3. Prices and costs incurred are obtained from equipment manufacturers. In some cases, costs are estimated.

4.2 Methodology

The project life was taken as 10 years. The total costs incurred for generation of electricity were classified into the syngas generation cost, syngas compression and storage cost, generator cost and cost for supplying and utilizing syngas. Depreciation, annual property tax, annual property insurance and annual interest costs were not accounted for in this study except for syngas generation cost determination. Further, it has been assumed in this study that the emergency power generation system will operate 8 hours a day for 30 days in a year.

4.2.1 Determination of Syngas Generation Cost

The syngas generation cost has been taken from the study of Wei et al. (2008). Wei et al. (2008) included the costs of equipment, building, installation, test run, annual property tax, annual property insurance, auxiliaries, overheads and annual interest costs as capital cost totaling to $62,490, which is equivalent to $6,249/yr. The cost of gasifier was $28,000. Further, Wei et al. (2008) included the costs of feedstock, electricity, manpower, waste treatment, maintenance, contingency and general expenses as operating cost totaling to $44,126.85/yr for the continuous operation of 2,080 h/yr (52 weeks per year, 5 days per week, 8 hours per day). But, in this study it has been assumed that syngas would be used for operating the generator only during emergency situations. Further, emergency usage is estimated as 30 days in a year. During emergencies it has been

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assumed that the generator would operate for 8 hours a day, i.e., 240 h/yr. To fulfill this requirement, the gasifier will operate for 12 hours a day for 30 days in a year totaling to 360 h/yr. This yields the total operating cost of $7,637/yr. Thus, the total syngas generation cost becomes $13,886/yr. Further, it has been assumed that the actual syngas generation duration would be 10 hours a day for 30 days in a year totaling to 300 h/yr. Wei et al. (2008) has assumed that the RFGG would run at 90% of its full capacity. This would yield 16,200 Nm^3 syngas per year running at the capacity of 60 Nm^3/yr for the actual syngas production hour of 300 h.

4.2.2 Syngas Compression and Storage Cost

The syngas compression system comprises of a hydraulic two stage gas booster system (compressor), a condenser, a purge tank and a vacuum pump. The cost of hydraulic compressor was obtained from the manufacturer to be $9,000. The costs of all other components were estimated to be $3,000, totaling to be $12,000 or $1,200/yr. The hydraulic compression operates with air. The cost of electricity to produce compressed air and to operate the vacuum pump has been considered negligible.

Two types of storage systems were considered in this study. First, the storage system with 30 commercial 0.1 m^3 (25 gal) stainless steel LPG tanks. The price of each tank was $150, totaling to $4,500. Next, the storage system with a single commercial high-pressure (17,237 kPa or 2,500 psi) and high-capacity (379 m^3 or 100 gal) storage tank, costing $5,500. For the storage system with a single high-capacity high-pressure storage tank, it has been considered that the operator responsible for syngas generation would handle the compression and storage of syngas as there would not be any necessity

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to change the tanks frequently. But for the multiple storage tank system, an operator would be needed and the labor cost would account for 4 manhours a day for 30 days in a year, costing $16/manhour, amounting to $1,920/yr. The advantage of using a single large-capacity high-pressure cylinder would be to reduce the need for an operator to flip the cylinders while filling them and would also reduce the loss of syngas while changing cylinders. Total compression and storage costs were found to be $1,750/yr and $3,570/yr for the single and multiple storage tank systems, respectively.

It has been assumed in this study that 90% of the generated syngas could be compressed and stored for the system with single storage tank system and only 70% could be stored with multiple storage tanks system, accounting for the possible losses of syngas. So, the volumes of stored syngas are 14,580 Nm^3/yr and 11,340 Nm^3/yr, for single and multiple storage tank systems respectively.

4.2.3 Cost of Purchase and Modification of Generator

The purchased generator is modified as explained in chapter 3. The total cost for the purchase of the generator has been obtained from the manufacturer as $750 and the cost for its modification has been estimated to be $250, totaling to $1,000.

4.2.4 Cost for Supplying and Utilizing Syngas

The system to supply and utilize syngas would comprise of mass flow controller, double stage pressure regulators, high pressure hoses, several valves and fittings and 4 manhours a day for 30 days in a year. The labor cost has been taken as $16/manhour and

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the costs for all the other remaining items have been taken as $3,000. Thus, the total cost incurred for supplying and utilizing syngas becomes $2,220/yr for both the systems.

It has been assumed in this study that 90% of the total stored syngas could be utilized to operate the generator. So, the final volumes of syngas actually being utilized were 13,122 Nm^3/yr and 10,206 Nm^3/yr, for single and multiple storage tank systems respectively.

4.2.5 Determination of Unit Cost of Syngas

The unit cost of syngas was determined by adding up all the incurred yearly costs and dividing by the annual syngas actually utilized.

4.2.6 Determination of Cost of Electricity Generation

The costs of electricity generation on syngas and gasoline were determined for the maximum electrical power outputs of the generator on both of these fuels, as obtained in chapter 3. The maximum electrical power outputs of the generator on syngas and gasoline were 1,392 W and 2,451 W respectively.

For syngas operation, total input energy was determined by computing the mass of syngas consumed for the run duration obtained for 1,380 kPa (200 psi) pressure drop using the ideal gas law and then multiplying the mass of syngas consumed by the lower heating value (LHV) of syngas. LHV of syngas generated from RFGG is 5.79 MJ/Nm^3, which is equivalent to 5.179 MJ/kg.

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For the gasoline operation, total input energy was determined as the product of LHV of gasoline, flow rate for maximum power output and the run duration for the consumption of 0.25 l of gasoline. The LHV of gasoline is 32.2 MJ/l.

The cost of total energy input was determined as the product of total energy input and the unit cost of each fuel in terms of energy value. The weekly retail price of regular grade gasoline for the year 2008 (January-September) was obtained from the Energy Information Administration website. The average price of gasoline was \$3.58 per gallon (\$0.95 per liter).

The total electrical energy output was determined as the product of electrical power output and the run duration (for pressure drop of 1,380 kPa (200 psi) for syngas operation and for the gasoline consumption of 0.25 l for gasoline operation) at the maximum electrical power output. Finally, the unit cost of per kWh electricity generation was determined as the ratio of the total cost of energy input to the generator and the total electrical energy obtained from the generator.

4.3 Results and Discussions

4.3.1 Unit Cost of Syngas and Gasoline in terms of Energy Value

Table 4.1 shows the unit cost of actually utilized syngas in terms of energy value. The unit cost of syngas actually utilized were found to be \$0.24 and \$0.33 per MJ of energy contained in syngas for the single and multiple storage tank systems respectively. Substantial reduction in unit price of syngas while using single storage tank instead of the multiple storage tanks is due to the incorporation of extra cost for manpower when using

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multiple cylinders and also due to the higher loss of generated syngas during compression and storage while continuously changing the cylinders.

The unit cost of gasoline in terms of energy value was \$0.03/MJ.

Table 4.1 Unit Cost of Syngas Utilized:

Particulars	Single Storage Tank System	Multiple Storage Tank System
Actual Syngas Utilized (Nm^3/yr)	13,122	10,206
Total Cost (\$/yr)	17,956	19,776
Unit Cost (\$/Nm^3)	1.37	1.94
Unit Cost in terms of Energy Value (\$/MJ)	0.24	0.33

4.3.2 Cost of Electricity Generation with Syngas and Gasoline

Cost of electricity generation provides insight over the monetary value of per kWh electrical energy generated. Lower the cost of electricity generation better is the system. For the maximum electrical power output, the costs of electricity generation with single and multiple storage tank systems for syngas were \$4.64/kWh and \$6.38/kWh, respectively and for gasoline operation, it was found to be \$0.56/kWh. Cost of electricity generation from syngas was substantially higher than that from gasoline. Further, the cost of electricity generation with the existing facility at Mississippi State University i.e., with multiple storage tank system was found to be the highest.

The reason for higher cost of electricity generated from syngas compared to gasoline is because of lower LHV for syngas. Further, the generator used was designed and optimized for gasoline operation but it was operated with syngas without any modifications of spark ignition timing and air to fuel ratio. Thus, to reduce the unit cost

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of electricity generation on syngas, variations in the existing system need to be done. In this economic analysis, one probable variation in storage system and its implication on cost of electricity generation has been shown. Likewise, several other variations in the existing system can be done in order to decrease the electricity generation cost. Most likely variations and their implications on overall cost of electricity generation might be:

- Installing higher capacity gasifier system would reduce the operating cost for syngas generation (Wei et al., 2008).
- Installing oxygen or steam gasifier would produce syngas with higher LHV (Bridgwater, 1995) and hence the cost for electricity generation would reduce.
- Optimizing generator for syngas operation by properly adjusting various influential parameters like air to fuel ratio and spark timing for efficient operation of the generator over the higher range of syngas flow might increase the electrical power output of the generator and help in decreasing the unit cost of electricity generation.
- Designing generators specifically for the syngas operation would enhance the performance of generator and the cost of electricity generation might decrease.
- Compressing syngas using higher capacity compressor would help in compressing more syngas efficiently and would decrease the unit electricity generation cost.

4.4 Conclusions

The cost of electricity generation was found to be higher for syngas operation compared to the gasoline operation. Although the cost of electricity generation with syngas was higher compared to that for gasoline operation, syngas could be a potential engine fuel during the emergency situations when there is no grid electricity supply and

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the gasoline fuel pumps are also closed. Further, syngas is bio-renewable and many harmful emissions can be reduced using syngas rather than gasoline as engine fuel, as evaluated in chapter 3. The price of gasoline is increasing every year whereas the price of syngas can be reduced by variations in operating parameters of the system comprising syngas generation, compression, storage and utilization. The unit price of syngas can be reduced in various ways; syngas generation from higher capacity gasifier, modifying existing generators to operate on syngas efficiently, developing generators specifically for syngas operation and using high-pressure high-capacity storage tanks.

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CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

Section 5.1 of this chapter concludes the whole work presenting the main findings of the study. Section 5.2 provides some direction towards the probable continuation of this work.

5.1 Conclusions

An effort to use syngas generated from biomass gasification as an alternative engine fuel to operate commercial residential generators, originally designed to be fueled with gasoline was successful. The generator was operated at syngas flow rates of 50, 60, 80 and 90 slm and the electrical power outputs obtained were 739 W (power rating 1), 915 W (power rating 2), 1392 W (power rating 3) and 1135 W (power rating 4) respectively. The overall efficiencies of the generator for syngas operation (13.8-19.1%) were found to be statistically significantly higher by around 37-123% than those obtained for the gasoline operation (7.3-11.4%) at each power rating. However, the maximum overall efficiency of the generator on gasoline was found to be 19.3% at the electrical power output of 2451 W and the gasoline flow rate of 1.42 lph. The run durations of the generator on syngas for a 1380 kPa (200 psi) pressure drop were in the range of 14-22 min. To achieve the desired electrical power outputs, flow rates of gasoline were in

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the range of 1.14-1.37 lph. The amounts of CO in generator exhaust emissions were statistically significantly lower by around 30-96% for syngas operation (1148-27135 ppm) compared to the gasoline operation (30563-48954 ppm) for each power rating. However, CO_2 emissions in the generator exhaust were always statistically significantly higher by around 33-167% for syngas operation (10.6-13.1%) compared to the gasoline operation (4.9-8.4%). NO_x emissions were always statistically significantly lower by around 54-84% for the syngas operation (31-94 ppm) compared to the gasoline operation (166-215 ppm).

The economic analysis yielded the costs of electricity generation during the emergencies using syngas as engine fuel to be $4.64/kWh and $6.38/kWh, respectively for the single and multiple storage tank systems whereas the cost for electricity generation using gasoline as engine fuel was found to be $0.56/kWh.

Although the maximum attainable electrical power output was lower and the cost of electricity generation was higher with syngas compared to that with gasoline, the overall efficiency was higher and the harmful emissions as NO_x and CO were lower while operating on syngas. The increase in CO_2 emissions during syngas operation would not contribute significantly towards environmental degradation as syngas is generated from biomass and hence, it is considered CO_2 neutral. In the present context, when gasoline price is increasing and the concerns over environmental protection are growing rapidly, syngas could be a potential alternative engine fuel. Further during the emergency situations when there is no grid electricity supply and the gasoline fuel pumps are also closed, alternative fuels like syngas can be used as a substitute for the conventional fuels. Increase in electrical power output and reduction in the unit price of syngas can be

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achieved by generating syngas from higher capacity gasifier and by using oxygen or steam as oxidizing agent for gasification, modifying higher capacity existing generators to operate on syngas efficiently, developing generators specifically for syngas operation, using high-pressure high-capacity storage tanks and recovering heat energy in exhaust. These would be important steps towards improving syngas operated personal power systems.

5.2 Recommendations

This study focused on utilizing syngas from biomass gasification to fuel commercially available generators. The performance and emissions of the generator on syngas were determined by modifying the generator to operate on syngas. For efficient engine operation, there exists the need to adjust and modify various influential parameters like engine spark timing, air to fuel ratio, etc. Thus, one of the most important future tasks can be the optimization of these engine parameters for using syngas as fuel. For the spark-timing adjustment, there might be the need to read the crank position when the firing starts and control that using external instrumentation. For controlling air to fuel ratio, the first step might be predicting air to fuel ratio using oxygen or lambda sensor, then there might be the need to convert the naturally aspirated air intake system into turbocharged system by installing mixer before air-syngas mixture is admitted into the engine. During this study, it was difficult to operate the generator at higher flows of syngas. Thus, the next important continuation of this work might be storing the syngas in high pressure high capacity storage tanks, so that the generator could be operated for longer durations and more tests could be performed as measuring the engine pressure

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using piezoelectric sensors, measuring exhaust temperatures, etc. Some of the other directions for future works might be working towards extracting heat energy in the generator exhaust or using syngas generated from steam or oxygen gasification as fuel for generator.

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