THE AIR GASIFICATION OF WOOD CHIPS IN A DOWNDRAFT GASIFIER

by

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TABLE OF CONTENTS

Page

CHAPTER 1 INTRODUCTION

CHAPTER 2 LITEERATURE REVIEW

CHAPTER 3 MATERIAL BALANCE PROCEDURES FOR DOWNDRAFT GASIFIERS

LIST OF TABLES

Page

CHAPTER 2 LITERATURE REVIEW

Table

CHAPTER 3 MATERIAL BALANCE PROCEDURES FOR DOWNDRAFT GASIFIERS

Table

CHAPTER 4 INFLUENCE OF OPERATING PARAMETERS ON DOWNDRAFT GASIFIER PERFORMANCE

Table

CHAPTER 5 INFLUENCE OF CHIP PHYSICAL PROPERTIES ON DOWNDRAFT GASIFIER PERFORMANCE

Table

CHAPTER 6 INFLUENCE OF TREE SPECIES ON DOWNDRAFT GASIFIER PERFORMANCE

Table

LIST OF FIGURES

Page

CHAPTER 2 LITERATURE REVIEW

Figure

CHAPTER 3 MATERIAL BALANCE PROCEDURES FOR DOWNDRAFT GASIFIERS

Figure

CHAPTER 4 INFLUENCE OF OPERATING PARAMETERS ON DOWNDRAFT GASIFIER PERFORMANCE

Figure

CHAPTER 5 INFLUENCE OF CHIP PHYSICAL PROPERTIES ON DOWNDRAFT GASIFIER PERFORMANCE

Figure

CHAPTER 6 INFLUENCE OF TREE SPECIES ON DOWNDRAFT GASIFIER PERFORMANCE

Figure

CHAPTER 1

INTRODUCTION

The conversion of biomass into fuels and chemicals is being extensively studied due to low content of sulfur and nitrogen in biomass and its renewable natures. The term biomass refers to all products of photosynthesis, such as wood, corn, and algae as well as to human and animal wastes. In the United States, wood, one of the major sources of biomass, provides about 2% of the total energy needs and could contribute up to 8% within the next decade (Zerbe, 1981). Coal, on the other hand, supplies about 17% of the total energy needs (Reed and Bryant, 1978). The fact that coal contains 1 to 5% sulfur and 5 to 20% ash (which requires higher costs to remove sulfur and for ash disposal) makes wood an attractive alternate energy resource in the United States.

The objective of this thesis is to report on a study of the air gasification of wood chips in a commercial downdraft gasifier. The study gathered complete material balance data and evaluated various performance measures for the gasifier. Several parameters influencing the gasifier performance were systematically investigated. They included chip moisture content, grate rotation speed, gas fan rotation speed, chip voidage, chip bulk density, and tree species. Performance measures included the dry feed rate, char yield, dry gas-to-dry feed ratio, air-to-dry feed ratio, carbon conversion, energy output rate, cold gas efficiency, and mass conversion efficiency.

The highlights of each ensuing chapter are summarized in the following sections. Various chapters present different aspects of biomass gasification.

Chapter 2 reviews the literature on biomass gasification. Topics covered include the availability of biomass resources, history of biomass gasification, types of gasification processes, types of gasifiers, kinetics of gasification, and modeling of downdraft gasifiers.

The anticipated impact of biomass conversion technologies depends heavily on the quantity of biomass that can be made available for conversion. The existing resource base comprises agricultural residues, manures, wood and bark mill residues, logging residues, noncommercial (cull) trees in the forests, and the organic fraction of the municipal solid wastes. However, not the entire resource base can be tapped, and the usable amount depends on energy costs, competition from other fuels and solar energy, and environmental and ecological factors.

The gasification of biomass (wood chips) is not a new technology. It was developed in about 1800 and used successfully during World War II in supplying fuel gas for almost 700,000 vehicles in Europe, Australia, South America, and the Pacific Islands.

Biomass gasification can be divided into four categories: air gasification, oxygen gasification, hydrogasification and pyrolysis. Among these, air gasification is the simplest process but gives a gas of low energy content. Oxygen gasification and hydrogasification can produce a higher energy gas suitable for distribution in pipelines or for the chemical synthesis of a variety of fuels and chemicals such as methanol, ammonia, methane, and gasoline. Pyrolysis can yield gas of medium energy and in addition produce oils and chars that have a utility of their own.

Various reactors have been developed for biomass gasification. To name a few: fixed beds, moving beds, entrained beds, rotary kilns, and fluidized beds. Moving bed will be studied in depth in this thesis.

The pyrolysis of biomass at low temperatures (200°C to 600°C), is a non-equilibrium process and it is normally followed by an oxygen, air, or steam conversion of the resulting oils, tar, and char to carbon monoxide, hydrogen, or methane. Gasification with air or oxygen occurs at a temperature range of 700°C to 1100°C (about 100°C higher in oxygen). Literature, focusing on the kinetics of gasification reactions, is reviewed under this section. The review includes experimental studies and modeling efforts on moving beds.

Material balance procedures are described in Chapter 3 for the air gasification of wood chips in a commercial downdraft gasifier. Not all stream flows need to be measured directly. Some downdraft gasifiers are open at the top, this configuration gives rise to difficulty in measuring the air input rate. Even though a nitrogen tracer technique was used previously to measure the gas output rate, it was abandoned in this study for the following reasons: a) a highly accurate measurement of nitrogen concentration (nitrogen is a major component of the wood gas) is necessary because of the nature of the indirect determination, and b) a longer experimental time is required to obtain the necessary data and hence larger quantities of feed are consumed.

An over specified system may be created when several stream rates and compositions are measured. A variety of possible material balance procedures, involving different combination of the measured variables, can be used to calculate other unknown information. However, the results obtained by different combinations may be inconsistent due to the problem cf over specification.

Based on the simplicity of the calculation procedure and the effect of the variability of the measured stream rates, four material balance procedures were selected and explored in detail. Data from other studies where more stream rates were measured were employed to compare the four methods. The best method was selected based on its ability to yield reasonable closure, ability to predict reasonable stream rate magnitudes, and sensitivity to measurement errors in the measured variables.

In Chapter 4, the influence of operating parameters on performance of downdraft gasifier was examined. Three operating parameters, the chip moisture content, grate rotation speed, and gas fan rotation speed, were varied independently to systematically investigate the performance of the gasifier. A total of 20 runs were conducted: 7 runs with the chip moisture content ranging from 5 to 23% wet basis, 6 runs with the grate rotation speed ranging from 0 to 21 rph (revolution per hour), and 6 runs were conducted for the gas fan rotation speed ranging from 1400 to 2600 rpm. Three different sources of chips were used in investigating the dependency of the performance indicators. The dry feed rate, char yield, the dry gas-to-dry feed and air-to-dry feed ratios, energy output rate, gas heating value, cold gas effieciency, and mass conversion efficiency measured the performance of the gasifier. Statistical analysis was performed to evaluate the experimental data and provide regression models for all performance indicators.

Chapter 5 explores the influence of chip physical properties on the performance of the downdraft gasifier.

The influences of chip properties, such as chip voidage and chip bulk density, on the performance of the gasifier are presented. A total of 6 runs with the chip voidage ranging between 0.33 and 0.56 were conducted. Even though a range of voidage was used, the chips showed only slight fluctuations in their bulk density. For the bulk density variation runs, distinct chip sources were gasified over different ranges of gasifier operating parameters. Six runs were conducted with cottonwood (140 kg/m^3) over a gas fan rotation speed range of 1400-2600 rpm. Four runs were conducted with black locust (195 kg/m^3) over a gas rotation speed range of 1400-2400 rpm. A total of five runs were performed using cottonwood with a low bulk density (140 kg/m^3) over a grate rotation speed range of 2-13 rph and five runs using cottonwood with a high bulk density (185 kg/m^3) over a grate rotation speed range of 2-8 rph. Each chip source had almost constant bulk density and all chip sources had similar voidage. Statistical analysis was applied to relate the experimental data to the chip properties and operating parameters. The significant difference test was employed to compare the regression models for the chip bulk density variation runs.

Chapter 6 presents a preliminary study of the influence of tree species on the downdraft gasifier performance. Four sources of chips collected from 4 different tree species, cottonwood, maple, black locust, and oak, were gasified under similar operating conditions. The fixed operating parameters included chip moisture (12-14%), gas fan rotation speed (1793 rpm), and grate rotation speed (4.1 rph). The chips from the different species exhibit some differences in both their physical and chemical properties.

The major conclusions drawn from the present study of wood chip-air gasification in a commercial downdraft gasifier are summarized in Chapter 7; some recommendations for future improvements are also outlined in this chapter.

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CHAPTER 2

LITERATURE REVIEW

The energy crisis of the past decade has prompted a search for alternative energy sources. One attractive source resulting from the search for alternate fuel is biomass. Due to its low sulfur and nitrogen content, utilities and small industries have considered biomass as a fuel because it can satisfy regulations on sulfur and NO_x emissions. Direct production of gaseous fuels from biomass has several advantages over direct combustion of solid fuels. The resulting gaseous fuels can be burned more efficiently and with less emissions; they can be distributed easily for domestic and industrial use; they can be used to operate engines for power generation and transportation; modern gas/oil burners can be easily retrofitted to use the gas; and the gas can be used for the chemical synthesis of liquid fuels and chemicals such as methanol, gasoline, and ammonia. There are however, some difficulties associated with the processing of biomass. Its wide distribution (non-point source) and low bulk density tend to increase costs for collection and transportation. The large number of biomass species and the variability of the material complicate the study of the fundamental aspects of biomass processing.

Direct combustion of biomass materials is generally inefficient and environmentally unacceptable. Thus, a variety of technologies have been developed to convert biomass into gaseous and liquid fuels to provide more acceptable use of this resource. This chapter presents a commonly used technology; gasification. It presents information on the availability of biomass resources, the history of biomass gasification, types of gasification processes, specific gasification systems, and kinetics of gasification.

BIOMASS RESOURCES

In general, biomass comprises a host of plant-derived materials that are abundant, inexpensive, and potentially convertible to fuels or chemicals by fermentation or chemical processing. Biomass materials exist as starch in corn, wheat, potatoes, cassara, etc; monomeric sugars (soluble oligomers) in corn syrup, molasses, raw sugar juice, sulfite waste liquors, etc.; ligno-cellulose in wood chips, crop residues, forest and mill residues, urban refuse, animal manures, etc. Among these sources, wood and wood residues are probably the most abundant.

Available Biomass Resources

Of the total 2.3 billion acres in the United States, 380 million acres (17%) are devoted to crops; 720 million acres (32%) are devoted to forests and woodlands; and 680 million acres (30%) are devoted to pasture or grazing land (Busche, 1985). Corn is the major source of starch because of its ample supply, low cost relative to other sources and established commercial systems for storing and transporting the grain. Lignocellulosic residues are abundant, but commercial collection systems are limited, and need to be further developed for exploitation of this potential resource.

A survey has indicated that from the estimated 1.8 billion annual dry tons of biomass materials are potentially available from U.S. cropland, grassland, and forests; that the 550 million of dry tons of biomass are in the form of wood chips, cereal straw, and cornstalks; and that the starch from 190 million tons of corn appear to be the most viable sources upon which to build a chemicals-from-biomass industry (Busche, 1985). However, cereal straw and corn stover (the major agricultural residues) have no infrastructure for collection. Consequently, corn and wood chips are considered as the only sources of renewable materials currently available in large supply. Figure 1 shows the geographical distribution of various sources of biomass in the United States.

Technical Considerations

Browning (1963) reported that almost all biomass materials, regardless of type, contain about 45% oxygen on a moisture and ash-free basis. Thus, cellulosic materials make poor solid fuels. However, the starch or lignocellulose in biomass has potential as a feedstock for the production of oxychemicals that retain the basic CH_2O structure (Paturau, 1969). This is the main reason why biomass is seriously considered as a source of oxychemicals.

The development of biomass processing is subject to the influences of economic and environment concerns. Costs for some common sources of various form of biomass are compared in Table 1. Biomass benification may be necessary due to its low energy density and the wide variety of species. Bain (1980) discussed a variety of biomass benefication processes such as drying, comminution, densification, physical separation, and chemical modification. The aim of these methods is to improve the biomass material properties for further processings. In drying, physically bound water is removed (the chemically bound water is not included). In comminution, the particle size is reduced to the desired size range by shredding, cutting, grinding, or pulverizating. In densification, the apparent particle density and the bulk density of a material are increased so as to lower transportation costs or processing equipment size by reducing the volume of material to be handled. In physical separation, various components of a parent material are separated into discrete subfractions. In chemical modification, the chemical structure of the parent material is changed into a more amenable form for further processing.

Biomass materials can be burned or gasified readily as a consequence of its high volatile content and its high oxygen content. These properties make it an attractive feedstock for gasification processes.

HISTORY OF BIOMASS GASIFICATION

According to Reed and Jantzen (1980), producer gas was discovered in the laboratory at the end of 18th century. Nevertheless, the technology did not come into commercial and domestic use until 1839 when the first gas producer was built by Bischof (Wyer, 1906). By 1880, several industries produced manufactured gas by pyrolyzing coal and biomass in iron retorts. Later, fireclay and then silica retorts made it possible to achieve higher pyrolysis temperatures. These plants operated with a thermal efficiency of 70 to 80% and produced a gas with a heating value of about 18 MJ/m^3. Further development of the producer gas technology was based on a process called the blue water-gas process (Griswold, 1946). It was named the blue water-gas because the gas burned with a blue flame. The process was designed to heat solid fuels to very high temperatures with a blast of air forming a low-energy gas (heating value about 4 MJ/m^3). The air blast was terminated and steam was blown in from the opposite end of the reactor yielding a high-energy gas (11 MJ/m^3). The operation of a carbureted water-gas set included an alternate heating (blast or blow) and gas-making (run) periods in its cycle. The standard cycle could increase the gas heating value. Gas with 19 MJ/m^3 could be obtained through cracking of oils at high temperatures (Reed and Jantzen, 1980).

The gasification industry continued to grow in the United States until the 1930s when natural gas gradually replaced manufactured gas. At that time, in the United States alone, there were about 1,200 plants built to produce gas. A shortage in natural gas and liquid fuels during World War II resulted in rejuvination of the producer gas industry in Europe and the Scandanavian countries. The Arab oil embargo of the past decade revived interest in the development of biomass gasification in the United States.

TYPES OF GASIFICATION PROCESSES

Figure 2 illustrates various processes through which biomass can be converted into gaseous or liquid fuels. These processes are air gasification [Graham and Huffman (1981); Walawender et al. (1985)], oxygen gasification [Graboski and Brogan (1987)], hydrogasification [Garg et al. (1987); Suzuki et al. (1984)], and pyrolysis [Derosiers and Lin (1983); Maa and Bailie (1973)]. The basic features of each process are summarized in the following paragraphs.

Air Gasification. When biomass is partially oxidized with a limited supply of air, it produces a low energy gas with a heating value of about 5.5 to 7.5 MJ/m^3. The gas is consisted of H_2 and CO, diluted with N_2. Although this method is the simplest process, the gaseous product is not of sufficient quality to be transported in pipelines. The low energy gas is however suitable for operation of boilers or engines.

Oxygen Gasification. When biomass is partially oxidized with a limited supply of oxygen, it produces a medium energy gas within heating value of about 11 MJ/m^3. This gas is suitable for limited pipeline distribution or for methanol, gasoline, ammonia, methane, or hydrogen synthesis.

Hydrogasification. When biomass is pyrolized under pressure with hydrogen, it can be converted to gaseous or liquid fuels. Gas produced by this method has a heating value of about 11 MJ/m^3. It is suitable for industrial process heat or as synthesis gas to make methanol, gasoline, ammonia, methane, or hydrogen. More recently, Garg _et_ _al_. (1987) employed a new technique, catalytic hydrogasification, to make pipeline quality gas from wood.

Pyrolysis. The word 'pyrolysis' is misleading as it itself means the destructive decomposition of biomass using heat to produce char, pyrolysis oil, and medium energy gas. Pyrolysis occurs in all gasification and combustion processes for both coal and biomass. The rate of heating and the level of temperature play important roles in determining the product distributions. Slow heating and low temperature tend to produce high char yields while fast heating and high temperature produce high gas yields. Tar (oil) is the dominant product when pyrolysis is conducted under moderate temperature in pyrolysis and fast heating.

TYPES OF GASIFIERS

Figure 2 includes some typical gasifiers that can be utilized for the different processes presented in the previous section. Although there are a wide variety of gasifiers, only the most commonly used gasifiers such as the updraft, downdraft, fluidized bed, and suspended bed are reviewed in this section. Reed and Bryant (1978) have discussed other types of reactors for biomass gasification. Table 2 summarizes the suitable feedstocks and scale of operation for each type of gasifier.

Updraft and Downdraft Gasifiers

Both updraft and downdraft gasifiers belong to the moving bed category. They differ from each other in the flow direction of solid and gas, which gives rise to different performances. Reed (1980) provides a detailed discussion of these two types of gasifiers.

Updraft Gasifier. Figure 3, shows a schematic diagram of an updraft gasifier. It has a simple construction which allows air to flow into the system through the grate at the bottom of the bed. When air contacts the hot char, the char burns and high temperatures are achieved. The hot combustion gas then enters a zone with an excess of char, causing CO_2 and H_2O to react with the char yielding a gas enriched in CO and H_2. Solids, added from the top of the bed, are dried and then pyrolyzed by the hot rising gases. Heat is exchanged between the descending biomass and the ascending gases (counterflow) decreasing the temperature of the exit gas while heating the solids. The volatile materials released by the pyrolizing solids are not subjected to thermal cracking and consequently the process produces a gas with a high tar content (about 20%). The high tar yield has restricted the scale-up of this type of gasifier. The sequence of reaction stages with respect to the solids in this gasifier is pyrolysis-reduction-combustion.

Downdraft Gasifier. Figure 4 illustrates a schematic diagram of a downdraft gasifier. In this type of gasifier, the solid and gas flow co-currently. This flow pattern allows for the thermal cracking of tars and oils in the gas due to the high temperatures they experience as they flow downward. The product gas typically contains about 0.1% tar. A higher char yield is obtained than in the updraft gasifier due to the absence of oxygen to react with the char. This gasifier is best suited for processing materials with high volatile contents such as biomass. The sequence of reaction stages with respect to the solid is pyrolysis-combustion-reduction.

Two types of common downdraft gasifiers are the choke-plate type and the stratified type. The choke-plate gasifier is designed with air injection in the choke region while the later is a cylindrical column with air entering at the top of the bed. Recently, Graboski and Brogan (1987) have been involved in the design and development of a scale-up prototype of the SERI stratified gasifier (Reed and Markson, 1985) capable of producing a maximum of 16,000 MJ/hr. This gasifier is shown in Figure 5. The wood pyrolysis zone extents only a few centimeters from top surface where it is maintained by a suplementary fuel burner. In this design, gas is not withdrawn from the bottom of the grate as in most common downdraft gasifiers. It is extracted through a cylindrical perforated punch plate which holds most of the char back.

The stratified downdraft gasifier used in this thesis has an ID of 0.6m (see Figure 6). Air is introduced to the gasifier from the open top as well as through a set of nozzels called tuyeres. Air is drawn through the system by means of a gas fan which is located downstream. Gaseous products are reduced as they pass through the bed of hot charcoal.

It has not been possible to scale-up downdraft gasifiers of the choke-plate type. However, the stratified SERI gasifier has been sucessfully scaled up by a factor of ten.

Other Types of Gasifiers

Fluidized Beds. Figure 7 shows a schematic diagram of a fluidized bed. Fluidized beds have been developed over the last few decades to provide uniform temperatures and efficient contacting between gases and solids in the process industry. Because of its high throughput, it is more compact than updraft and downdraft gasifiers. The high velocity gas carries the ash and fine char out of the system and the solids must be separated in cyclones. The beds usually contain either an inert material such as sand or a reactive material such as limestone or catalysts to provide heat transfer, gas-cleaning or catalytic action. The solids are kept in suspension (simulating a fluid) by the rising gas. Solid biomass mixes with the hot bed material which provides high heat transfer rates between the bed solids and the biomass resulting in good gas yields. A fluidized bed can sometimes be scaled up by a factor of one hundred.

Suspended Beds. Figure 8 illustrates a schematic diagram of a suspended bed. Suspended beds are commonly used for suspended combustion of coal and fine particles of biomass such as sawdust. The sequence involved in this type of beds is gasification-combustion. This gasifier is designed to achieve sufficient gas-solid contact through a vortex action. Suspended beds are successful in large-scale operations.

The choice of a gasifier is affected by several important criteria.

a) Chemical environment: air, oxygen, hydrogen, and slow or fast pyrolysis.

b) Heat transfer and mass transfer:

  i) direct: updraft (countercurrent flow), downdraft (cocurrent flow), fluidized bed, and suspended bed.

  ii) indirect: solids (fluidized bed), liquids, and gaseous recirculation.

c) Types and forms of feedstock: biomass or municipal solid waste; pellets, chips, or powder.

d) Types of ash: dry ash or slag.

e) Pressures: high or low.

f) Scale of operation.

KINETIC MODELING

Proper design of a gasifier requires understanding of the mechanism and knowledge of the kinetics of the biomass gasification reactions consisting of biomass pyrolysis and char gasification. The terminology is defined below:

a) Pyrolysis: The thermal devolatilization of virgin solids yielding char and volatiles.

b) Gasification: The reduction of char to produce additional gas.

Pyrolysis of biomass, which contains approximately 80% volatile materials, proceeds through a complex series of concurrent and consecutive chemical reactions. The reaction pathways are influenced by particle size, heating rate, temperature, and pressure. Slow heating favors the formation of more char, and less tar and gas. On the other hand, rapid heating produces less char, and more tar and gas. However, tar is decomposed into either char or gases at higher temperatures. Maa and Bailie (1973) investigated the role of particle size on the controlling mechanisms (chemical reaction or heat transfer) of biomass pyrolysis. Antal (1980) revealed that under high pressure conditions, char formation is favored over gas formation.

Shafizadeh (1968) has proposed the simplified mechanism for cellulose pyrolysis shown in Figure 9. His mechanism consists of three primary and two secondary reactions. The primary reactions (reactions 1, 2, and 3 in Figure 9) are the decomposition of biomass, whereas the secondary reactions (reactions 4 and 5) are decomposition of the tar.

Reaction 1 includes reactions such as depolymerization, hydrolysis, oxidation, dehydration, and decarboxylation; it occurs at a significant rate at about 250°C. Reaction 2 is the formation of tar, sometimes known as levoglucosan; it takes place at temperatures above 250°C. Reaction 3 represents the fragmentation of biomass to give char. The process of pyrolysis can be summarized by the following reactions;

$$\text{Biomass} \longrightarrow \text{Gas} + \text{Char} + \text{Tar}$$

$$\text{Tar} \longrightarrow \text{Char} + \text{Gas}$$

Char is composed primarily of carbon. It can be reduced to synthesis gas through heterogeneous reactions with carbon dioxide, steam, and hydrogen via the following reactions;

$$C + CO_2 \longrightarrow 2CO$$

$$C + H_2O \longrightarrow CO + H_2$$

$$C + 2H_2 \longrightarrow CH_4$$

A gas phase reaction, known as water gas-shift reaction, also occurs. It is catalyzed by the ash components in the char.

$$CO + H_2O \longrightarrow CO_2 + H_2$$

The reactivity of biomass chars in a gaseous atmosphere is a complicated function of temperature, particle structure, carbon source, and the thermal history of the char. Shafizadeh and DeGroot (1982) determined that char gasification is the rate limiting step in the production of gaseous fuels from biomass.

Biomass pyrolysis and char gasification, combine to give the overall gasification process. There have been a large number of studies focusing on investigating the kinetics of pyrolysis and char gasification. These studies are reviewed with the emphasis on wood pyrolysis and wood char gasification.

Wood Pyrolysis

Wood pyrolysis has a long history, dating back to the ancient Chinese and Egytians who used the tarry products for embalming (see, e.g., Reed and Jantzen (1980)). Through the mid 1900's wood pyrolysis was used to obtain a variety of products including charcoal, acetic acid, wood alchohol, tar, and gases. Wood consists mainly of cellulose, hemicellulose, and lignin. Brown (1971) has found that the product yield obtained when wood is completely pyrolyzed is about the same as the yield obtained by separately pyrolyzing proportional amounts of the major wood constituents. When wood is heated in the absence of oxygen, hemicellulose decomposes first between 200 to 260°C, followed by the cellulose between 240 to 350°C. The lignin is gradually decomposed between 280 to 500°C (Shafizadeh, 1982).

The products from wood decomposition can be divided into three groups:

1) a carbonaceous solid (char)
2) a mixture of liquid compounds (tar), and
3) a mixture of gases

Shafizadeh (1982) showed that the cellulose and hemicellulose constituents decompose to form mainly volatile products and that the lignin constituent decomposes to form mainly char.

Kinetic data for the primary and secondary reactions shown in Figure 9 have not been obtained due to the limitations of the experimental methods used to determine the kinetic parameters of wood pyrolysis. Two commonly used methods to determine the kinetics of wood pyrolysis are the Isothermal Thermogravimetric Analysis (TGA) and the non-isothermal TGA. Isothermal (static) TGA measures the weight loss as a function of time at a fixed temperature while the non-isothermal (dynamic) TGA measures the weight loss as a function of temperature at a fixed heating rate. However, both methods suffer from two major drawbacks: a) The capability of commercially avaiable instruments to measure sample weight loss as a function of time or temperature allows TGA to account only for the reactions to volatile products (reactions 1 and 2 in Figure 9). b) The inaccurate knowledge of sample temperature (assuming the inert gas temperature is the actual reaction temperature inside the sample) gives rise to wide variations in the activation energies for pyrolysis reported in literature. The choice of temperature is important because by using the appropriate temperature, the activation energy range can be reduced to between 109 to 139 KJ/mole.

The heat of wood pyrolysis can also be measured by the Differential Thermal Analysis (DTA). The temperature difference between a thermocouple embedded inside the sample and another thermocouple placed in the inert material is measured. If the reaction is endothermic the sample temperature lags behind the reference temperature, wheareas for an exothermic reaction the sample temperature leads the reference temperature. Pyrolysis of cellulosic material is an endothermic reaction with a reported heat of pyrolysis of about 268 J/gm.

Several researchers have postulated that the degradation of wood can be approximated by Arrhenius-type kinetics, especially the first-order kinetics. Thurner et al. (1980) investigated the kinetics of wood pyrolysis in the range of 300 to 400°C at atmospheric pressure under nitrogen atmosphere. Using DTA and a first-order kinetic model, they estimated activation energies of wood pyrolysis to gas, tar and char as 88.6, 112.7, and 106.5 KJ/mole, respectively. The kinetic data were then used to describe the yield of the various pyrolysis products. They found that the best prediction was obtained when an integral-mean temperature, obtained from the temperature-time curve, was used as the reaction temperature.

Pitt (1962) has proposed a multiple-reaction model for coal pyrolysis to account for a wide range of activation energies. This model assumes that many first-order parallel reactions are completing with each other, and that the number of reactions is large enough to use the continuous probability function

$$\int_0^\infty f(E)\, dE = 1$$

where E desinates the activation energy and f(E) is the activation energy distribution function. The activation energy distribution function is determined experimentally. Raman _et_ _al_. (1981) applied this model to study the devolatilization reactions of feedlot manure with the thermogravimetric analyzer.

The pyrolysis of wood is a chemical reaction coupled with the transport of heat and mass. Consider a single piece of wood placed in a stream of inert gas and exposed to high temperatures. The thermal decomposition of wood is made possible through the penetration of sufficient energy from the bulk stream to the material inside the particle. Similarly, the reaction products are transported out of the particle through the void spaces in the particle to the bulk stream. For wood pyrolysis, the process can be outlined by the following steps:

1) thermal decomposition of the wood cells
2) intraparticle transport of the reaction products
3) film transport of the reaction products

The above steps can be regarded as a series of resistances where the slowest step is the rate determining step. To determine the intrinsic kinetics of wood pyrolysis, it is necessary to conduct the experiments for conditions under which chemical reaction is the rate-controlling step. Thurner *et al*. (1980) conducted experiments on wood and concluded that the intraparticle transport of the reaction products was the rate-controlling step at 550°C. At this temperature, the rate of chemical reaction was found to be higher than the mass and heat transport rates.

Kinetic data for wood above 340°C are different from those obtained at lower temperatures. Therefore, at temperatures higher than 340°C, the kinetics must be determined from the experimental data obtained at that temperature (Atika, 1956). Since tar is decomposed at long reaction times, the experiment is conducted over a long period (3 to 10 minutes) to measure the kinetic parameters free from secondary reactions. These points must be considered in performing tests to calculate the kinetic parameters of wood pyrolysis.

Pyrolysis of wood is not only influenced by temperature, it is also highly influenced by the particle size. A model has been developed by Maa and Bailie (1973) based on the unreacted-core shrinking model to predict the time required for completion of pyrolysis of cylindrical rods. The pyrolysis phenomena was systematically investigated in the temperature range of 430 to 1200°C. The model combined chemical kinetic equations with the heat transfer equations and assumed that reaction took place at an interface between the unreacted shrinking core of non-pyrolyzed solid and a layer of pyrolyzed material. This model is similar to that proposed by Yagi and Kunii (1955) for non-catalytic heterogeneous gas-solid reactions. Using the pseudo-steady state approximation, three coupled energy balance equations were formulated and solved simultaneously to predict the controlling mechanism for different particle sizes. For a cylindrical wood dowel with radius less than 0.1cm, the controlling mechanism was chemical reaction. For a cylindrical wood dowel with radius greater than 3.0cm, the controlling mechanism was heat transfer. For a radius between 1.0 and 3.0cm, both chemical reaction and heat transfer were important for the determination of the time for reaction.

Beaumont and Schwob (1984) considered the influence of physical and chemical parameters on wood pyrolysis.

Parameters investigated were temperature, particle size, extractives, moisture, and catalysts. The conclusions drawn are outlined below.

a) Influence of temperature

Four distinct regions were distinguished according to temperature (see Figure 10): drying region (under 200°C); roasting region (220 to 330°C); pyrolysis region (330 to 450°C); and gasification region (above 500°C). In the pyrolysis region, the major product is pyrolytic oil (about 50%). True char and a low gas yield are obtained. Figure 11 shows the variation of the gas composition with temperature. Carbon dioxide predominates at temperatures below 300°C while carbon monoxide increases rapidly at temperatures above 450°C. Methane starts to appear at temperatures above 350°C. Hydrogen is expected to be detectable at temperatures above 600°C (gasification region which will be discussed later).

b) Influence of particle size

Coarser particles yield more char and gas, and less oil. This phenomena is only observed in fast pyrolysis. For slow pyrolysis, wood pyrolysis is independent of particle size.

c) Influence of wood moisture

High moisture promotes charring and lower oil yields. The qualitative composition of the oil remains unchanged. However, qualitative shifts are observed. Heating of the particles is hindered by the heat requirement for moisture evaporation resulting in a decrease in the oil yields.

d) Influence of a catalyst

Samples impregnated with basic and acidic catalysts show that acidic catalysts promote dehydration and furaldehyde formation whereas basic catalysts favor gasification and charring.

Char Gasification

One of the major products of wood pyrolysis is char. Char can be further reduced to form more gaseous products at high temperatures (above 500°C). The char gasification reactions consist primarily of heterogeneous reactions between char and gases such as hydrogen, carbon dioxide, and steam. The principal objective in char gasification is to convert carbon in the char to gases enriched in carbon monoxide and hydrogen. The produced carbon monoxide can also react with the steam via the water-gas shift reaction. This reaction is assumed to occur as a result of heterogeneous catalysis on the char surface at temperatures of about 600°C.

Graboski (1980) has proposed a model for the kinetics of the char gasification reactions at temperatures above 500°C. He considered a porous char particle model to describe the phenomena of char gasification. Figure 12 shows the proposed model. A series of resistances to mass transfer can be found in char gasification reactions. They are listed below.

1) Diffusion of reactants across the stagnant film to the external surface.
2) Diffusion of gas through the pores toward the center of the particle.
3) Absorption, surface reaction, and desorption on the pore walls.
4) Diffusion of products out of the pores.
5) Diffusion of product across the stagnant film to the gaseous environment.

Several assumptions such as steady state, convective heat transfer across the film, negligible radiation heat transfer, and Arrhenius-type kinetic expression were used in the development of the char gasification rate expression. Graboski (1980) did not conduct any experiments to verify the model.

Gasification of char may be controlled by pore diffusion since reactions occur basically within the particle. The effectiveness factor and Thiele modulus are traditionally used in chemical reaction engineering to describe pore diffusion. The effectiveness factor, η, is defined as the ratio of the actual average reaction rate within the particle to the rate based on the surface concentration (Satterfield, 1970).

$$\eta = \frac{(r_{average})}{(r_{surface})}$$

The effectiveness factor is a function of the dimensionless group termed the Thiele modulus which depends on the diffusivity in the pore, the rate constant for reaction, pore dimension, and external surface concentration.

In addition to mass transfer and pore diffusion, the surface kinetics also play an important role in char gasification. The surface kinetics depend on the specific reaction as well as the char characteristics.

Three effects, mass transfer, pore diffusion, and kinetics combine to give an overall global kinetic rate expression. At low temperatures, the kinetic rate constant approaches zero and hence the pore diffusion and mass transfer processes are very fast relative to the kinetics. As temperature increases, the effect of pore diffusion is important, and at very high temperature the effect of mass transfer dominates. Overall, the true kinetic data must be free from intrusions.

Some investigations of catalytic effects in char gasification have been conducted (Graboski (1980), Shafizadeh and DeGroot (1982), and Tingley and Morrey (1973)). Wood is known to contain minerals such as iron, calcium, and magnesium. These metals are potentially catalytic substances that can influence the water gas-shift and char-steam gasification reactions. For a gram of cottonwood, 869μg of calsium, 668μg of potassium, 324μg of magnesium, 18μg of sodium, and 5μg of iron have been reported by Shafizadeh and DeGroot (1982). However, the levels of minerals present in wood are highly influenced by the source of wood and surface contamination. Rensfelt (1978) found that 2% of K_2CO_3 catalyst in peat char tripled the rate of the char-steam reaction.

The chemistry of wood char and the factors controlling its reactivity are poorly understood. Shafizadeh and DeGroot (1982) proposed a model to determine the reactivity of wood char with steam and CO_2 under gasification conditions. The effect of catalysts was of great interest in their study. The results of the study illustrate that char gasification can be effectively catalyzed even with a very low level of catalyst addition. However, information on the nature of the char such as the structure of char or the preparation of chars under different pyrolysis conditions can further improve the assessment of the rates of gasification of wood chars.

MODELING OF DOWNDRAFT GASIFIERS

Although moving bed gasifiers have been used extensively for processing biomass residues into fuels, design is primarily based on art and experience. Several investigators have attempted to model moving beds in the hope of developing engineering design procedures [Reed and Markson (1985); Ernesto (1977); Deroiser and Lin (1983); Buekens and Schoeters (1983)].

Among these attempts, Reed and Markson (1985) developed a preliminary model to simulate the behavior of a stratified downdraft gasifier. The model related the time and distance required for pyrolysis and gasification to the operating conditions of the gasifier. Two predominant zones exist in the stratified downdraft gasifier: a flaming pyrolysis zone and a char reduction zone.

Flaming Pyrolysis Zone

Unlike updraft gasifiers, air and wood are introduced at the top of the stratified gasifier where the simutaneous occurance of both pyrolysis and combustion takes place in a very short length of the bed. Tars and oils produced are burned to provide additional energy for further pyrolysis. This phenomena is known as flaming pyrolysis. An extremely large volume of volatiles is generated causing a gas boundary layer to surround the pyrolyzed material. Sufficient heat can penetrate the gas layer to maintain the pyrolysis only if the surface temperature of the biomass is about 800°C. If the surface temperature rises to 900°C, high resistance to the heat flux reduces the pyrolysis rate. This compensating effect is able to maintain a particle surface temperature range between 800 to 900°C. Products from the combustion zone cannot diffuse back to the pyrolyzed material until the completion of the pyrolysis stage. In modeling this stage, a version of Huff's empirical equation (1985) for combustion, modified with respect to oxygen concentration was used to estimate the time required for completion of flaming pyrolysis. Given a solid flow rate, the reaction time calculated was used to predict the length of the flaming pyrolysis zone.

Char Reduction Zone

Char reduction is the second aspect to be considered in modeling a stratified downdraft gasifier because this reaction is the rate determining step for the overall gasification of biomass. Several studies have concentrated on describing char reduction in updraft gasifiers. The concepts are not applicable to downdraft gasifiers since in updraft gasifiers, hot char contacts incoming air (oxygen) resulting in nearly complete conversion of char. This phenomena, is not present in downdraft gasifiers where char is reduced by the down flowing gases.

Along with the heterogeneous gas-solid reactions, a homogeneous endothermic gaseous phase reaction (the water gas-shift reaction) takes place. Both gases and char are cooled as reduction proceeds. During this stage the concentration of carbon monoxide increases. The rate of disappearance of char is expressed in terms of Arrhenius rate expression which incorporated the density of char in the rate constant.

Overall Gasification

The models proposed for the two stages are combined to estimate the overall dimensions of a downdraft gasifier required for various types of biomass and operating conditions. Only rough qualitative comparisons can be made with the model since sufficient experimental data are lacking for comparison.

CONCLUSICN

This chapter has reviewed different aspects of biomass gasification including the availability of biomass, history of biomass gasification, types of biomass gasification processes, types of gasifiers, kinetics of biomass gasification, and gasifier modeling. Even though biomass gasification is a broad subject, the topics presented are sufficient for the basic background. The following chapter considers material balance procedures that can be used for the analysis of downdraft gasifiers.

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Table 1. Costs of Biomass (Busche, 1985).

Years	(¢/dry kg)		
	1980	1985	1990
Corn stover	3.3	4.6	6.8
Whole tree wood chips	2.9	4.0	5.7
Pre-treated wood chips	6.8	11.0	15.9
Biosugar ex Lignocellulosics			
Enzyme/acid pretreat	17.6	28.4	42.5
Concentrated acid/recycle	17.9	27.1	39.9
Dilute acid/extrusion	19.4	30.9	46.1
Concentrated acid/ once-through	27.8	41.2	59.1
Corn syrup (as glucose)	18.5	22.9	30.2

Table 2. Suitable Feedstocks and Scale of Operation for Various Types of Gasifiers.

Types of Gasifiers	Suitable Feedstocks				Scale of Operation	
	Chips	Pellets	Sawdust	Straw	Large	Small
Updraft	X	X				X
Downdraft	X	X				X
Fluidized	X	X	X	X	X	
Suspended			X	X	X	

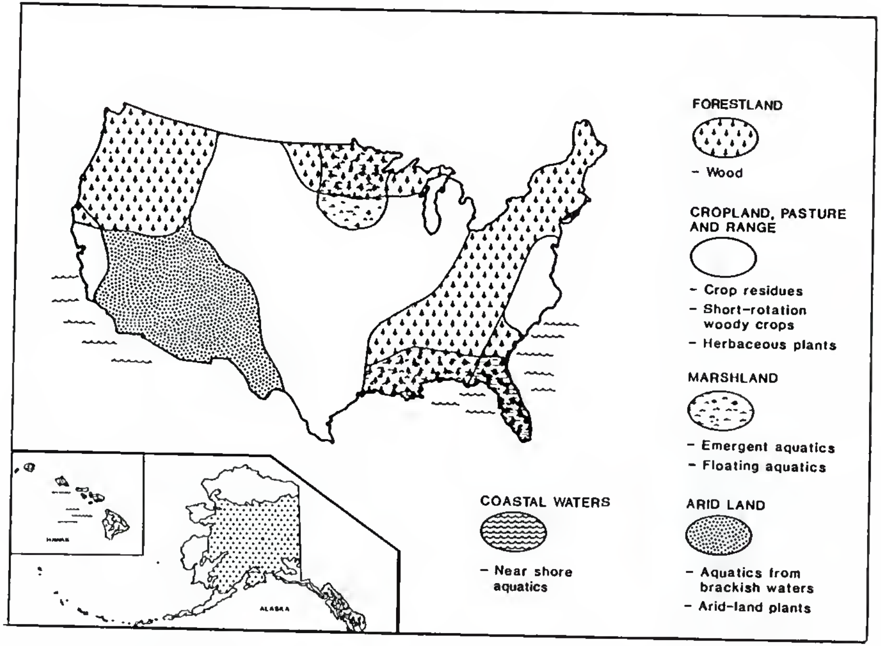


Figure 1. Geographical Distribution of Biomass in the United States (Busche, 1985).

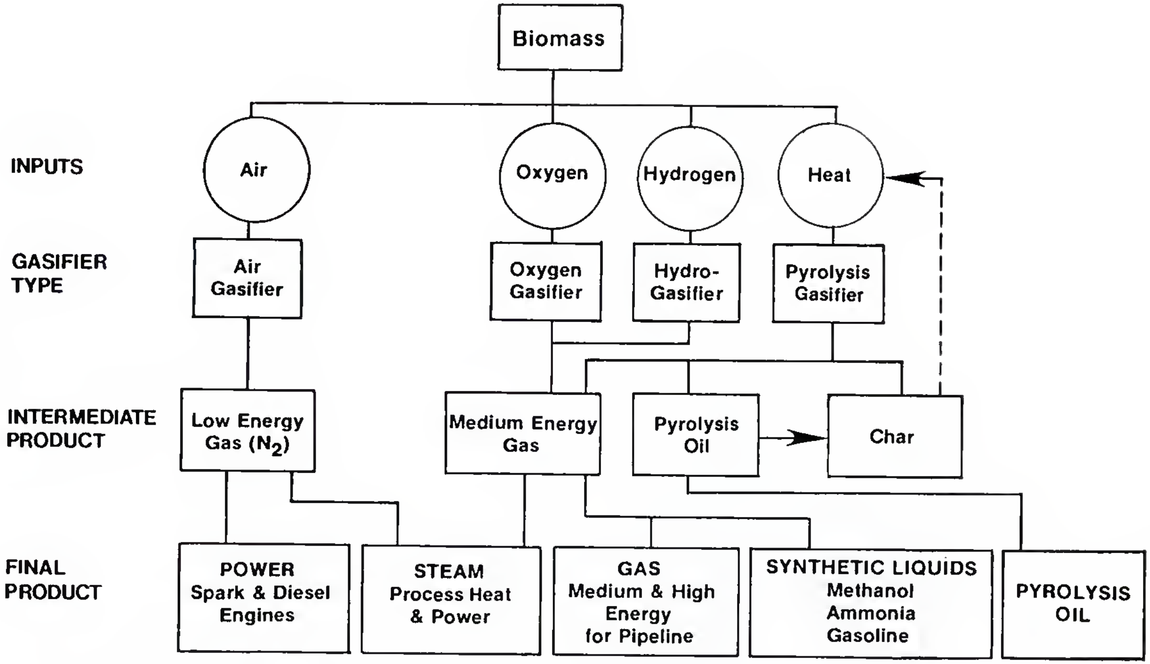


Figure 2. Types of Biomass Gasification Processes and Gasifiers (Reed and Bryant, 1978).

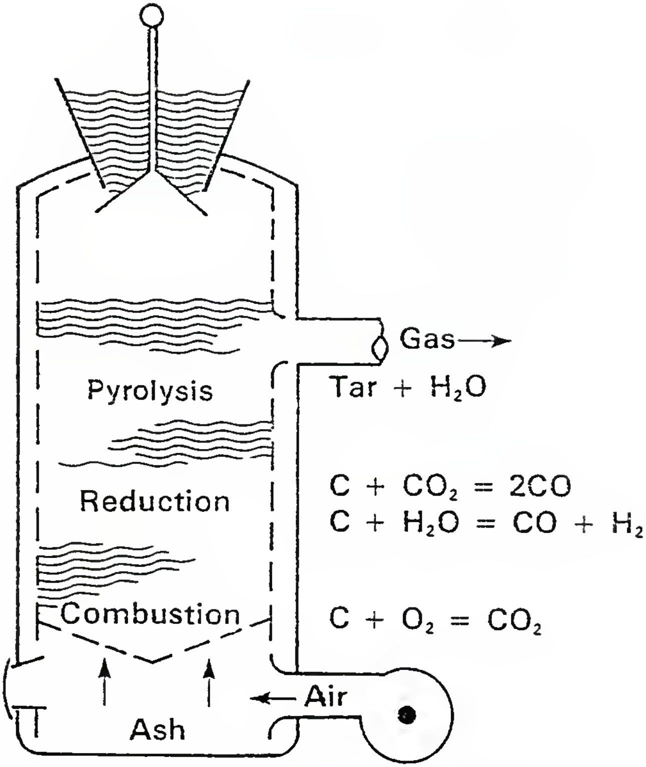


Figure 3. Schematic of an Updraft Gasifier (Reed and Bryant, 1978).

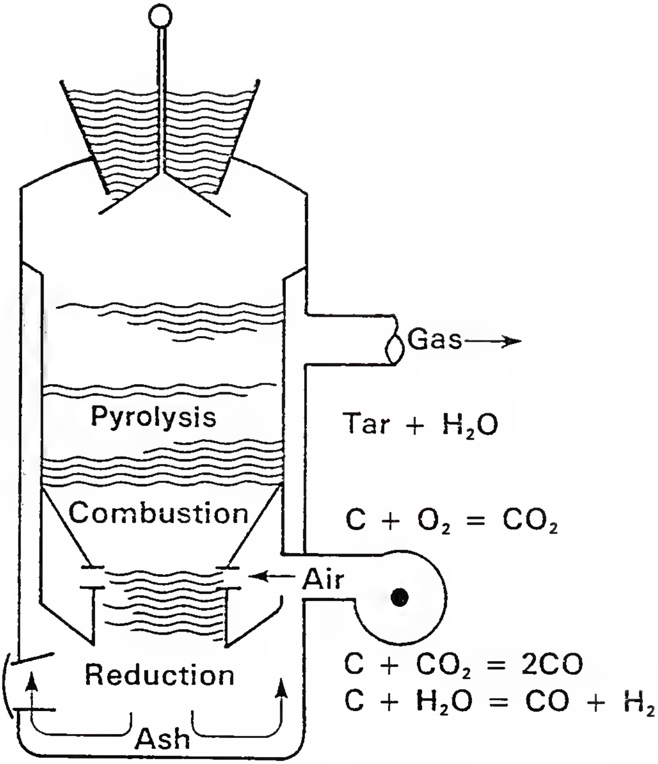


Figure 4. Schematic of a Downdraft Gasifier (Reed and Bryant, 1978).

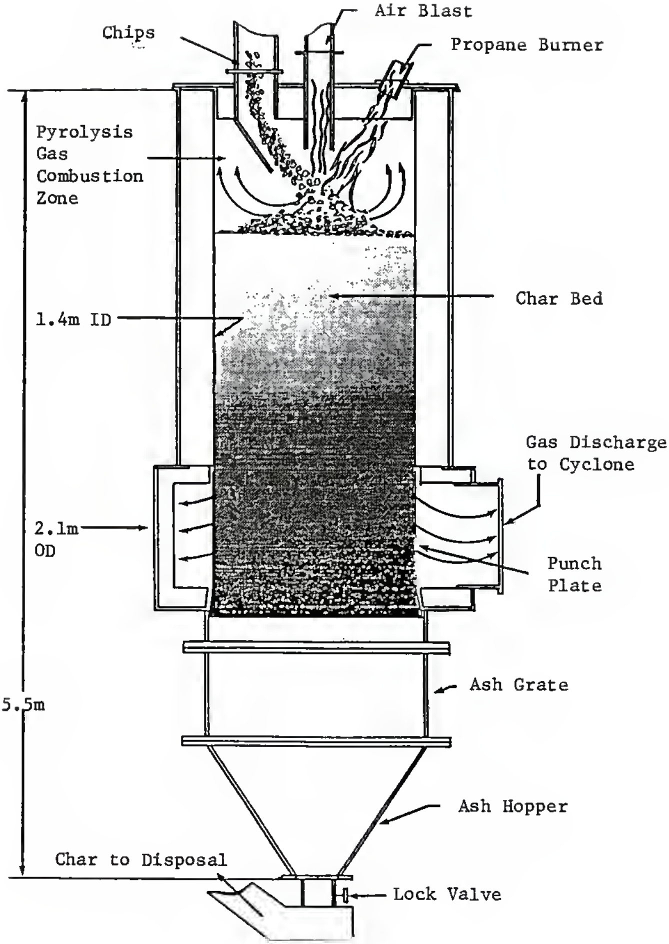


Figure 5. Prototype Downdraft Gasifier (Graboski and Brogan, 1987).

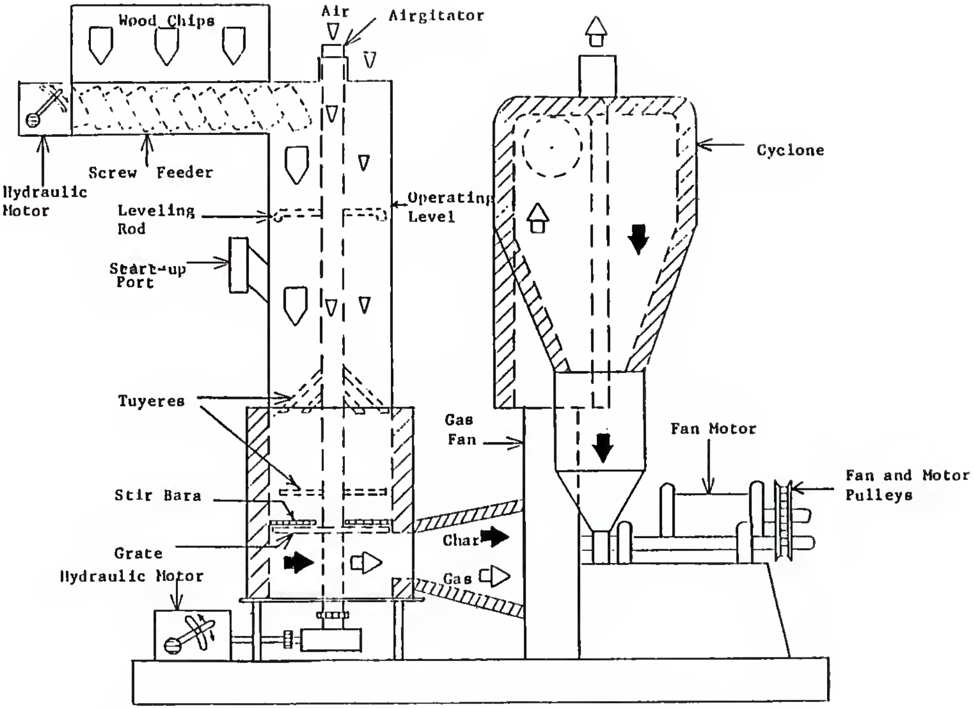


Figure 6. A Commercial Stratified Downdraft Gasifier.

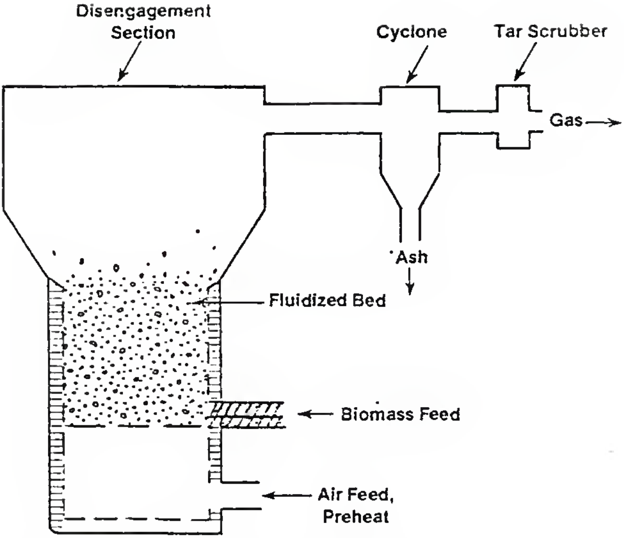


Figure 7. Schematic of a Fludized Bed (Reed and Bryant, 1978).

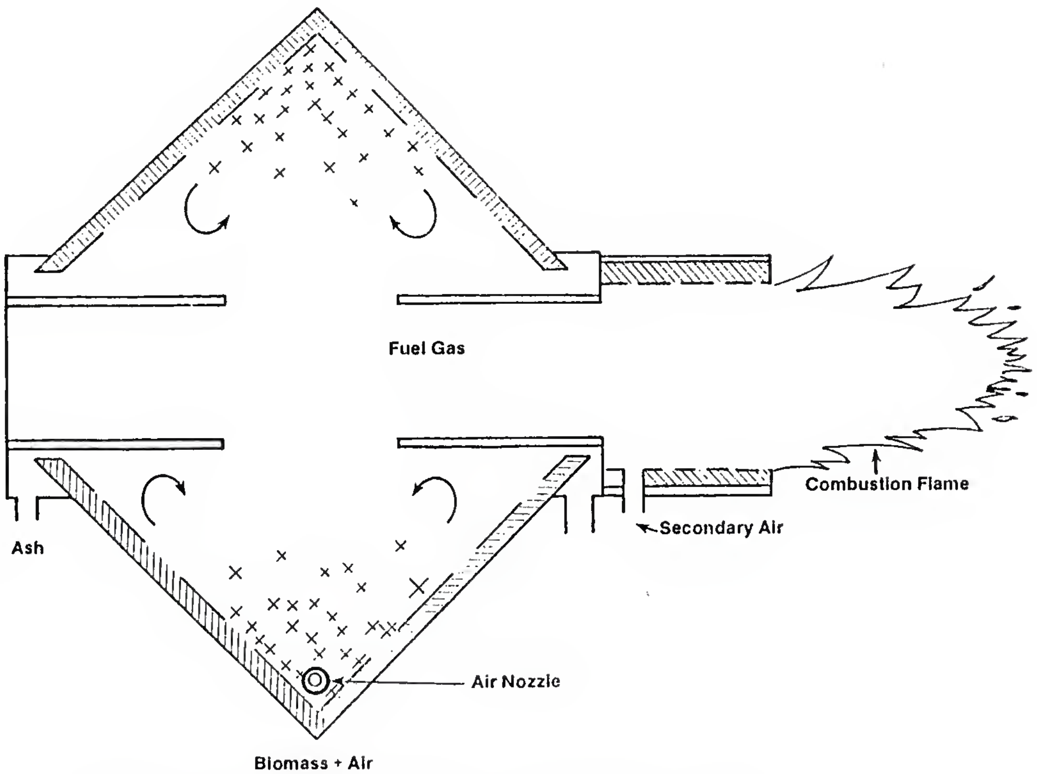


Figure 8. Schematic of a Suspended Bed (Reed and Bryant, 1978).

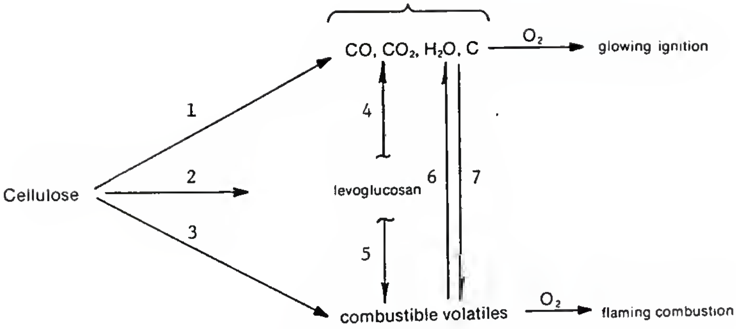
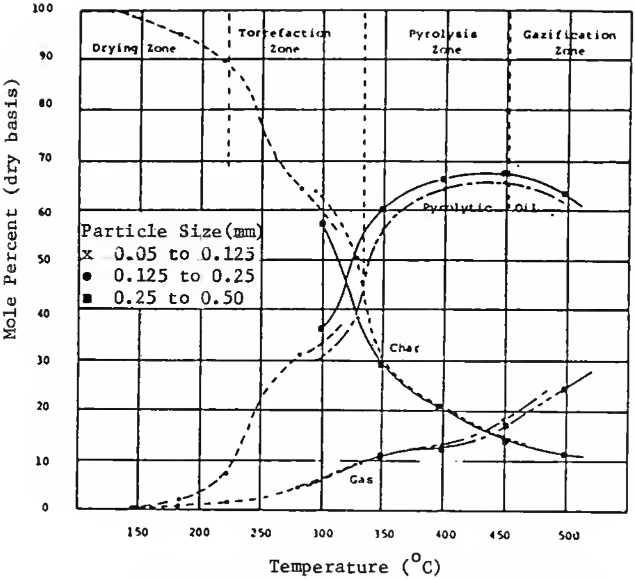


Figure 9. Pyrolysis of Cellulosic Material (Shafizadeh, 1968).



Fifure 10. Distinct Regions in a Gasification Process According to Temperature (Beaumont and Schwob, 1984).

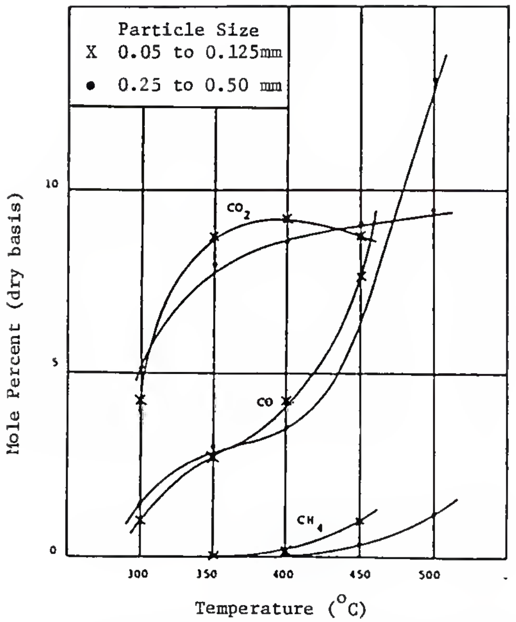


Figure 11. Variation of Gas Compositions with Temperatures (Beaumont and Schwob, 1984).

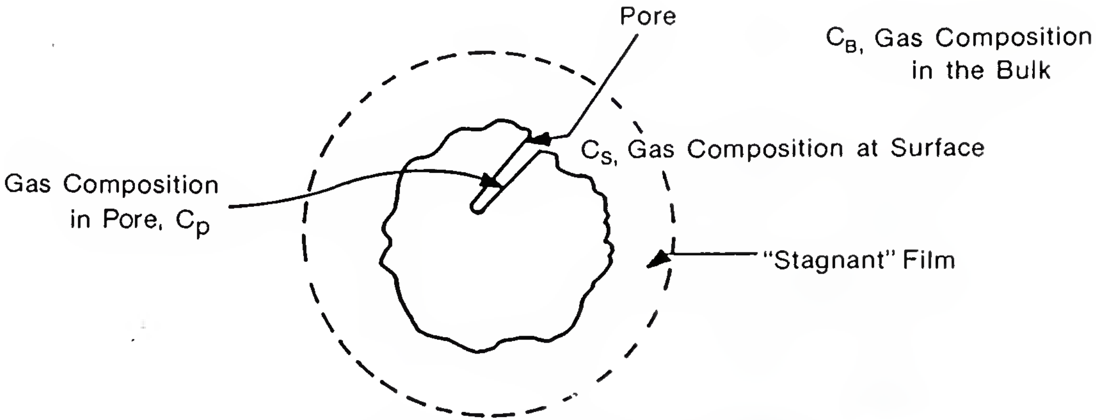


Figure 12. Proposed Model for the Char Gasification Process (Graboski, 1980).

CHAPTER 3

MATERIAL BALANCE PROCEDURES FOR DOWNDRAFT GASIFIERS

The objective of this chapter is to develop the concepts and solution procedures required to determine the distribution of material flows in downdraft wood chip gasifiers with least sensitivity to measurement variability. Only a few researchers have performed complete material balance calculations for moving bed downdraft gasifiers to date. Graham and Huffman (1981) appear to be the first to report complete material balances for a commercial downdraft wood gasifier with an output of 1,000 MJ/hr. Walawender et al. (1985) presented material balance data for a commercial downdraft wood gasifier with a working capacity of 320 to 1,600 MJ/hr. Most recently, Graboski and Brogan (1987) reported material balances for a prototype commercial downdraft wood gasifier capable of producing up to 15,800 MJ/hr.

This work presents the material balance procedures developed for the Buck Rogers 'Gasifire' TM. The gasifier is similar to the one used by Walawender et al. (1985). The configuration of the gasifier permits convenient measurement of three stream rates. This has given rise to an over specified system where the requirement of satisfying the zero net degrees of freedom condition is violated. For an over specified system, Reklaitis (1983) demonstrated that contradictory results can be obtained even if the procedure used is properly specified because of the extraneous information. Often, it is impossible to satisfy all of the imposed conditions in this situation. The presence of inconsistency indicates incorrect information and may result in unrealistic predictions.

In the present study, several material balance procedures are used to describe the gasifier. The results of calculations from each method are inconsistent with each other to varying degrees. The objective of this chapter is to discuss some of the possible material balance procedures for the downdraft gasifier based on their capabilities for predicting relatively acceptable results with minimum sensitivity to measurement variability. Data from other studies on downdraft gasifiers have also been used to compare the various selected approaches.

PREVIOUS WORK

The two most complete studies are the works of Walawender et al. (1985) and Graboski and Brogan (1987). These two studies involve direct measurements of most of the gasifier streams. A simplified schematic encompassing the systems investigated by both groups is presented in Figure 1. The dashed line in the diagram indicates the propane supplemental fuel stream, used in the system investigated by Graboski and Brogan (1987).

Walawender _et_ _al_. (1985) measured the chip feed rate, dry gas output rate, tar, and condensate (mass ratio of condensate-to-dry gas), whereas Graboski and Brogan (1987) measured the chip feed rate, air input rate, propane input rate, and char output rate.

Walawender _et_ _al_. (1985) measured all of the stream rates involved in their system except the air input rate which was calculated from a nitrogen balance. The air input rate was not measured due to the difficulty presented by the open top gasifier used in their work. The dry gas output rate was determined using a nitrogen tracer technique. In this technique, a known volumetric flow rate of nitrogen tracer was injected into the product gas stream to allow for the indirect determination of the gas output rate. However, this technique is not always practical. Several disadvantages exist with this method. They are: a) a large consumption of feedstock in an experimental run in order to maintain the operation of the process for determining the gas output rate, and b) high consistency is required in the nitrogen concentration.

The feedstock input rate was measured by timing the cumulative on time of their constant speed screw feeder. Calibration of the feeder was conducted by collecting and weighing the feeder discharge over a specified time interval. The calibration coupled with the recorded feeder operating time and total run time made the determination of the feedstock input rate possible. This method of measuring the feedstock input rate can give variations due to slight fluctuations in the calibration, bulk density variations, low bin levels and other factors.

The char output rate was determined by collecting and weighing the char over specified time intervals. This method is probably the simplest procedure and has been employed by several researchers to determine the char output rate.

Walawender _et al_. (1985) also measured both the tar and condensate output rates relative to the dry gas output rate by purging a small side draw from the main gas stream and sending it through a series of packed filters and condensers. The packed filters trapped the tarry mist while the condensers removed the water contained in the gas stream. The tar yield was reported to be only a small fraction of the total effluents (about 0.13%). The collected condensate was weighed and its mass was divided by the mass of the dry side draw stream to give the mass ratio of condensate-to-dry gas.

In developing their prototype downdraft gasifier, Graboski and Brogan (1987) measured all input stream rates and some of output stream rates. Since the gasifier under investigation was a closed system, they were able to measure the air input stream with an orifice meter. The main problem with the air measurement was leakage from the screw feeder. Attempts were made by them to account for the air leakage.

The wet gas output rate was determined through the inlet air flow and a nitrogen balance; the wet gas composition was determined with a mass spectrometer. They reported that the nitrogen composition of the wet gas could be determined accurately and thus the determination of the wet gas output rate was directly tied to the air measurement.

The feedstock input rate was determined from a calibration for their screw feeder. This method of measurement is sensitive to the calibration as well as pressure. The char output rate was measured by collecting and weighing the total char effluent over a specified time interval. The condensate was included in the wet gas stream determination as one of its components. Tar was neglected due to its small amount.

PRESENT WORK

The gasifier description and material balance equations are outlined below.

System Description

The gasifier under investigation has 2 input streams, wet chips and air, and 3 output streams, char, dry gas, and condensate. Figure 2 presents a system schematic indicating all the stream variables and the associated stream composition variables. The wet chip feed stream consists of 2 sub-streams, the dry chip feed stream and the chip moisture stream. The tar stream is neglected due to its small amount as reported by earlier studies (Walawender *et al*. (1985), Graham and Huffman (1981)). The moisture in humid air is also neglected due to its small amount.

The definitions of the stream flow variables and stream composition variables in Figure 2 are given below.

a) Fw - The wet chip feed rate (kg/hr).
b) F - The dry chip feed rate (kg/hr).
c) W - The chip moisture rate (kg/hr).
d) A - The dry air input rate (kg/hr).
e) G - The dry gas output rate (kg/hr).
f) CH - The char output rate (kg/hr).
g) L - The condensate output rate (kg/hr).
h) $X_{I,J}$ - The weight fraction of element J in stream I (dry basis).

It is more convenient to use the elemental weight fractions than molecular species in a reacting system because elements are conserved even with the presence of chemical reaction. The elements considered are carbon (C), hydrogen (H), Oxygen (O), and nitrogen (N). Sulfur is neglected due to its small amount. Other elements are lumped as ash.

The conveniently measured streams for the gasifier under investigation are the wet chip input stream, char output stream, and condensate-to-dry gas ratio. The downdraft gasifier is constructed with its top opened to atmosphere for simplicity in introducing feedstock and air. This configuration presents a difficulty in directly measuring the air input stream. However, this stream can be determined by material balance. Several methods can be developed to perform this calculation. These methods will be detailed later.

The gas stream rate is also not measured, since the nitrogen tracer technique used by Walawender et al. (1985) is not employed. By eliminating this technique, the experimental run time is reduced from 5 hours to approximately 2-3 hours and hence a sizable amount of feed material can be conserved. The gas output rate can be indirectly calculated using material balance techniques which will be discussed later.

The feedstock input rate is measured by weighing the feedstock delivered to the gasifier to maintain the bed at a set operating level for a selected time interval. This simple method for determining the feedstock input rate requires no calibration of a screw feeder and is less sensitive to feed bulk density variations. The collection and weighing method is employed to measure the char output rate.

Tar measurement is not conducted due to its extremely small amount. The condensate-to-dry gas ratio is measured as outlined by Walawender et al. (1985). The measurement of this ratio is highly influenced by the success in collecting all of the condensate. The collected condensate is usually low since some condensate is trapped in the packed filters and lines and some is carried away by the gas stream. When measuring the volume of the side draw gas, it is necessary to correct for temperature and pressure.

Material Balance Equations

Based on the law conservation of mass, the problem of determining all the material flows entering or leaving the downdraft gasifier is simply a problem of solving a suitable set of linear algebraic equations. The possible material balances for the simplified gasification system shown in Figure 2 consist of the following equations.

1.) Overall Material Balance

$$(F + W) + A = G + CH + L \tag{1}$$

2.) Carbon Elemental Balance (dry basis)

$$F\ X_{F,C} = G\ X_{G,C} + CH\ X_{CH,C} \tag{2}$$

3.) Nitrogen Elemental Balance (dry basis)

$$F\ X_{F,N} + A\ X_{A,N} = G\ X_{G,N} + CH\ X_{CH,N} \qquad (3)$$

4.) Oxygen Elemental Balance (dry basis)

$$F\ X_{F,O} + A\ X_{A,O} + W\ X_{W,O} = G\ X_{G,O} + CH\ X_{CH,O} + L\ X_{L,O} \qquad (4)$$

5.) Hydrogen Elemental Balance (dry basis)

$$F\ X_{F,H} + W\ X_{W,H} = G\ X_{G,H} + CH\ X_{CH,H} + L\ X_{L,H} \qquad (5)$$

6.) Ash Balance (dry basis)

$$F\ X_{F,ASH} = CH\ X_{CH,ASH} \qquad (6)$$

The chip moisture stream rate, W, can be determined using the following equation.

$$W = M\ \{F + W\} = M\ Fw \qquad (7)$$

where M is the chip moisture fraction based on a wet basis. The term {F + W} used above is the wet chip feed rate.

In practice, the ash balance should be avoided due to the high variability of char ash and the small magnitude of wood ash. The ash content of char fluctuates significantly due to sampling problems and other factors. Therefore, this balance equation is not recommended for relating the chip feed rate to the char output rate.

Besides the material balance equations given above, there is a subsidiary relation between the gas output rate and the condensate output rate that can be conveniently measured. This relationship is defined as follows

$$R = L/G \qquad (8)$$

where R is the condensate-to-dry gas ratio.

The above equations are based on the following assumptions.

a) Tar is neglected in the balance equations due to its extremely small amount relative to other stream rates.

b) Dry gas is assumed to be an ideal gas in evaluating the condensate-to-dry gas ratio.

c) For simplicity, wood chips and char are assumed to consist of only carbon, nitrogen, hydrogen, oxygen, and ash elements.

d) The moisture in humid air is neglected.

Stream Compositions

In this work, the weight fractions of carbon, nitrogen, hydrogen, and ash in both wood chips and char are measured directly. An elemental analyzer (Perkin Elmer 240b Elemental Analyzer) is used to determine the carbon, nitrogen, and hydrogen weight fractions (dry basis). The ash fractions are determined by combusting the wood chips and char in a furnace (Thermolyn Type 1500 Furnace) at 600 - 630°C into ash residue. The weight fraction of oxygen is evaluated by difference.

An on-line process gas chromatograph is employed to detect the components of the dry gas. These components include H_2, C_2H_4, C_2H_6, CO, CO_2, N_2, and CH_4. The molar compositions measured are used to determine the elemental weight fraction composition of the dry gas.

Some of the stream elemental weight fractions are fixed by nature. These include the oxygen and hydrogen in the chip moisture and condensate (water) and the nitrogen and oxygen in the dry air.

Besides the elemental weight fractions, the moisture fraction in wet wood chips, M, is measured by using a moisture balance (Ohas Moisture Balance) while the condensate-to-dry gas ratio, R, is determined by collecting and weighing the condensate in the sample stream gas and converting the measured volume of the dry gas to mass basis using the ideal gas law and the dry gas molecular weight.

MATERIAL BALANCE PROCEDURES

Excluding the ash balance equations, 5 possible material balance equations are available. These equations contain 5 stream variables and 16 stream composition variables. The number of independent balance equations is 4. The chip moisture input stream, W, is not considered as a separate stream as it is incorporated into the wet chip feed rate through Equation 7. All of the stream composition variables are either conveniently measured (elemental compositions of chips, char, and gas) or fixed by nature (elemental compositions of air and water). This reduces the number of unknown variables to 5, the number of stream rate variables;

chip input rate, air input rate, char output rate, condensate output rate, and gas output rate.

In the course of an experiment, the chip input rate, char output rate, and ratio of condensate-to-dry gas can be conveniently measured. The number of streams measured create a problem of over specification since the net degree of freedom for this system is not zero. It is -3 if all of the measurements are used (Net degree of Freedom = The number of unknown variables - (The number of independent equations + The number of specified variables + The number of subsidiary equations)). For an over specified system, the remaining variables can be calculated from several different balance combinations; however, the resultant solutions by the different approaches are likely to be inconsistent even though the procedure employed is properly specified. This is a consequence of the inherent variability of the data.

Possible Material Balance Procedures

Based on the 5 possible material balance equations and the 3 measured stream variables, a total of 60 material balance procedures are possible by using different combinations of the measured stream variables and material balances. All possible combinations are presented in Table 1 where the material balances and measured stream variables used are marked with X's. The air and gas streams are not used because they are not conveniently determined experimentally in this work.

Specification of at least one of the stream rates is necessary for an unique solution. If no stream rates are specified, the number of independent material balance equations is less than the number of unknown variables.

Methods 1 through 10 in Table 1 employ only 1 measured stream rate. To solve for the 4 unknown stream variables, 4 material balance equations are needed. Ten material balance alternatives are possible using either the chip feed stream (5 methods) or the char output stream (5 methods). Simultaneous solution is required to solve for the unknown stream variables.

When the ratio of condensate-to-dry gas is used, the original material balance equations have to be rewritten. Every term in this set of equations is divided by the dry gas output rate to yield these ratios: F/G, A/G, CH/G, and L/G. Since the ratio of condensate-to-dry gas is specified, there are only 3 unknown ratios remaining. Three material balance equations are required for solution and 10 alternatives are possible as shown in Table 1. However, these methods do not permit unique specification of the stream rates. Specification of either the chip feed rate or the char output rate will permit unique definition of all the remaining stream rates.

The chip feed stream and char output stream combination gives rise to 10 different material balance options, so do the chip feed stream and the condensate-to-dry gas ratio combination and the char output stream and the condensate-to-dry gas ratio combination. With 2 stream variables specified, only 3 material balances are required to yield solution. Not all of these methods require simultaneous solution. Methods involving the chip feed stream, char output stream, nitrogen balance, and carbon balance result in simple algebraic solution. The fact that air and condensate contain no carbon allows the direct determination of the gas output stream by substitution of both the chip feed rate and char output rate into the carbon balance. The result can be used to determine the air input rate from the nitrogen balance. Since the condensate contains no nitrogen, this calculation is straightforward. Finally, the condensate output rate can be evaluated using either the overall, oxygen, or hydrogen balances.

A total of 10 procedures are possible using all of the 3 measured stream variables. In order to solve for the 2 unknown variables, the air and gas rates, 2 material balances are needed. The possible combinations are given in Table 1. Since the air input stream is present in the overall, oxygen, and nitrogen material balance equations, methods with any combination of these 3 equations result in simultaneous solution (Methods 52, 54, and 59 in Table 1).

Selected Material Balance Procedures

Since it is impossible to present information on all the material balance procedures given in Table 1, four representative methods have been chosen for detailed analysis. Each method is compared based on the data for the present work as well as the previous data (Walawender *et al*. (1985), Graboski and Brogan (1987)). In selecting the 4 methods, the following considerations were used as guidelines.

1) Simplicity of the calculation procedure. Methods involving simple calculation procedures should be selected. From Table 1, it appears that methods with 1 stream specified give rise to complicated calculation procedures (solving 4 simultaneous equations). Preliminary calculations with the single stream methods, using the chip feed rate, indicate that some of them yield negative stream rates. Methods which use all three stream variables result in simple calculation procedures but offer little advantage since they all rely on the measured condensate-to-dry gas ratio. Consequently, only the two stream variable methods and the single stream method involving the condensate-to-dry gas ratio were explored in detail.

2) Effect of different combinations of material balance equations. The methods selected should be based on different combinations of material balance equations to identify which balances are to be preferred.

3) Effect of measured streams employed. The magnitudes of the various stream variables are quite different. Therefore it is important to identify which stream variables are preferred. Magnitude wise, the chip feed rate is the largest streams of these measured streams. Sometimes it is not easy to measure the chip feed rate, therefore other stream measurements may be necessary. The char output rate and the condensate-to-dry gas ratio are of small magnitudes and generally they are under estimated. The uncertainties in stream rates and the large range of stream magnitudes suggest the necessity of choosing procedures with different measured stream combinations for evaluation.

Based on these guidelines, the number of methods was reduced to four. The selected material balance procedures are Method 21, Method 41, Method 47, and Method 17 in Table 1. These 4 methods are designated as Method A, Method B, Method C, and Method D respectively for the remainder of the discussion. The specifics of each method are outlined in the following sections.

Method A. The wood chip input rate, and char output rate are the measured stream rates used in this method. This choice reduces the number of unknown stream variables to 3 which are the air input rate, gas output rate, and the condensate output rate. Only 3 equations are needed in this method. Since air contains no carbon, Equation 2 is used to calculate the dry gas output rate and thus forces a perfect closure in carbon. From the determined value of the dry gas, the air output rate is calculated from Equation 3. The nitrogen contents in both the feed and char are of negligible amount thus providing further simplification. The closure in nitrogen component is forced to unity. Finally, using Equation 1, the condensate output rate is determined by forcing closure in the overall material balance and the ratio of condensate-to-dry gas can be calculated. Oxygen and hydrogen closures are used to assess the reliability of this method. This method does not require the solution of simultaneous equations.

Method B. This method involves one of the least reliable measurements, the condensate-to-dry gas ratio. The other measurement used is the char output rate which is small and subject to large error. The unknown stream variables are the chip feed rate, the air input rate, and the gas output rate. The condensate output rate is incorporated into the gas output rate through the definition of the condensate-to-dry gas ratio, R. This method requires three independent equations. Equations 1, 2, and 3 are used and solution of simultaneous equations is necessary. The oxygen and hydrogen closures measure the reliability of this method. This method is selected to give a comparison to Method A based on different measured stream variables.

Method C. Using the same specified stream variables as in the second method, the condensate-to-dry gas ratio and the char output rate, three simultaneous equations, Equations 2, 3, and 4, are used to solve for the chip input rate, the air input rate, and the dry gas output rate. The closures in the overall and hydrogen component balances measure the reliability of this method. This method is selected as to allow for further evaluation of Method B based on different material balance equations.

Method D. In this method, the only measured variable used is the condensate-to-dry gas ratio, R. Unlike the previous methods, the char output rate is an unknown. As discussed earlier, when this ratio is used, only 3 material balance equations are needed. Since none of the selected methods employs the hydrogen balance, this method will utilize this equation as one of the 3 equations. Equations 2, 3, and 5 are rewritten such that every term is divided through by the dry gas output stream in order to give the ratios of F/G, A/G, and CH/G. These ratios when multiplied by the G/F ratio yield another set of ratios: CH/F, A/F, and G/F. Normally, the ratio of char-to-dry feed is converted to char yield which is defined as the char-to-dry feed percent. Note that if the char output rate is given, this method is analogous to Method B and Method C with the carbon, nitrogen, and hydrogen closures forced to unity. Since ratios are involved in this method, either the measured char output rate or the measured chip feed rate can be used to uniquely determine the other stream rates. The overall closure and the oxygen closure measure the reliability of this method.

All methods described in the preceding sections are applicable to this system if the experimental data are perfect. Nevertheless, experimentally gathered data are seldom perfect, and some methods may be better than others depending on the stream rates selected and their sensitivities to variation. In the following sections, each of the four selected methods will be evaluated in detail.

RESULTS AND DISCUSSION

To illustrate the differences between the selected material balance methods, a sample case based on the air gasification of maple chips is used. Average elemental stream compositions are given in Table 2 along with a summary of the measured stream rates.

Results of the calculations are summarized in Table 3. Method A gives a closure in the oxygen component of 104% and a closure in the hydrogen component of 89%. The calculated condensate-to-dry gas ratio is 0.08 which is 7% higher than the measured value. The dry chip input rate calculated by Method B is about 59.9% higher than the experimental measurement and the calculated char yield is about 39.2% lower than the measured value. The closures in the oxygen and hydrogen components are 102% and 87%, respectively, which are very close to Method A.

Method C calculates a dry chip feed rate which is 4.6% lower than the measured value. The calculated char yield is 4.8% higher than the measured char yield. The overall closure is 99.3% whereas the hydrogen component closure is 83%. The last method, Method D, gives a char yield which is 27% lower than the experimentally measured ratio. The overall closure is 103% and the oxygen component closure is 106%.

The results obtained by the four methods are inconsistent with each other due to the problem of over specification in this system. Usually, in the case of over specification, it is not possible to satisfy all of the imposed conditions.

The results obtained reveal that all the methods properly predict the relative stream magnitudes. They predict that the largest stream is the dry gas output stream. The next largest stream is the air input stream followed by the dry chip feed stream. The char output stream is a small stream while the condensate output stream is the smallest.

Each method seems to provide satisfactory results on certain criteria and inadequate results on others. From the comparison of the closure determinations, all these methods indicate reasonably good closures even though some methods give poor results on the stream rates. For instance, the last method yields reasonably good closure in the overall material balance but a large deviation in the char yield. Method B also gives good closures but the calculated dry chip feed rate is too high. Method A and Method C yield good results in both the closures and the stream magnitudes.

These results suggest that the choice of acceptable procedures should be based on other criteria such as the ability of the methods to closely predict the measured stream rates and the sensitivity of the procedures to the inherent measurement errors. Therefore, it is necessary to examine data of other researchers with more measured streams since the present sample case gives no indication of how well the procedures can predict the major streams especially the air input stream and the gas output stream.

To illustrate the importance of these considerations, the four methods are used to analyze the data reported by Walawender _et_ _al_. (1985) and Graboski and Brogan (1987). Their data are used because they involve more directly measured stream variables. The specifics of the measurement procedures have been discussed earlier. The material balance data summary for each investigation is presented in Table 4. Graboski and Brogan (1987) introduced an additional inlet stream, the propane supplemental fuel stream, to maintain the fire zone at the top of the chip bed. Since this results in additional ratio between the propane stream and the dry gas output stream, Method D cannot be applied to their data. However, this method can be applied to the data provided by Walawender _et_ _al_. (1985).

The results of the calculations are given in Tables 5 through 8. Since not all of the streams involved in these two studies are measured experimentally, only certain comparisons are meaningful. Walawender _et_ _al_. (1985) measured the gas output stream indirectly (nitrogen tracer) providing the appropriate comparisons between the calculated gas output rate and the measured gas output rate. Graboski and Brogan (1987) determined the air input stream allowing the comparisons between the calculated air input rates and the measured air input rates.

Method A gives reasonable predictions for both gas output rate and air input rate when compared to the directly measured gas output rate reported by Walawender _et_ _al_. (1985) and the directly measured air input rate reported by Graboski and Brogan (1987). In Table 5, the deviation for the gas output rate ranges from 1 to 30% while that of air input rate ranges from 4 to 28%. The deviation in the air input stream calculation for the data of Walawender _et_ _al_. (1985) is approximately equal to the deviation of the gas output stream calculation due to the indirect determination of air input stream from the gas output stream. This phenomena is not observed in the data of Graboski and Brogan (1987). The pressure and the possible air leakage in their closed system are suspected to be the major reasons resulting in unbalanced deviations. The oxygen closure falls between 82 and 113% for both the data of Walawender _et_ _al_. (1985) and Graboski and Brogan (1987). The hydrogen closure falls between 56 and 87% in the data of Walawender _et_ _al_. (1985) while the hydrogen closure in the data of Graboski and Brogan (1987) is about 104%. However, the calculated condensate-to-dry gas ratio shows a larger deviation in the data of Walawender _et_ _al_. (1985) which ranges from 67 to 88% than in the data of Graboski and

Brogan which ranges from 13 to 16%. This is due to the fact that the measurement procedure used by the former is not as reliable as the measurement procedure employed by the later (wet gas determination).

In Table 7, the calculated dry chip feed rate, gas output rate, and the air input rate using Method B are of extremely rate low magnitudes compared to the reported observations, especially the large negative values calculated using the data of Graboski and Brogan (1987). The minimum percentage errors found are 60% for the dry chip feed rate, 67% for the gas output rate, and 71% for the air input rate. This strongly suggests that this method is incapable of predicting reasonable stream magnitudes when the measured stream variables used are the char output stream and the condensate-to-dry gas ratio. It should be pointed out that both stream variables are of small magnitude. This method gives an oxygen closure range of 95 to 100% and a hydrogen closure range of 63 to 82% for the data of Walawender et al. (1985). As for the data of Graboski and Brogan (1987), closure falls in the range of 93 to 113%.

Table 7 presents the results of Method C in calculating the gas output rate, the air input rate, and the chip feed rate. Similar to Method B, this method yields unrealistic values for the dry chip feed rate, gas output rate, and air input rate. In some instances, the calculated stream rates are much lower than the reported stream rates while in others they are much higher than the reported stream rates. For example, the calculated dry chip feed rates are 91% lower than the data of Walawender et al. (1985) and 10,500% higher than the data of Graboski and Brogan (1987). For the gas output rate, the lowest stream rate caculated is 92% lower than the data of Walawender et al. (1985) whereas the highest stream rate calculated is 10,100% higher than the data of Graboski and Brogan (1987). The lowest air input rate calculated is 92% lower than the data of Walawender et al. (1985) and the highest gas output rate calculated is 9,000% higher than the data of Graboski and Brogan (1987). Even though these calculated stream rates are of unrealistic magnitudes, they give good overall closure (about 100%) and hydrogen closure (80 to 85% in the data of Walawender et al. (1985) and 98 to 111% in the data of Graboski and Brogan (1987)).

The results of calculations for Method D are given in Table 8. This method yields reasonable results for the gas-to-feed and air-to-feed ratios, but gives poor results for the char yield. Error as high as 450% is found in the char yield comparison. The oxygen closures range from 102 to 110% and the hydrogen closures range from 106 to 130%. The major drawback of this method is that it merely calculates ratios rather than the actual magnitudes of stream rates.

Evidently, the closure determination itself is not sufficient to tell how good the material balance procedure is. The reliability of the material balance procedure should also be judged base on its capabilities in terms of predicting the major stream magnitudes. The principal finding of these comparisons is that even though a material balance procedure is incapable of predicting acceptable stream magnitudes, it may give good elemental closures (Method B , Method C, and Method D). Overall, Method A not only gives satisfactory closures, but also predicts relatively close stream magnitudes when compared to those directly measured streams.

Before selecting the best method, the reliability of the four methods should also be evaluated based on their sensitivities to the measurement errors inherent in the chip feed rate, char output rate, and the condensate-to-dry gas ratio. Since each method involves different stream variables and material balance equations, it is necessary to discuss the reliability and sensitivity of each approach with respect to the stream variables and the stream composition variables.

In the present study, the measurement error involved in measuring the chip feed rate is ±6% while that of the char output rate is ±20%. The char output rate has a higher variation due to the following factors: a) possible burning of char during the collection period, b) fine char exiting from the discharge system is light and a small portion can be carried away by the air draft, and c) cyclone inefficiency. The magnitudes of these stream measurement errors allow comparison of the sensitivities of the four methods to chip feed rate errors and char output rate errors.

Graboski and Brogan (1987) gave the magnitude of measurement errors for both the chip feed rate (+10%) and air input rate (+3%). The fact that the gas output rate is determined from the air input rate through the nitrogen balance and the high accuracy attainable in the nitrogen detection, the anticipated error for the gas output rate is expected to be that of the air input rate. Similarly, since the gas compositions can be determined with precision, the measurement error of the condensate-to-dry gas ratio is directly tied to the gas output rate. Therefore, the error of this ratio is assumed to be +3%.

Besides the measurement error for the stream variables, the measurement errors or variability inherent in the determination of the stream compositions can also affect the sensitivities. The elemental compositions of chips determined by the elemental analyzer (carbon, hydrogen, and nitrogen) have low standard deviations. Typical standard deviations are reported in Table 9 (based on the sample case). The ash composition in chips is highly influenced by the sample used for ash analysis, especially by the proportion of bark present in the sample. Nonrepresentative samples tend to increase the standard deviation. The oxygen composition is evaluated by difference. Chip oxygen has a small standard deviation because wood chips are not only low in ash content, hydrogen content, and nitrogen content, but also show little variation in carbon content.

Char has negligible amount of hydrogen and nitrogen. Its major components are carbon, ash, and oxygen. Table 9 shows that the carbon in char fluctuates due to the fluctuating ash content. The fluctuation in the char ash content in the char reported in Table 9 is not very large due to the small sample size (3 samples) used. Oxygen is calculated by difference and its degree of variation is reflected by these determined compositions.

The gas chromatograph provides accurate determinations of gas compositions. The standard deviations of the elemental compositions are low as indicated in Table 9. This is highly desirable if the gas output rate is to be determined indirectly.

Tables 10 and 11 present the results of the sensitivity calculations. Table 10 shows the sensitivity analyses of the four methods with the chip feed rate and the char output rate variations based on the present data (maple chips). Table 11 presents the sensitivity analyses of the four methods with the chip feed rate and the condensate-to-dry gas ratio variations based on data reported by Graboski and Brogan (1987). The calculated stream rates are compared to the stream rates determined using the average value of stream measurements (see Tables 3 through 7).

In the present study, varying the average chip feed rate by ±6% in Method A gives almost proportional changes in the gas output rate and the air input rate as shown in Table 10. Similar sensitivity is indicated in Table 11. It appears that this method is not highly influenced by small measurement errors in the chip feed rate.

Varying the average char output rate by ±20% in Method A changes the gas output rate by ±2.3% and the air input rate by ±2.3% (see Table 10). In Method B, these same streams change by ±25%. In Method C, the upper bound is +22% for both streams while the lower bound is -27% for both streams. The principal finding of this analysis is the low sensitivity of Method A to the measurement error in the char stream rate.

Varying the average condensate-to-dry gas ratio by +3% in Method B gives modest changes in the dry chip feed rate, gas output rate, and air input rate. The results are shown in Table 11. Increasing this variable by 3% causes these stream rates to increse up to a maximum of 2.3 times higher than the stream rates calculated based on the average condensate-to-dry gas ratio. In Method C, the 3% increase doubles the dry chip feed stream, gas output stream, and air input stream when compare to those stream rates obtained using the average condensate-to-dry gas ratio. These results indicate the high sensitivities of Method B and Method C to the measurement error of this ratio.

In Method A, since both feedstock (wood chips) and char contain negligible amounts of nitrogen, the determination of the air input rate is directly influenced by the calculation of the gas stream rate. The typical dry weight percent of nitrogen in the dry gas is about 45-50% while those of the chips and char are about 0.5%. This indirect determination of the dry gas output rate using the carbon balance is considered as a reliable method due to the high accuracy in the dry gas elemental composition measurements and the nearly constant carbon content in chips (wood chips contain about 45-48 dry weight percent of carbon). The carbon content in char does not affect the calculation significantly because of its small rate compared to both the dry chip input rate and the gas output rate.

Method A is also insensitive to the measurement errors in the stream compositions. This is because the method is insensitive to the char output rate (small magnitude) which is the only stream that shows considerable fluctuation in its elemental composition. Using the standard deviation given in Table 9 for the carbon element in char, the deviations of the gas output rate and the air input rate are not affected significantly (about ±3%).

From the comparison of closure calculations as well as the sensitivity analyses, Method A appears to be the most suitable method for determining both input and output rates. This method not only provides reasonably good closures on hydrogen and oxygen, it is also least sensitive to measurement errors. It gives gas output rate and the air input rate magnitudes close to the observations. This method is straightforward and no extensive calculation is involved. This method does not depend on the condensate-to-dry gas ratio. This measured variable is usually lower than the predicted value due to several factors: a) some condensate is trapped in the sample system, and (b) some material is not condensed and carried away by the gas.

CONCLUSION

This chapter presents material balance procedures for a downdraft gasifier without utilizing the nitrogen tracer technique. An over specified system is generated due to additional information on several stream flow measurements.

Four different material balance methods have been explored for determining the input flow rates and output flow rates to and from the gasifier. The reliability of each method is established based on closure determinations, ability to predict stream magnitudes, and sensitivity analysis. Method A, involving both the measured chip feed rate and char output rate, is selected because it gives satisfactory closures and reasonable magnitudes of stream flow rates. It is also least sensitive to the measurement errors of the stream rates and stream compositions. The chapters to follow will employ the Method A to investigate the influence of operating parameters (Chapter 4), chip physical properties (Chapter 5), and tree species (Chapter 6) on the performance of a commercial downdraft gasifier.

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Table 1. Possible Material Balance Procedures.

Possible Methods	Material Balance Equations					Stream Rates				
	Overall	Carbon	Nitrogen	Hydrogen	Oxygen	Feed	Char	Air	Gas	Condensate-to-Dry Gas
	1 Stream Specified									
1	X	X	X	X		X				
2	X	X	X		X	X				
3	X	X		X	X	X				
4	X		X	X	X	X				
5		X	X	X	X	X				
6	X	X	X	X			X			
7	X	X	X		X		X			
8	X	X		X	X		X			
9	X		X	X	X		X			
10		X	X	X	X		X			
11	X	X	X							X
12	X	X		X						X
13	X	X			X					X
14	X		X	X						X
15	X		X		X					X
16	X			X	X					X
17		X	X	X						X
18		X	X		X					X
19		X		X	X					X
20			X	X	X					X

Table 1. (continued).

Possible Methods	Material Balance Equations					Stream Rates				
	Overall	Carbon	Nitrogen	Hydrogen	Oxygen	Feed	Char	Air	Gas	Condensate-to-Dry Gas
					2 Streams Specified					
21	X	X	X			X	X			
22	X	X		X		X	X			
23	X	X			X	X	X			
24	X		X	X		X	X			
25	X		X		X	X	X			
26	X			X	X	X	X			
27		X	X	X		X	X			
28		X	X		X	X	X			
29		X		X	X	X	X			
30			X	X	X	X	X			
31	X	X	X			X				X
32	X	X		X		X				X
33	X	X			X	X				X
34	X		X	X		X				X
35	X		X		X	X				X
36	X			X	X	X				X
37		X	X	X		X				X
38		X	X		X	X				X
39		X		X	X	X				X
40			X	X	X	X				X
41	X	X	X				X			X
42	X	X		X			X			X
43	X	X			X		X			X
44	X		X	X			X			X
45	X		X		X		X			X
46	X			X	X		X			X

Table 1. (continued).

Possible Methods	Material Balance Equations					Stream Rates				
	Overall	Carbon	Nitrogen	Hydrogen	Oxygen	Feed	Char	Air	Gas	Condensate-to-Dry Gas
	2 Streams Specified									
47		X	X		X		X			X
48		X	X	X			X			X
49		X		X	X		X			X
50			X	X	X		X			X
	3 Streams Specified									
51	X	X				X	X			X
52	X		X			X	X			X
53	X			X		X	X			X
54	X				X	X	X			X
55		X	X			X	X			X
56		X		X		X	X			X
57		X			X	X	X			X
58			X	X		X	X			X
59			X		X	X	X			X
60				X	X	X	X			X

Table 2. The Average Elemental Compositions of Maple Chips and the Experimentally Determined Stream Variables.

Elemental Compositions	(Weight Percent) Dry Chip	Char	Dry Gas	Dry Air	H_2O
Carbon	48.66	73.71	19.53	0.00	0.00
Oxygen	43.16	4.93	30.40	23.30	88.89
Hydrogen	6.00	0.67	1.72	0.00	11.11
Nitrogen	0.30	0.49	48.32	76.70	0.00
Ash	1.88	20.20	0.00	0.00	0.00

Measured Variables	
Wet Chip Feed Rate (kg/hr)	91.91
Chip Moisture Content (% wet basis)	7.80
Dry Chip Feed Rate (kg/hr)	84.74
Char Output Rate (kg/hr)	4.74
Char Yield (% dry basis)	5.59
Condensate-to-Dry Gas (mass ratio)	0.072

Table 3. Comparison Between Measured and Calculated Stream Variables.

Method A

Measured Condensate-to-Dry Gas Ratio	Calculated Condensate-to-Dry Gas Ratio	Percent Off (%)
0.072	0.079	+7.0

Method B

Measured Dry Chip Feed Rate (kg/hr)	Calculated Dry Chip Feed Rate (kg/hr)	Percent Off (%)
84.74	135.50	+59.9

Measured Char Yield (%)	Calculated Char Yield (%)	Percent Off (%)
5.59	3.40	-39.2

Method C

Measured Dry Chip Feed Rate (kg/hr)	Calculated Dry Chip Feed Rate (kg/hr)	Percent Off (%)
84.74	80.83	-4.6

Measured Char Yield (%)	Calculated Char Yield (%)	Percent Off (%)
5.59	5.86	+4.8

Method D

Measured Char Yield (%)	Calculated Char Yield (%)	Percent Off (%)
5.59	4.10	-27.0

Table 4. Material Balance Summary Data for Walawender et al. (1985) and Graboski and Brogan (1987).

[Walawender et al., 1985]

Run No.	Inputs (kg/hr)				Outputs (kg/hr)				
	Wet Chips	Dry Air	H_2O	Total	Dry Gas	Char	Tar	H_2O	Total
1001	32.0	43.1	0.5	75.6	66.3	0.9	0.09	7.4	74.7
1002	32.0	45.2	0.5	77.7	68.0	0.9	0.14	7.4	76.4
1003	35.7	62.1	0.4	98.2	92.9	1.4	0.09	7.1	101.5
1004	52.7	74.0	1.0	127.7	113.0	1.8	0.14	12.2	127.1
1005	58.1	76.8	0.5	135.4	117.0	1.2	0.09	10.8	129.1
1006	89.1	112.1	1.0	202.2	173.8	3.0	0.27	19.7	196.8
1007	96.2	140.4	0.7	237.3	218.9	2.5	0.18	22.9	244.5
1008	104.5	202.1	1.1	343.7	302.1	4.1	0.54	43.3	350.0

[Graboski and Brogan, 1987]

Run No.	Inputs (kg/hr)				Outputs (kg/hr)			
	Wet Chips	Dry Air	Propane	Total	Dry Gas	Char	H_2O	Total
2001	529.8	1081.0	10.1	1620.9	1409.4	27.2	131.6	1568.2
2002	668.1	1330.4	10.1	2008.6	1772.1	33.1	124.2	1929.4

Table 5. Results of Material Calculations Using Method A Based on Reported Data [Walawender et al. (1985) and Graboski and 8rogan (1987)].

	Original Data		Method A			
Run No.	Reported[#] Gas Output Rate (kg/hr)	Reported[*] Air Input Rate (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off (%)	Calculated Air Input Rate (kg/hr)	Percent Off (%)
			[Walawender et al., 1985]			
1001	66.3	43.1	82.4	+24.3	53.2	+23.5
1002	68.0	45.2	84.6	+24.5	54.7	+20.9
1003	92.9	62.1	92.0	-0.9	59.4	-4.3
1004	113.0	74.0	132.0	+16.8	85.2	+15.2
1005	117.0	76.8	151.9	+29.9	98.1	+27.8
1008	173.8	112.1	221.6	+27.5	143.1	+27.7
1007	218.9	140.4	240.7	+10.0	155.4	+10.7
1008	302.1	202.1	265.7	-12.0	171.6	-15.1
			[Graboski and 8rogan, 1987]			
2001	1409.4	1081.0	1289.4	-8.5	870.3	-19.5
2002	1772.1	1330.4	1623.2	-8.4	1098.6	-17.4

	Original Data	Method A			
Run No.	Reported Condensate-to-Dry Gas Ratio	Calculated Condensate-to-Dry Gas Ratio	Percent Off (%)	Oxygen Closure (%)	Hydrogen Closure (%)
		[Walawender et al., 1985]			
1001	0.11	0.02	-79.2	102	79
1002	0.11	0.01	-88.0	98	75
1003	0.08	0.02	-76.0	113	76
1004	0.11	0.03	-71.0	100	84
1005	0.09	0.02	-78.0	100	81
1006	0.11	0.03	-70.0	102	87
1007	0.10	0.04	-66.5	103	86
1008	0.14	0.02	-83.5	82	56
		[Graboski and 8rogan, 1987]			
2001	0.085	0.072	-15.5	100	104
2002	0.066	0.074	+13.3	100	105

[#] Graboski and 8rogan (1987) calculated the gas output rate using the nitrogen balance.

[*] Walawender et al. (1985) calculated the air input rate using the nitrogen balance.

Table 6. Results of Material Balance Calculations Using Method B Based on Reported Data [Walawender *et al*. (1985) and Graboski and Brogan (1987)].

	Original Data		Method B			
Run No.	Reported# Gas Output Rate (kg/hr)	Reported* Air Input Rate (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off (%)	Calculated Air Input Rate (kg/hr)	Percent Off (%)
[Walawender *et al*., 1985]						
1001	68.3	43.1	5.6	-91.5	3.6	-91.6
1002	68.0	45.2	6.2	-90.9	4.1	-91.0
1003	92.9	62.1	7.2	-92.9	4.3	-93.1
1004	113.0	74.0	13.7	-87.9	8.9	-87.9
1005	117.0	76.8	10.0	-91.5	6.5	-91.5
1006	173.8	112.1	19.4	-88.9	12.4	-88.9
1007	218.9	140.4	17.3	-92.1	11.0	-92.2
1008	302.1	202.1	22.1	-92.7	14.7	-92.7
[Graboski and Brogan, 1987]						
2001	1409.4	1081.0	470.4	-66.6	317.4	-70.6
2002	1772.1	1330.4	-11027.8	-677.0	-7463.4	-661.0

	Original Data	Method B			
Run No.	Reported Dry Chip Feed Rate (kg/hr)	Calculated Dry Chip Feed Rate (kg/hr)	Percent Off (%)	Oxygen Closure (%)	Hydrogen Closure (%)
[Walawender *et al*., 1985]					
1001	31.50	3.47	-89.0	96	78
1002	31.50	3.62	-88.5	96	80
1003	35.30	4.80	-86.4	96	63
1004	51.70	7.93	-84.7	97	84
1005	57.60	5.56	-90.3	97	81
1006	88.10	12.01	-86.4	96	82
1007	95.50	10.51	-89.0	96	80
1008	139.40	14.51	-90.0	95	81
[Graboski and Brogan, 1987]					
2001	476.8	189.30	-60.3	99	93
2002	601.3	-4263.50	-738.0	100	113

\# Graboski and Brogan (1987) calculated the gas output rate using the nitrogen balance.

* Walawender *et al*. (1985) calculated the air input rate using the nitrogen balance.

Table 7. Results of Material Balance Calculations Using Method C Based on Reported Data [Walawender *et al*. (1985) and Graboski and Brogan (1987)].

	Original Data		Method C			
Run No.	Reported# Gas Output Rate (kg/hr)	Reported* Air Input Rate (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off (%)	Calculated Air Input Rate (kg/hr)	Percent Off (%)
			[Walawender *et al*., 1985]			
1001	66.3	43.1	6.1	-90.9	3.9	-91.0
1002	68.0	45.2	6.7	-90.2	4.4	-90.3
1003	92.9	62.1	7.7	-91.7	4.6	-92.6
1004	113.0	74.0	14.2	-87.4	9.2	-87.5
1005	117.0	76.8	10.9	-90.6	7.1	-90.7
1006	173.8	112.1	21.5	-87.7	13.8	-87.7
1007	218.9	140.4	19.3	-91.2	12.3	-91.2
1008	302.1	202.1	25.1	-91.7	18.7	-91.8
			[Graboski and Brogan, 1987]			
2001	1409.4	1081.0	586.2	58.4	-395.5	-63.4
2002	1772.1	1330.4	181225.0	10126.0	+122652.1	+9119.0

	Original Data	Method C			
Run No.	Reported Dry Chip Feed Rate (kg/hr)	Calculated Dry Chip Feed Rate (kg/hr)	Percent Off (%)	Overall Closure (%)	Hydrogen Closure (%)
		[Walawender *et al*., 1985]			
1001	31.50	3.82	-88.5	101	80
1002	31.50	3.78	-88.0	100	82
1003	35.30	4.97	-85.9	101	65
1004	51.70	8.11	-84.3	100	84
1005	57.80	5.90	-89.8	101	84
1006	88.10	12.80	-85.5	101	85
1007	95.50	11.30	-88.2	101	83
1008	166.41	15.61	-90.6	101	85
		[Graboski and Brogan, 1987]			
2001	476.80	229.9	-51.8	100	98
2002	601.30	63613.3	+10479.0	100	111

Graboski and Brogan (1987) calculated the gas output rate using the nitrogen balance.

* Walawender *et al*. (1985) calculated the air input rate using the nitrogen balance.

Table 8. Results of Material Balance Calculations Using Method D Based on Reported Data (Walawender et al., 1985).

	Original Data		Method D			
Run No.	Reported Gas-to-Dry Feed Ratio	Reported* Air-to-Dry Feed Ratio	Calculated Gas-to-Dry Feed Ratio	Percent Off (%)	Calculated Air-to-Dry Feed Ratio	Percent Off (%)
			[Walawender et al., 1985]			
1001	2.10	1.37	2.06	-2.1	1.33	-0.2
1002	2.16	1.43	2.11	-2.2	1.40	-2.8
1003	2.63	1.76	2.47	-6.0	1.48	-16.0
1004	2.19	1.43	2.03	-6.9	1.32	-7.7
1005	2.03	1.33	2.22	+9.4	1.47	+10.0
1006	1.97	1.27	1.97	-0.1	1.26	-0.8
1007	2.29	1.47	2.07	-9.5	1.32	-10.2
1008	2.92	1.95	1.89	-35.3	1.26	-35.8

	Origianl Data	Method D			
Run No.	Reported Char Yield (%)	Calculated Char Yield (%)	Percent Off (%)	Overall Closure (%)	Oxygen Closure (%)
		[Walawender et al., 1985]			
1001	2.86	15.72	+450	104	111
1002	2.86	15.81	+454	103	108
1003	3.97	7.05	+78	110	129
1004	3.48	15.72	+351	103	106
1005	2.08	11.10	+433	102	109
1006	3.41	16.40	+382	104	108
1007	2.62	13.40	+412	104	110
1008	3.97	19.72	+397	104	109

* Walawender et al. (1985) calculated the air input rate using the nitrogen balance.

Table 9. Means and Standard Deviations for All Elemental Compositions of Chips, Char, and Dry Gas Based on Sample Case Data (Maple Chips).

Element	Dry Weight Percent (%)					
	Chips		Char		Dry Gas	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Carbon	48.7	0.10	73.7	5.50	19.5	0.35
Hydrogen	6.0	0.09	0.7	0.07	1.7	0.05
Oxygen	43.2	0.11	4.9	5.50	30.4	1.15
Nitrogen	0.3	0.02	0.5	0.05	48.3	1.20
Ash	1.9	0.61	20.2	0.14	0.0	0.00

Table 10. Results of Sensitivity Analyses Using Sample Case Data (Maple Chips).

Average Wet Chip Feed Rate (kg/hr)	Standard Deviation (%)	Average Char Ourput Rate (kg/hr)	Standard Deviation (%)
84.74	±6.0	4.74	±20

Method A

Wet Chip Feed Rate Used (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off Based on Average Feed Rate	Calculated Air Input Rate (kg/hr)	Percent Off Based on Average Feed Rate
98.51	215.4	+7.9	135.3	+7.8
85.31	183.6	-7.8	115.7	-7.8

Char Output Rate Used (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off Based on Average Char Output Rate	Calculated Air Input Rate (kg/hr)	Percent Off Based on Average Char Output Rate
5.94	204.0	+2.3	128.4	+2.4
3.54	194.8	-2.3	122.6	-2.3

Table 10. (continued).

Char Output Rate (kg/hr)	Calculated Dry Feed Rate (kg/hr)	Percent Off Based on Average Char Output Rate	Calculated Gas Output Rate (kg/hr)	Percent Off Based on Average Char Output Rate	Calculated Air Input Rate (kg/hr)	Percent off Based on Average Char Output Rate
			Method B			
5.94	175.2	+25.6	414.0	+25.6	260.3	+25.7
3.54	104.5	-25.1	246.9	-25.1	155.2	-25.1
			Method C			
5.94	9B.9	+22.4	224.1	+22.3	140.8	+22.1
3.54	59.0	-27.0	133.6	-27.1	B3.9	-27.2

Table 11. Results of Sensitivity Analyses Using the Data of Graboski and Brogan (1987).

Run No.	Average Wet Chip Feed Rate (kg/hr)	Standard Deviation (%)	Average Condensate-to-Dry Gas Ratio	Standard Deviation (%)
2001	529.8	+10.0	0.085	+3.0
2002	668.1	+10.0	0.066	+3.0

Method A

Run No.	Wet Chip Feed Rate Used (kg/hr)	Calculated Gas Output Rate (kg/hr)	Percent Off Based On Average Feed Rate	Calculated Air Input Rate (kg/hr)	Percent Off Based on Average Feed Rate
2001	582.8	3142.7	+10.6	2120.4	+11.0
2002	734.9	3955.6	+10.5	2677.2	+10.5

Table 11. (continued).

Run No.	Condensate-to-Dry Gas Ratio Used	Calculated Dry Chip Feed Rate (kg/hr)	Percent Off Based on Average Condensate-to-Dry Gas Ratio	Calculated Gas Output Rate (kg/hr)	Percent Off Based on Average Condensate-to-Dry Gas Ratio	Calculated Air Input Rate (kg/hr)	Percent Off Based on Average Condensate-to-Dry Gas Ratio
			Method B				
2001	0.088	375.2	+10.1	917.6	+11.5	619.1	+11.5
2002	0.068	10837.9	+228.0	30891.5	+226.0	20771.8	+226.0
			Method C				
2001	0.088	458.6	+9.5	1154.9	+10.6	779.2	+10.6
2002	0.068	6161.9	-95.0	17362.1	-95.7	11750.5	-95.7

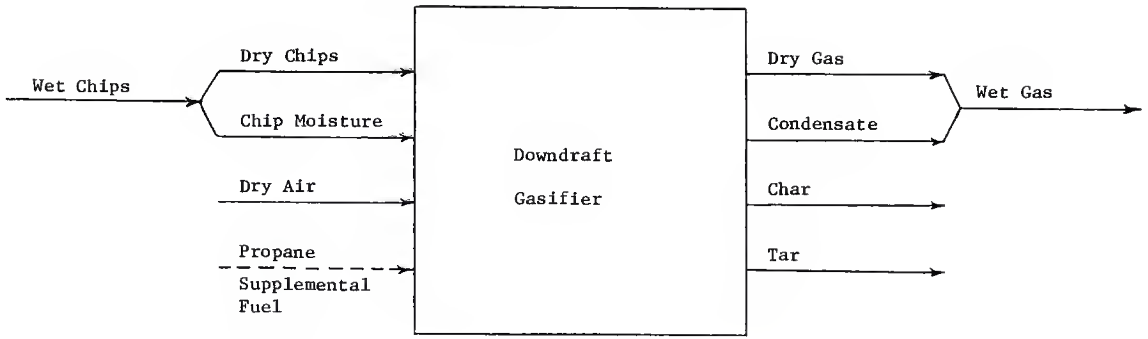

Figure 1. Schematic of a Downdraft Gasifier with All Input and Output Streams.

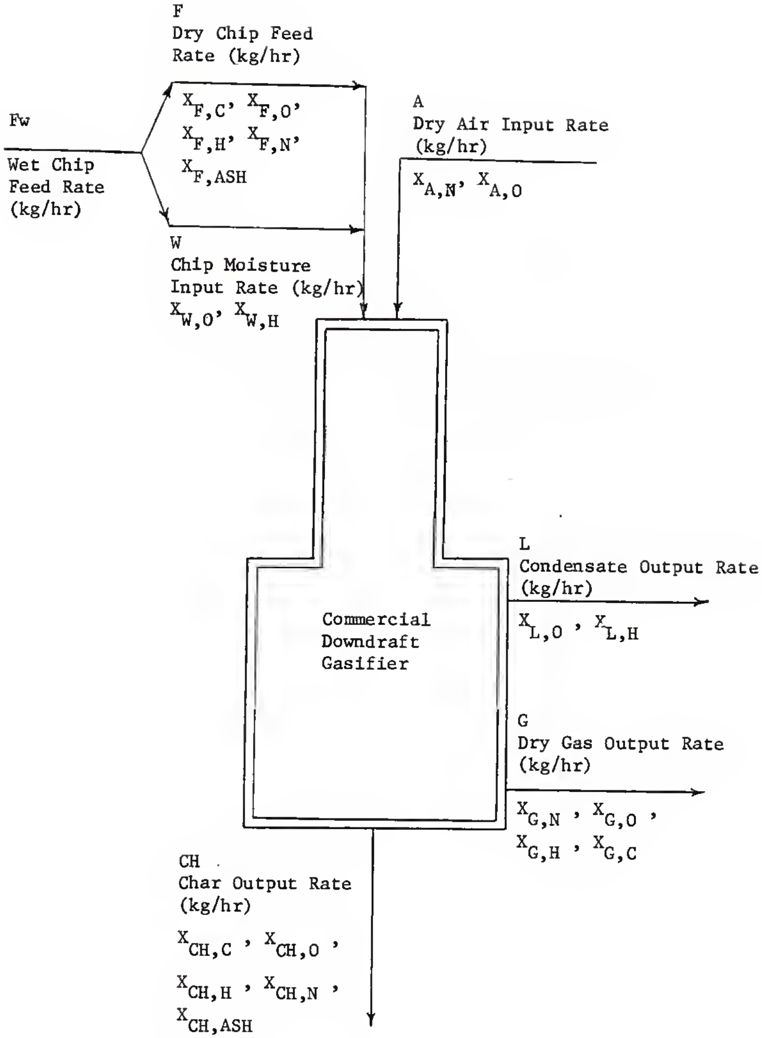

Figure 2. Schematic of the Air Gasification of Wood Chips.

CHAPTER 4

INFLUENCE OF OPERATING PARAMETERS ON DOWNDRAFT GASIFIER PERFORMANCE

Downdraft gasification has been practiced for over a century for the production of low energy gas from wood and charcoal. The technology has been used mainly in times of energy shortages to provide fuel gas for both mobile and stationary applications. The bulk of the literature on the subject has primarily consisted of qualitative descriptions of specific systems. In the older literature, only fragmentary qualitative information has been presented on gasifier performance.

More recently, a few studies have been published which present complete material balance data and various gasifier efficiency measures. Graham and Huffman (1981) were the first to report material balances and conversion efficiencies for a commercial-scale wood gasifier. They also presented limited data on the effects of wood species, chip size and chip moisture content. Walawender _et_ _al_. (1985) reported material balances and conversion efficiencies over a four-fold range of feed rates with a commercial downdraft gasifier. Walawender _et_ _al_. (1987) also presented limited data on the effects of feed type (chips and pellets), bed support and grate rotation.

Unfortunately, in the previous studies of the influence of operating parameters on gasifier performance, the data have been limited in number and in some cases more than one parameter was varied simultaneously. The objective of the present work was to conduct a systematic investigation of the influences of three operating parameters on the gasification of cottonwood chips in a commercial-scale downdraft gasifier (Buck Rogers Gasifier). The parameters studied were the chip moisture content, the grate rotation speed and the gas fan rotation speed. Each parameter was varied independently.

EXPERIMENTAL FACILITIES AND PROCEDURES

Gasifier Description

Figure 1 presents a schematic diagram of the gasifer used in this study. It is similar in construction to the gasifers used by Walawender et al. (1985). The unit has a nominal diameter of 0.6m and the top is open to the atmosphere. There is no throat (constriction) in the unit as in conventional designs. The bed is supported by a rotating perforated grate which is driven by a hydraulic motor. The grate rotation speed is controlled by a hydraulic fluid flow splitter. The grate is attached to a hollow shaft ("airgitator") which provides secondary air through the tuyeres. The gas fan, coupled to the base of the gasifier, draws air into the top of the unit and gas and char out of the bottom. The fan rotation speed is controlled by using combinations of pulleys of various diameters on the fan and fan motor drive shafts.

Wood chips are fed to the top of the unit with a screw feeder. Feed is introduced periodically to restore the bed depth to the operating level (the bed is allowed to drop about 15 cm before refilling to the operating level). Gas and char discharge from the fan and pass through a cyclone to separate the char. The char is conveyed from the base of the cyclone to a holding bin (not shown in Figure 1) via two screw conveyors arranged in series to maintain a gas seal. The gas then flows to a flare (not shown in Figure 1) for incineration. Prior to flaring, a side draw of the gas is taken continuously for analysis.

Operating Procedure

The gasifier operating procedure is detailed below.

(1) Start-up. The empty gasifier, gas fan, cyclone and flare were preheated to about 382°C to prevent condensation of water and tar when the chips were introduced. Preheat was accomplished with a portable propane burner which was inserted into the start-up port and fired for 25-30 minutes with the gas fan running. Next a second propane burner was inserted in the flare to insure ignition of the initial product. With the grate rotation off, the portable burner was withdrawn, chips were added to the gasifier to a depth of about 15cm and the burner was reintroduced to ignite them. This procedure was repeated until the bed level reached just above the tuyeres. At this

point, both portable burners were withdrawn, the grate rotation was started, the start-up port was sealed and the bed was filled with chips to the operating level. Temperatures were then monitored (below the grate, at the fan inlet and at the flare inlet) to determine when steady state was reached. Normally 1.5 hours were required to complete start-up.

(2) Gas analysis and condensables measurement. After the completion of step 1, a side draw of the gas was taken for analysis and condensate determination. The specific procedures will be detailed later. This step was conducted for a 1.5-2 hour period.

(3) Char and feed rate measurements. Concurrently with step 2, char and feed rates were determined at 20-30 minute intervals by direct weighing. The specifics will be detailed in the next section.

(4) Shut-down. Feeding was stopped and the bed level was allowed to drop. When the bed dropped to the tuyere level, flame appeared on the surface of the bed and further decrease in bed level resulted in rapidly rising temperatures in the system. At this point, the gas fan was shut off to prevent excessive temperature. The fan was turned on periodically, for brief intervals, to exhaust the remaining solids. Shut-down normally required 1 hour.

Measurements

The following items were directly measured during the steady state period of operation.

(1) Feed rate. The wet feed rate was determined by weighing all chips fed to the gasifier. The operating level was set at the start of the steady state period and weighed quantities of chips were periodically manually charged to restore the operating level. The weights of chips added for each 20-30 minute interval in the steady state period were recorded.

(2) Char output rate. The char output rate was obtained by placing the char holding bin on a scale and recording the weight at 20-30 minute intervals. This was done concurrently with the feed rate determinations.

(3) Gas analysis. The composition of the dry gas was determined with an Applied Automation on-line process gas chromatograph (GC) which drew a continuous sample from the side draw. The GC had a cycle time of 11 minutes and was able to detect the following components: H_2, CO_2, CO, CH_4 and N_2 (major components) along with traces of C_2H_4, C_2H_6 and C_3H_6 (minor components).

(4) Condensables. The side draw used for dry gas analysis was also used for the determination of condensables. The sample stream was drawn at a rate of about 0.56 m^3/hr through two filters (in series) packed with

glass wool, to remove most of the tar mist. Since the amount of tar was found to be negligible in the previous work (Walawender *et al*. (1985)), it was not measured. The gas was then passed through two water cooled condensers in series to remove most of the water. The remaining water removal was accomplished by passing the gas through two receivers in series placed in a cold water bath. The faint trace of smoke that remained was removed by passing the gas through a tightly packed glass wool filter. Flow through the sample train was maintained with the aid of a Gast compressor which provided suction. The compressor discharge was passed through a wet test meter followed by a drierite column and then to the GC. The total volume recorded by the wet test meter was corrected for temperature, pressure and water of saturation. The total mass of aqueous condensate was obtained from the total volume of the aqueous condensate. These two quantities were used to determine the liquid-to-dry gas mass ratio.

(5) Temperature and pressure. Temperatures were monitored at the following locations in the system; just below the upper tuyeres, below the lower tuyeres, just above the grate, below the grate, at the fan inlet and at the flare inlet. Temperatures were recorded with a multipoint temperature recorder. Pressure was measured at the fan inlet with a water manometer. Pressures were recorded

manually at 20-30 minute intervals. The fan suction pressure was identical to the bed pressure drop.

(6) Chip moisture content. The chip moisture content was determined 4-5 times over the course of each experiment using an Ohas moisture balance. Readings from the balance were within a few tenths of a percent of those determined by the standard ASTM procedure.

(7) Chip bulk density. The bulk density of the feed was measured 4-5 times over the course of each experiment. The chips were dropped into a box of known volume, leveled to the surface of the box, and weighed.

In addition to the above items, the dry gas production rate and the air input rate were determined indirectly.

(8) Dry gas production rate. This was determined by making a carbon balance on the gasifier. The measured feed and char rates coupled with the elemental analyses of the feed and char and the dry gas composition permitted the calculation of the dry gas rate.

(9) Air input rate. This was determined by making a nitrogen balance on the gasifier. The calculated dry gas rate coupled with the dry gas composition and the known composition of air were used to calculate the air input rate. The small amounts of nitrogen in the feed and char were neglected in this calculation.

Operating Parameters

Three parameters were investigated in this study, the chip moisture content, the grate rotation speed and the gas fan rotation speed. Each parameter was varied independently. Cottonwood chips with an initial moisture content of about 30% were air dried to the moisture content desired for each experiment.

Moisture Content. An adequate supply of dry chips was prepared for each experiment at a given moisture content. Seven runs were conducted with moisture contents ranging between 5 and 23% wet basis. In all the runs, the fan rotation speed was maintained constant at 1795 rpm and the grate rotation speed was maintained constant at 6 rph.

Grate Rotation Speed. The grate rotation speed was controlled with a hydraulic fluid flow splitter. Seven experiments with grate rotation speeds ranging between 0 and 21 rph were conducted. The fan rotation speed was fixed at 1795 rpm and the chip moisture content was maintained at 6-8% for all of the experiments.

Gas Fan Rotation Speed. The gas fan rotation speed was varied by changing the diameters of the pulleys on the fan and fan motor drive shafts. Six experiments with fan rotation speeds ranging between 1400 rpm and 2600 rpm were conducted. The grate rotation speed was fixed at 4.1 rph and the chip moisture content was maintained at 12-14% for all runs.

Chemical and Physical Analyses

A variety of chip properties were determined for each individual experiment. These consisted of the moisture content, ash content, elemental analysis and bulk density. Moisture and ash were determined by the standard ASTM procedures. Elemental analyses were conducted with a Perkin-Elmer Model 240b Elemental Analyzer. Ash and elemental analyses were also conducted on the char produced in each run.

For each parameter studied, the same source of chips was used for the set of experiments; however, the source varied for the different parameters. For the moisture content variation runs, the chips were obtained from 12 year old trees and the bark and small branches were included in the feedstock. For the grate rotation speed variation runs, the chips were obtained from the trunk and major limbs of a 40-50 year old cottonwood tree (no bark included). For the fan rotation speed variation runs, the chips were obtained from deadfall cottonwood limbs, some containing bark and small branches.

Additional properties were determined for each chip source. These consisted of the chip size distribution, the chip voidage, the gross heat of combustion and analyses for cellulose, hemicellulose and lignin. Size distributions were obtained by screening and the average chip thickness was determined based on the chip thickness for each size fraction. Voidage was determined by dropping chips into a box of known volume, leveling to the surface of the box, and then filling the voids with fine sand and determining the mass of sand required. Tapping was necessary to fill the void space; consequently, the packed density of the sand was used to calculate the void volume. The gross heat of combustion was measured with a Parr bomb calorimeter using the standard ASTM procedure. Cellulose, hemicellulose and lignin were determined by an independent laboratory. Neutral-detergent (cell wall), acid-detergent fiber, and permanganate lignin test, as described by Goering and Van Soest (1970), were used for these determinations.

Table 1 summarizes of the chemical properties for each chip source. Means and standard deviations are given when multiple determinations were made. Table 2 presents a summary of the physical properties for each chip source.

TREATMENT OF DATA

Calculations

The performance of the gasifier can be evaluated in terms of a variety of measures extracted from the dry gas analyses, the measured and calculated stream rates and the properties of the chips. These measures can be classified as either efficiency related or throughput related indicators. Several different ratios or percentages serve as indicators of gasifier efficiency. These consist of the char yield, dry gas-to-dry feed ratio, air-to-dry feed ratio, mass conversion efficiency, cold gas efficiency and carbon conversion. Additional efficiency indicators can be obtained from the dry gas composition and heating value. The liquid-to-dry gas mass ratio is another efficiency indicator, useful for evaluation of the chip moisture content variation experiments.

Several indicators are based on the dry feed rate. The dry feed rate was evaluated from the average wet feed rate and the average chip moisture content for the run. No adjustments were made for the ash in either the chips or char since the ash content of the chips was generally less than 2% on a dry basis. The following define the various efficiency indicators.

(1) Char yield, the ratio of the average char rate for a run divided by the average dry feed rate of the chips, multiplied by 100.

(2) Gas-to-feed ratio, the ratio of the dry gas rate to the dry feed rate of the chips.

(3) Air-to-feed ratio, the ratio of the air input rate to the dry feed rate of the chips.

(4) Mass conversion efficiency, the mass ratio of the dry gas rate to the combined input rates of wet feed and air.

(5) Dry gas heating value, the summation of the products of the molar (volume) fraction compositions of each of the dry gas components and the standard heat of combustion for that component. It includes both the major and minor gas components. The volume basis is 42°C and 76cm Hg.

(6) Cold gas efficiency, the ratio of the energy content of the dry gas produced from a unit mass of dry feed to the energy content of a unit mass of dry feed, with both energy contents based on standard heats of combustion.

(7) Carbon conversion, the ratio of the mass of carbon in the dry gas produced from a unit mass of dry feed to the mass of carbon in a unit mass of dry feed.

(8) Liquid-to-gas ratio, the mass ratio of the aqueous condensate rate to the dry gas rate.

Additional indicators provide measures of the system throughput. These indicators are the dry feed rate and the cold gas energy output rate.

(9) Energy output rate, the product of the cold gas efficiency, the dry feed rate, and the gross heat of combustion of the dry feed (chips).

Statistical Analyses

Regression analyses were conducted to relate the various efficiency and throughput indicators to the operating parameters. The SAS (Statistical Analysis System) software package was used for this purpose.

RESULTS

A total of 20 runs were conducted; 7 for moisture content variation, 7 for grate rotation speed variation and 6 for gas fan rotation speed variation. Table 3 presents a summary of the operating parameters, the chip bulk density, the above grate temperature, the pressure drop, and the efficiency and throughput indicators for all of the experiments. The table is arranged according to the operating parameter investigated. Table 4 summarizes the average dry gas compositions for each run and is arranged in the same sequence as Table 3. Both the major and minor gas components are included in Table 4.

The results from the chip moisture content variation experiments are presented graphically in Figures 2-5. The lines or curves in each figure represent the results of the regression analyses. Figure 2 illustrates the relationships between the gas heating value (GHHV), gas-to-feed ratio (G/F), air-to-feed ratio (A/F) and cold gas efficiency (CGE), and the chip moisture content. Figure 3 shows the relationships for the char yield and mass conversion efficiency. Figure 4 illustrates the variations in the average concentrations of the major gas components as functions of the chip moisture content. Figure 5 presents the dependence of the throughput indicators, energy output rate and dry feed rate, on the chip moisture content.

The results for the grate rotation speed variation experiments are presented in Figures 6-9. The curves in each figure represent the results of the regression analyses. Figure 6 presents the dependence of the gas heating value, gas-to-feed ratio, air-to-feed ratio, and cold gas efficiency on the grate rotation speed. Figure 7 illustrates the dependencies of the char yield and mass conversion efficiency. Figure 8 shows the variations in the average concentrations of the major gas components as functions of chip moisture content. Figure 9 presents the relationships between the throughput indicators, energy output rate and dry feed rate, and grate rotation speed.

The results for the gas fan rotation speed variation are given in Figures 10-13. The lines in each figure represent the results of the regression analyses. Figure 10 presents the relationships between the gas heating value, gas-to-feed ratio, air-to-feed ratio and cold gas efficiency, and fan rotation speed. Figure 11 shows the relationships for the char yield and mass conversion efficiency. Figure 12 illustrates the variations in the average compositions of the major gas components and fan rotation speed. Figure 13 shows the dependence of the energy output rate and dry feed rate on gas fan rotation speed.

The significant regression models for each operating parameter and the model parameters and statistics are summarized in Table 5. The models in Table 5 describe the lines or curves presented in Figures 2-13.

DISCUSSION

In the chip moisture content variation runs, the wet feed rate was approximately constant and the chip bulk density increased slightly with increasing moisture content as shown in Table 3. Figure 2 illustrates that as the chip moisture content increases, each one of the efficiency indicators (gas heating value, gas-to-feed ratio, air-to-feed ratio, and cold gas efficiency) decrease linearly.

Figure 3 shows that as chip moisture content increases, the mass conversion efficiency decreases linearly. This indicates that some of the additional water, due to the increasing chip moisture content, is not being converted to dry gas. Estimates, based on equilibrium calculations for the water-gas shift reaction, reveal that about 50% of the moisture entering with chips is consumed for chip moisture contents of 15% and higher. The equilibrium calculations also permit prediction of the liquid-to-gas mass ratio. The predicted ratios compare favorably with the experimental liquid-to-gas ratios presented in Table 3 for chip moisture variation.

Figure 3 also indicates a minimum in the char yield at 12-15% moisture. However it should be noticed that the range of variation in the char yield is small. This small variation in char yield has a negligible effect on the gas-to-feed ratio since its effect is masked by much larger changes in the amount of gas resulting from the decline in the air input rate.

Figure 4 illustrates the variations in the compositions of the major components of the dry gas. The nitrogen concentration declines due to the decline in the air-to-feed ratio with increasing chip moisture. The concentrations of CO_2 and H_2 increase while that of CO decreases due to the action of the water-gas shift reaction. The concentration of methane is small and remains essentially constant.

Figure 5 presents the variations in the throughput indicators as functions of chip moisture content. Both the energy output rate and the dry feed rate show linear decreases.

As the chip moisture content increases, the below grate temperature remains relatively constant as shown in Table 3.

On the other hand, the temperature in the vicinity of the upper tuyeres decreases as chip moisture content increases, indicating that the active zone of the gasifier drops deeper into the bed. The bed pressure drop remains relatively constant as chip moisture content increases.

The principal effects of increasing chip moisture content in the gasifier under investigation are:

(1) to reduce gasifier throughput in terms of the dry feed rate,

(2) to reduce the cold gas efficiency as a consequence of the higher concentration of CO_2 and lower concentration of CO in the dry gas,

(3) to reduce the energy output rate as a consequence of (1) and (2), and,

(4) to reduce the mass conversion efficiency as a consequence of incomplete water utilization.

In the grate rotation speed variation runs, the chip bulk densities and moisture contents were relatively constant as shown in Table 3. Figure 6 illustrates that as the grate rotation speed increases from zero, sharp changes take place in the gas heating value, gas-to-feed ratio, and air-to-feed ratio up to a grate rotation speed of about 4 rph. The variations are best described by logarithmic functions. The cold gas efficiency passes through a maximum at about 4 rph and then gradually declines. The maximum cold gas efficiency is about 70%.

Figure 7 shows that the variation of the mass conversion efficiency is similar to that for the cold gas efficiency. The maximum mass conversion efficiency is about 92% at a grate rotation speed of 4 rph. The figure also presents the variation in char yield with increasing grate rotation speed. The char yield rises rapidly over the range of 0-4 rph. The relationship between char yield and grate rotation speed is best described by a second order polynomial.

Figure 8 presents the variations in the compositions of the major dry gas components as functions of the grate rotation speed. The concentration of nitrogen is initially high due to the high air-to-feed ratio. It drops sharply as the grate rotation speed increases and then passes through a minimum at about 4 rph. The concentrations of CO and H_2 pass through maxima in the same range of grate rotation speed. The changes in the gas composition are directly reflected in the variation of the heating value of the dry gas.

Figure 9 illustrates the relationships between the throughput indicators and the grate rotation speed. The energy output rate increases in a nonlinear fashion and is best described by a second order model. The dry feed rate behaves in a similar fashion.

As the grate rotation speed increases, the below grate temperature decreases as shown in Table 3. The temperature in the vicinity of the upper tuyeres decreases as the grate rotation speed increases, indicating that the active zone of the gasifier drops deeper into the bed. Inspection of the pressure drop data in Table 3 shows that the agitation produced by the rotating grate serves to reduce the bed pressure drop as the grate rotation speed increases even though the flow rate through the gasifier increases.

The principal findings from the grate rotation speed variation experiments with the gasifier under investigation are:

(1) maximum efficiencies are obtained at a grate rotation speed of about 4 rph, and,

(2) increasing throughputs can be obtained at the expense of gradually diminishing gasifier efficiencies beyond a grate rotation speed of 4 rph.

In the gas fan rotation speed variation runs, the chip bulk densities and moisture contents were relatively constant as indicated in Table 3. Figure 10 shows that as the fan rotation speed increases that gradual linear increases take place in the gas-to-feed ratio and air-to-feed ratio, a gradual linear decrease takes place in the gas heating value, and the cold gas efficiency remains essentially constant.

Figure 11 indicates that as the fan rotation speed increases the mass conversion efficiency remains essentially constant at 71-72%. The char yield shows a slight linear decrease. The char yield points designated by hexagons in Figure 11 represent experiments in which the char was burning. These points have been excluded from the regression model. The char yield variation has an insignificant effect on the gas-to-feed ratio since it is masked by large changes in the dry gas rate resulting from the increase in the air input rate.

Figure 12 presents the variations in the compositions of the major gas components as functions of the fan rotation speed. The concentration of nitrogen shows a slight increase due to the increase in the air-to-feed ratio. The concentrations of hydrogen and methane are relatively constant. A slight increase in the CO_2 concentration is indicated in the figure with a corresponding decrease in the CO concentration. Overall, only minor concentration changes take place.

Figure 13 presents the variations in the throughput indicators as functions of the fan rotation speed. Both the energy output rate and dry feed rate increase linearly with increasing fan rotation speed.

The air input rate is directly proportional to the fan rotation speed. The amount of air drawn by a given fan is a function of the fan characteristics (the suction it produces). Consequently the results of our fan rotation speed variation experiments are only of qualitative value. Although the linear trends that we have found can be expected with other fans, the slopes and/or intercepts of the linear models will change.

As the fan rotation speed increases, the above grate temperature increases as shown in Table 3. The temperature in the vicinity of the tuyeres also increases. The pressure drop data in Table 3 show that as the fan rotation speed increases, the bed pressure drop increases linearly as expected.

The principal effects of increasing the fan rotation speed in the gasifier under investigation are:

(1) to increase the gasifier throughput in terms of the energy output rate and dry feed rate, and,

(2) to increase throughput without appreciably altering the efficiencies or gas composition.

The results of the present work have established the effects of three operating variables, chip moisture content, grate rotation speed and gas fan rotation speed, on the efficiency and throughput indicators for the particular gasifier under investigation. The relationships that have been obtained can be used as guidelines for adjusting the operating conditions for optimum gasifier efficiency or for maximizing the gasifier throughput. Low moisture content favors both high efficiency and high throughput; however, the costs associated with chip drying also need to be considered. Moderate grate rotation speed (3-5 rph) favors high efficiency, while further increase in the grate rotation speed reduces efficiency. Consequently a trade-off is necessary between efficiency and throughput. Since the gas fan rotation speed does not influence efficiency, the maximum possible fan speed should be used to obtain maximum throughput.

CONCLUSION

This study has examined the influence of three operating parameters on the performance of a downdraft gasifier with cottonwood chips as the feedstock. An increase in the chip moisture content was found to decrease both the gasifier efficiency and throughput. Increasing the grate rotation speed was found to increase the throughput; however, the gasifier efficiency passed through a maximum at moderate grate rotation speeds. Increasing gas fan rotation speed was found to increase the gasifier throughput without altering the gasifier efficiency.

Although this chapter presents a starting work towards the systematic evaluation of operating parameters influencing gasifier performance, the effects of other parameters remain to be determined. Some of these parameters include the wood species and the chip voidage. These variables will be investigated in the next chapter.

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Table 1. Chip Chemical Properties.

	CHIP MOISTURE CONTENT VARIATION		GRATE ROTATION SPEED VARIATION		GAS FAN ROTATION SPEED VARIATION	
Elemental Analysis	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
C	48.56	1.02	48.47	0.27	49.44	0.22
H	5.78	0.17	5.96	0.10	6.00	0.07
N	0.30	0.24	0.08	0.11	0.04	0.10
O	44.26	0.10	44.19	0.10	42.71	0.10
Ash	1.10	0.25	1.50	0.44	1.81	0.34
Heat of Combustion (kJ/gm)	19.7	0.3	19.9	0.2	20.0	0
Wet Moisture Content (%)	-	-	7.40	0.80	13.37	0.85
Lignin Percent	25.29		25.95		29.64	
Cellulose Percent	45.80		48.66		44.04	
Hemi-Cellulose Percent	20.51		14.61		15.72	

Table 2. Chip Physical Properties.

	CHIP MOISTURE CONTENT VARIATION		GRATE ROTATION SPEED VARIATION		GAS FAN ROTATION SPEED VARIATION	
	Screen Opening (cm)	Weight Percent (%)	Screen Opening (cm)	Weight Percent (%)	Screen Opening (cm)	Weight Percent (%)
	>2.54	3.45	>2.54	10.22	>2.54	9.23
	1.27-2.54	48.28	1.27-2.54	60.58	1.27-2.54	58.97
	0.97-1.27	15.86	0.97-1.27	10.95	0.97-1.27	11.28
	0.33-0.97	26.20	0.33-0.97	15.33	0.33-0.97	17.44
	< 0.33	6.15	< 0.33	2.92	< 0.33	3.08
Average Thickness (cm)	0.71		0.58		0.56	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Bulk Density of Chips (kg/m^3)	139	4.65	148	9.29	138	2.56
Voidage Percent (%)	48.87		45.11		48.32	

Table 3. Summary of Operating Parameters and Performance Measures.

Run No.	Moisture of Chips (wet basis)	Grate Rotation (rph)	Fan Speed (rpm)	Bulk Density (wet basis)	Temperature above Grate (°C)	Pressure Drop (cm. H_2O)
CHIP MOISTURE CONTENT VARIATION						
101	5.4	5.00	1794	133	749	3.0
102	7.2	5.00	1794	134	760	2.3
103	9.4	5.00	1794	139	760	3.0
104	10.6	5.00	1794	139	760	1.8
105	15.7	5.00	1794	139	760	2.0
106	19.4	5.00	1794	145	771	2.0
107	22.4	5.00	1794	144	754	2.3
GRATE ROTATION SPEED VARIATION						
201	8.0	0.00	1794	159	760	6.6
202	6.0	2.76	1794	140	749	3.8
203	7.0	3.37	1794	141	749	3.3
204	8.2	4.08	1794	157	749	2.8
205	7.2	5.00	1794	134	760	2.3
206	8.2	13.33	1794	150	716	2.0
207	7.2	20.69	1794	151	688	1.5
GAS FAN ROTATION SPEED VARIATION						
301	13.00	4.08	1389	138	721	1.3
302	13.00	4.08	1636	134	732	2.5
303	14.00	4.08	1793	140	727	3.3
304	12.00	4.08	1987	138	743	4.3
305	14.20	4.08	2373	137	743	5.6
306	14.00	4.08	2561	141	760	6.3

Table 3. (continued).

Run No.	Wet Feed Rate (kg/hr)	Dry Feed Rate (kg/hr)	Char Yield (%)	Gas-to-Feed Ratio (G/F)	Air-to-Feed Ratio (A/F)	Condensate-to-Gas Ratio
CHIP MOISTURE CONTENT VARIATION						
101	79.9	75.6	5.44	2.50	1.67	0.070
102	77.2	71.6	5.53	2.45	1.59	0.060
103	78.4	71.0	5.40	2.43	1.61	0.065
104	83.8	74.9	4.87	2.54	1.70	0.098
105	77.8	65.4	4.87	2.47	1.60	0.033
106	80.1	64.6	4.98	2.48	1.59	0.093
107	78.3	60.8	5.71	2.45	1.58	0.094
GRATE ROTATION SPEED VARIATION						
201	28.4	26.1	1.49	4.69	4.37	0.056
202	59.8	56.2	4.22	2.81	2.03	0.056
203	68.8	64.0	4.21	2.65	1.83	0.071
204	75.6	69.4	5.19	2.64	1.84	0.058
205	77.2	71.6	5.53	2.45	1.59	0.060
208	99.5	91.4	11.71	2.35	1.63	0.083
207	135.8	126.0	14.15	2.25	1.56	0.020
GAS FAN ROTATION SPEED VARIATION						
301	61.2	53.3	4.16	2.44	1.50	0.076
302	69.1	60.1	3.52	2.51	1.58	0.066
303	74.2	63.8	3.29	2.54	1.56	0.082
304	81.4	71.6	2.53	2.52	1.56	0.044
305	97.0	83.2	2.84	2.58	1.62	0.071
306	104.1	89.5	3.70	2.57	1.62	0.082

Table 3. (continued).

Run No.	Mass Conversion Efficiency	Gas Heating Value (MJ/m^3)	Cold Gas Efficiency (CGE)	Carbon Conversion	Energy Output Rate (MJ/hr)
CHIP MOISTURE CONTENT VARIATION					
101	0.92	5.92	0.69	0.91	1030
102	0.92	6.04	0.70	0.92	980
103	0.90	5.88	0.67	0.92	936
104	0.90	5.81	0.70	0.93	1028
105	0.89	5.88	0.69	0.93	888
106	0.88	5.85	0.69	0.93	876
107	0.85	5.81	0.67	0.92	803
GRATE ROTATION SPEED VARIATION					
201	0.86	3.13	0.66	0.98	342
202	0.91	5.37	0.70	0.95	782
203	0.91	5.66	0.69	0.94	884
204	0.90	5.55	0.68	0.92	942
205	0.92	6.04	0.70	0.92	980
206	0.86	5.70	0.61	0.80	1117
207	0.85	5.70	0.58	0.79	1460
GAS FAN ROTATION SPEED VARIATION					
301	0.92	6.15	0.71	0.94	757
302	0.92	6.11	0.72	0.95	870
303	0.93	6.04	0.73	0.96	926
304	0.94	6.11	0.73	0.97	1037
305	0.93	5.89	0.72	0.97	1190
306	0.92	5.89	0.71	0.95	1275

Table 4. Dry Gas Compositions.

Run No.	Average Mole Percent of Gas Composition						
	N_2	CO	H_2	CO_2	CH_4	C_2H_4	C_2H_6
				CHIP MOISTURE CONTENT VARIATION			
101	47.5	23.3	14.3	11.7	2.3	0.6	0.1
102	45.6	22.7	16.1	12.6	2.2	0.6	0.1
103	46.8	21.3	15.8	12.9	2.2	0.7	0.1
104	46.9	22.0	16.1	12.1	2.0	0.6	0.1
105	45.2	21.0	17.3	13.6	2.1	0.6	0.1
106	44.6	19.8	17.9	14.7	2.1	0.7	0.1
107	45.4	19.0	17.7	14.9	2.2	0.6	0.1
				GRATE ROTATION SPEED VARIATION			
201	68.1	13.5	9.6	8.0	0.7	0.1	0.0
202	51.0	20.9	14.7	11.0	1.8	0.5	0.1
203	48.7	21.4	15.2	11.9	2.0	0.6	0.1
204	49.0	20.2	16.2	12.1	1.8	0.6	0.1
205	45.6	22.7	16.1	12.6	2.2	0.6	0.1
206	49.3	17.7	15.5	13.8	2.5	0.8	0.2
207	49.9	16.3	14.6	14.9	2.8	0.9	0.3
				GAS FAN ROTATION SPEED VARIATION			
301	42.1	23.5	18.9	13.2	1.7	0.5	0.1
302	43.2	23.1	18.3	12.9	1.8	0.5	0.1
303	42.4	22.3	19.2	13.8	1.6	0.5	0.1
304	42.7	22.8	18.3	13.6	1.8	0.6	0.1
305	43.4	21.6	18.8	14.0	1.5	0.5	0.1
306	43.5	21.4	18.7	14.1	1.6	0.6	0.1

Table 5. Regression Models.

	<u>CHIP MOISTURE CONTENT VARIATION</u>		
Dependent Variables	Regression Models (X is the chip moisture content in percent)	R^2	PR>F
Dry Feed Rate	$= 79.68-0.819(X)$	0.8735	0.0020
Char Yield	$= 6.90-0.285(X)+0.01(X)^2$	0.6773	0.1041
G/F	$= 2.49-0.0008(X)$	0.0209	0.7570
A/F	$= 1.67-0.0041(X)$	0.3316	0.1761
Mass Conversion Efficiency	$= 0.94-0.00335(X)$	0.8950	0.0043
CGE	$= 0.70-0.000726(X)$	0.1332	0.4769
GHHV	$= 6.00-0.009(X)$	0.4397	0.1511
Energy Output Rate	$= 1084-11.74(X)$	0.7722	0.0212
N_2	$= 47.63-0.125(X)$	0.5742	0.0485
CO	$= 24.28-0.232(X)$	0.9391	0.0003
H_2	$= 14.15+0.179(X)$	0.8421	0.0036
CO_2	$= 10.85+0.183(X)$	0.9093	0.0009
CH_4	$= 2.21-0.00503(X)$	0.1101	0.4673

Table 5. (continued).

Dependent Variables		GRATE ROTATION SPEED VARIATION Regression Models (Y is the grate rotation speed in rph)	R^2	PR>F
Dry Feed Rate	=	$36.87+8.750(Y)-0.129(Y)^2$	0.9297	0.0049
Char Yield	=	$1.35+0.996(Y)-0.018(Y)^2$	0.9969	0.0001
G/F	=	$2.79-0.138\ \ln(Y)$	0.9872	0.0001
A/F	=	$2.05-0.168\ \ln(Y)$	0.9895	0.0001
Mass Conversion Efficiency	=	$0.93-0.00677(Y)+0.000136(Y)^2$ $-0.0741\ \exp(-Y)$	0.9298	0.0309
CGE	=	$0.73-0.011(Y)+0.000176(Y)^2-0.075\ \exp(-Y)$	0.9761	0.0062
GHHV	=	$5.40+0.163\ \ln(Y)$	0.9631	0.0005
Energy Output Rate	=	$510+92.03(Y)-2.39(Y)^2$	0.8620	0.0190
N_2	=	$48.68-0.193(Y)+0.013(Y)^2+19.52\ \exp(-Y)$	0.9696	0.0089
CO	=	$23.06-0.425(Y)+0.00449(Y)^2-9.63\ \exp(-Y)$	0.9301	0.0307
H_2	=	$15.15+0.178(Y)-0.0101(Y)^2-5.618\ \exp(-Y)$	0.9715	0.0081
CO_2	=	$10.80+0.318(Y)-0.00586(Y)^2-2.853\ \exp(-Y)$	0.9860	0.0028
CH_4	=	$1.71+0.0691(Y)-0.000782(Y)^2-0.979\ \exp(-Y)$	0.9683	0.0095

Table 5. (continued).

Dependent Variables		GAS FAN ROTATION SPEED VARIATION Regression Models (Z is the gas fan rotation speed in rpm)	R^2	PR>F
Dry Feed Rate	=	9.02+0.03(Z)	0.9967	0.0016
Char Yield*	=	4.03-0.000197(Z)	0.0727	0.7303
G/F	=	2.33+0.000101(Z)	0.8009	0.0160
A/F	=	1.40+0.0000897(Z)	0.7867	0.0184
Mass Conversion Efficiency	=	0.926	-	-
CGE	=	0.720	-	-
GHHV	=	6.50-0.00023(Z)	0.8406	0.0101
Energy Output Rate	=	144+0.44(Z)	0.9982	0.0001
N_2	=	40.957+0.000996(Z)	0.6151	0.0648
CO	=	25.871-0.00176(Z)	0.8763	0.0060
H_2	=	18.74-0.0000272(Z)	0.0012	0.9487
CO_2	=	11.84+0.000886(Z)	0.7199	0.0327
CH_4	=	1.97-0.000161(Z)	0.4162	0.1665

* Excluding the two runs with burning char.

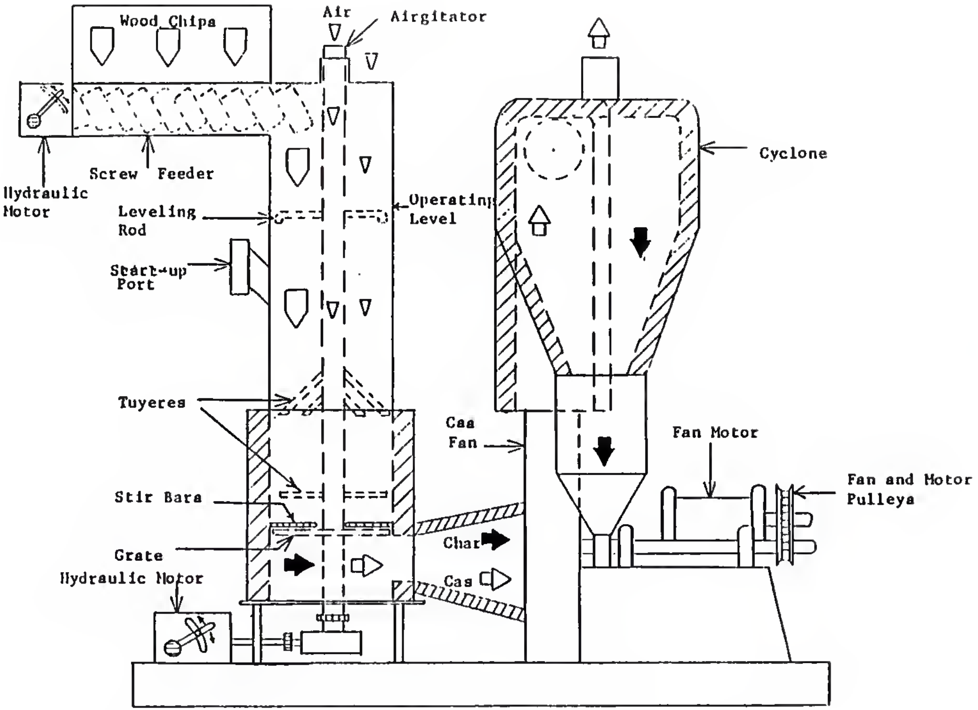

Figure 1. Commercial Gasifier.

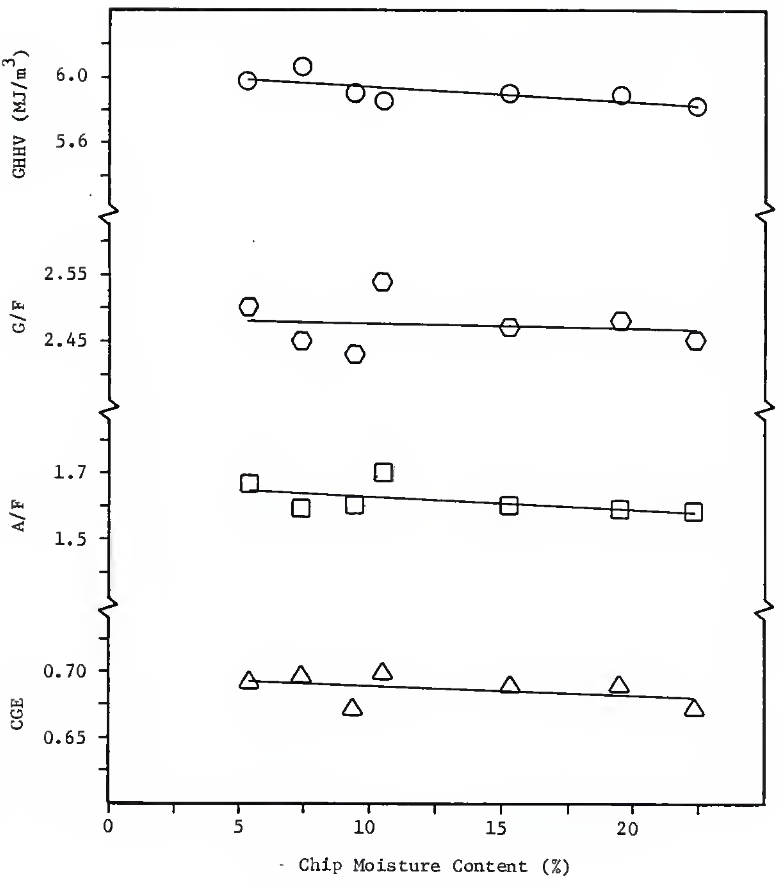

Figure 2. Relationships Between Gas Heating Value (GHHV), Gas-to-Feed Ratio (G/F), Air-to-Feed Ratio (A/F), and Cold Gas Efficiency (CGE), and Chip Moisture Content.

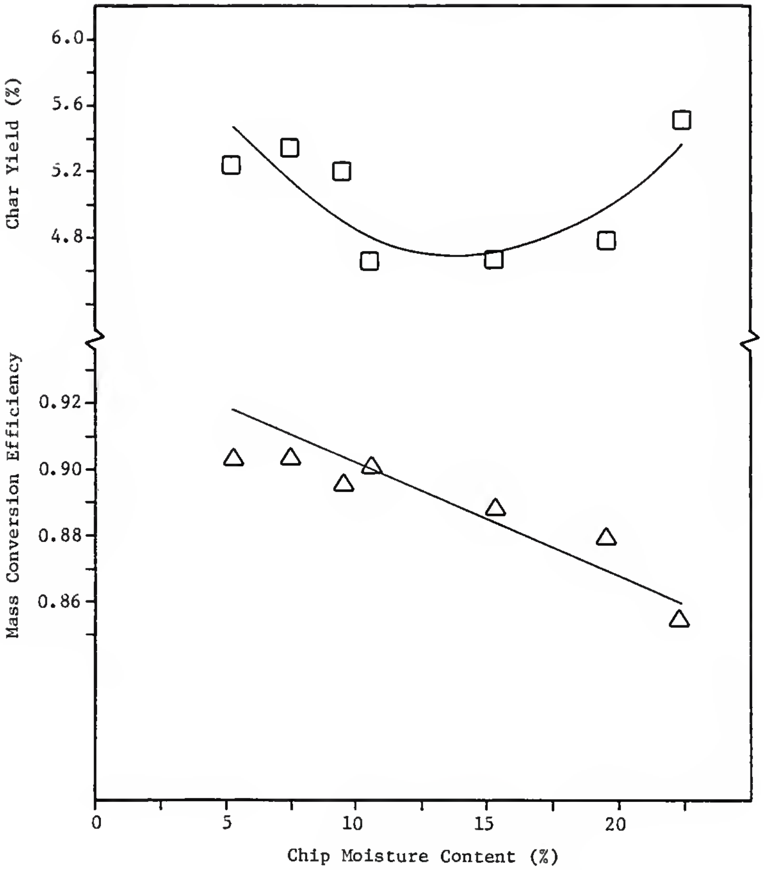

Figure 3. Relationships Between Char Yield and Mass Conversion Efficiency, and Chip Moisture Content.

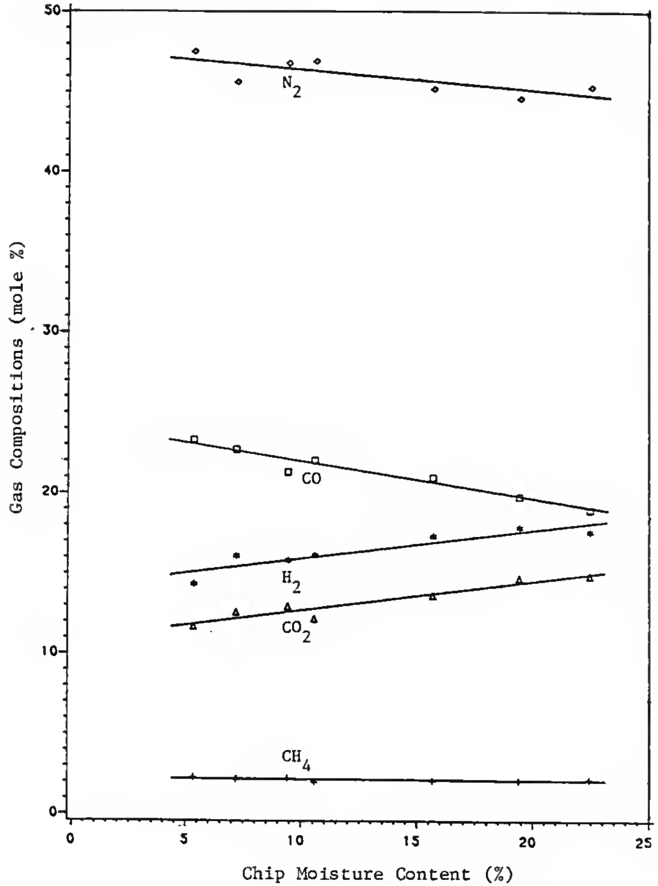

Figure 4. Gas Composition versus Chip Moisture Content.

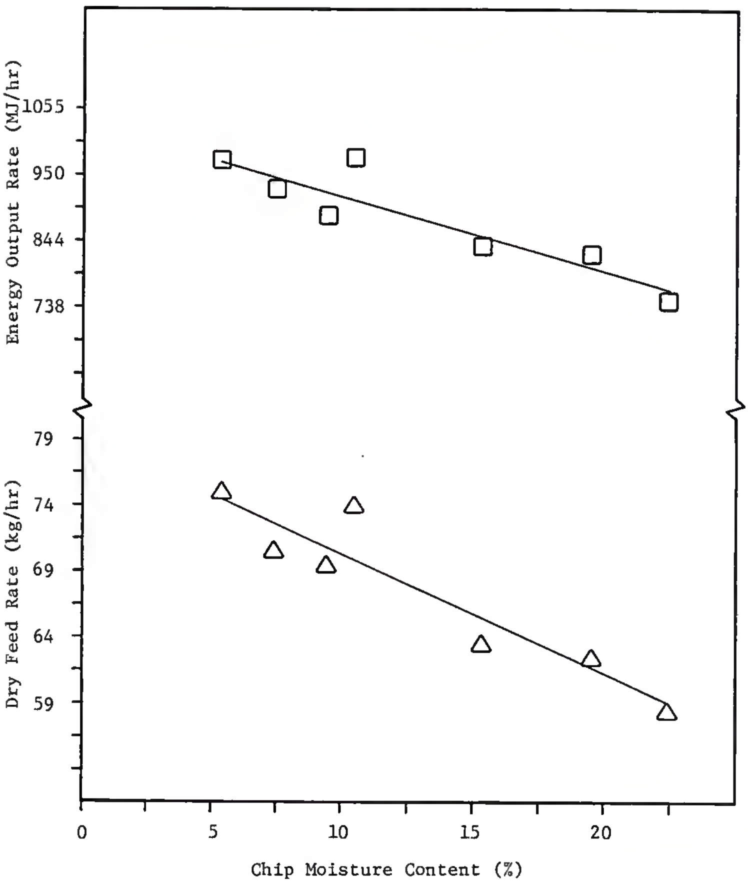

Figure 5. Relationships Between Energy Output Rate and Dry Feed Rate, and Chip Moisture Content.

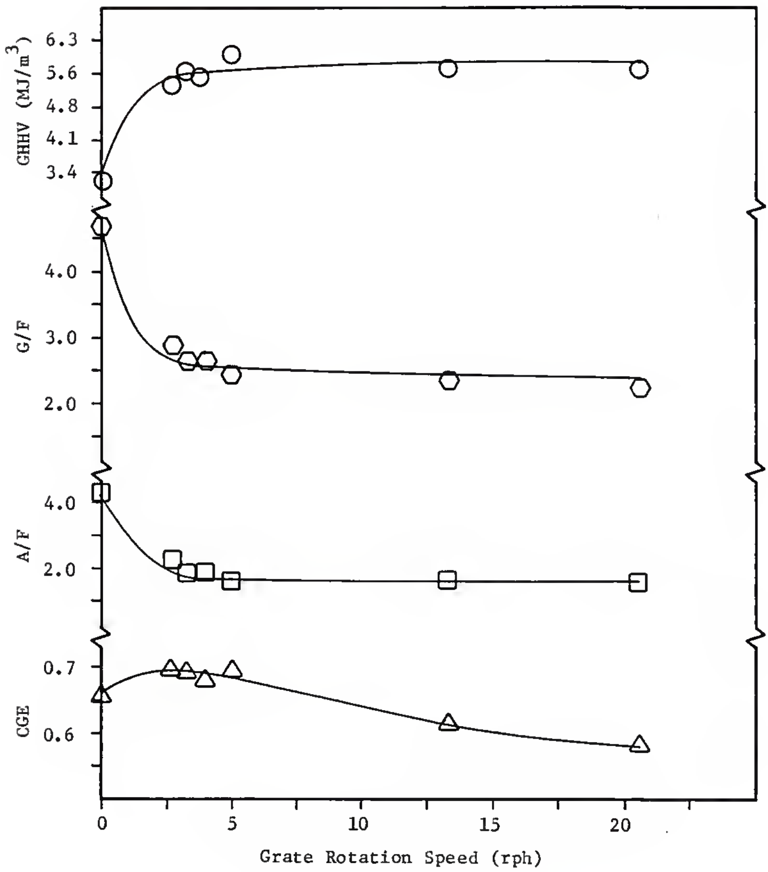

Figure 6. Relationships Between Gas Heating Value (GHHV), GAs-to-Feed Ratio (G/F), Air-to-Feed Ratio (A/F), and Cold Gas Efficiency (CGE), and Grate Rotation Speed.

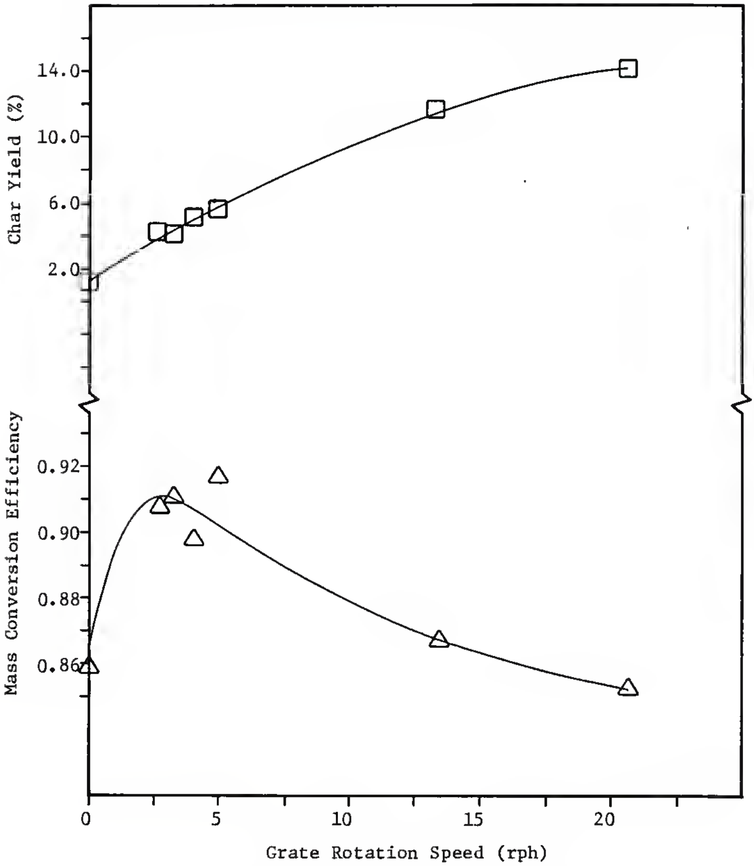

Figure 7. Relationships Between Char Yield and Mass Conversion Efficiency, and Grate Rotation Speed.

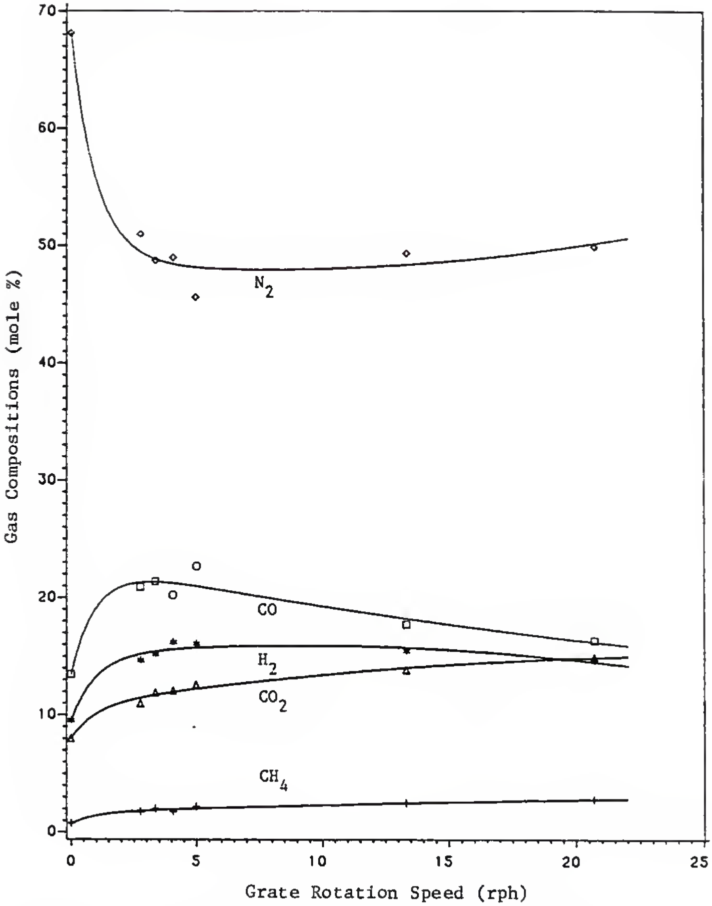

Figure 8. Gas Composition versus Grate Rotation Speed.

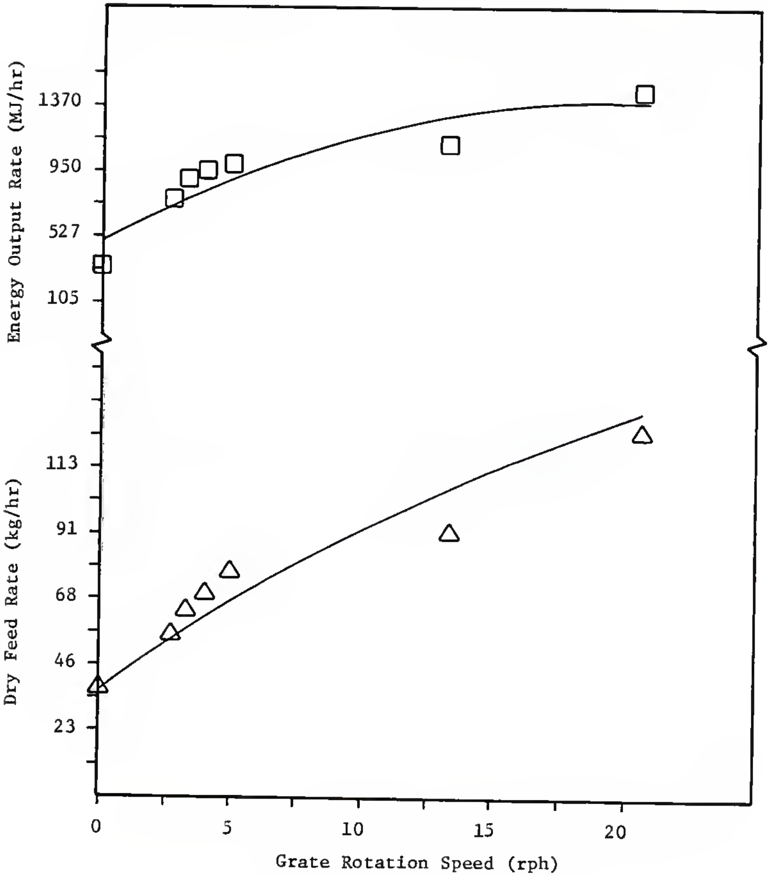

Figure 9. Relationships Between Energy Output Rate and Dry Feed Rate, and Grate Rotation Speed.

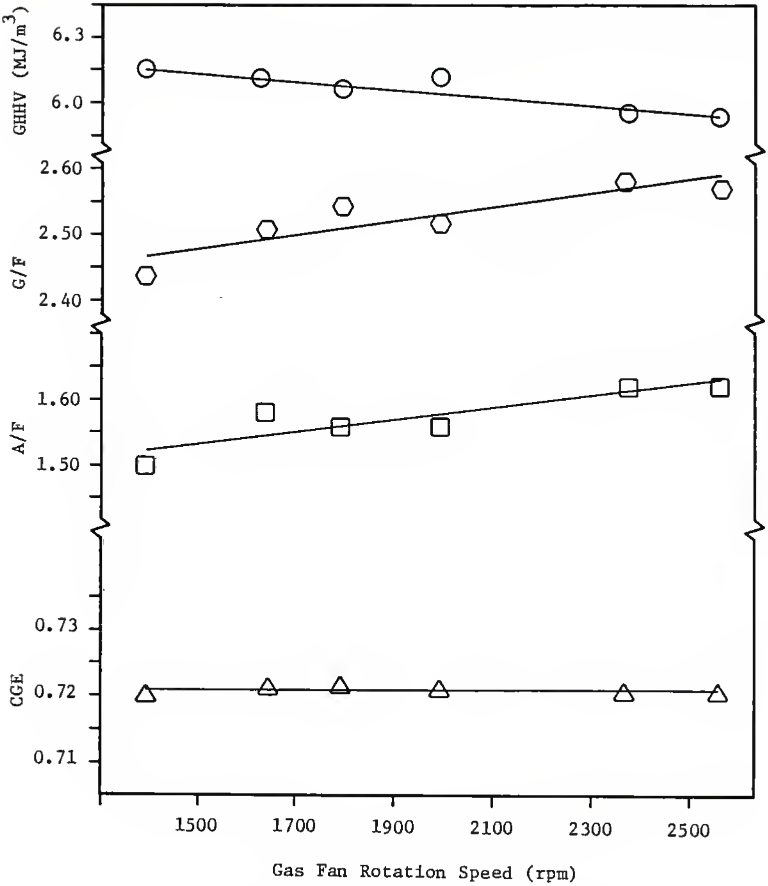

Figure 10. Relationships Between Gas Heating Value (GHHV), Gas-to-Feed Ratio (G/F), Air-to-Feed Ratio (A/F), and Cold Gas Efficiency (CGE), and Gas Fan Rotation Speed.

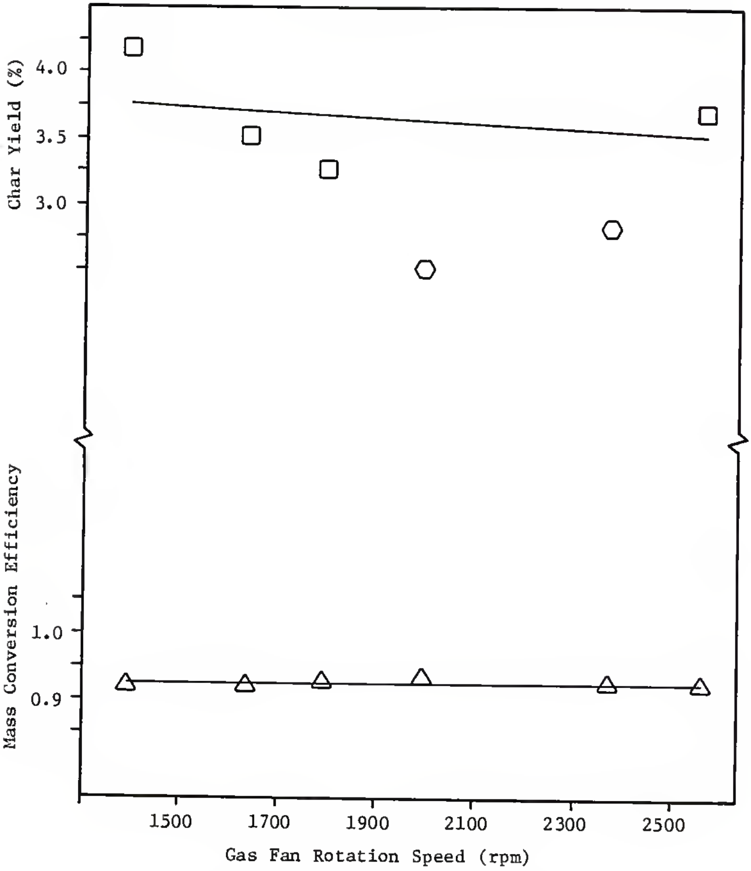

Figure 11. Relationships Between Char Yield and Mass Conversion Efficiency, and Gas Fan Rotation Speed.

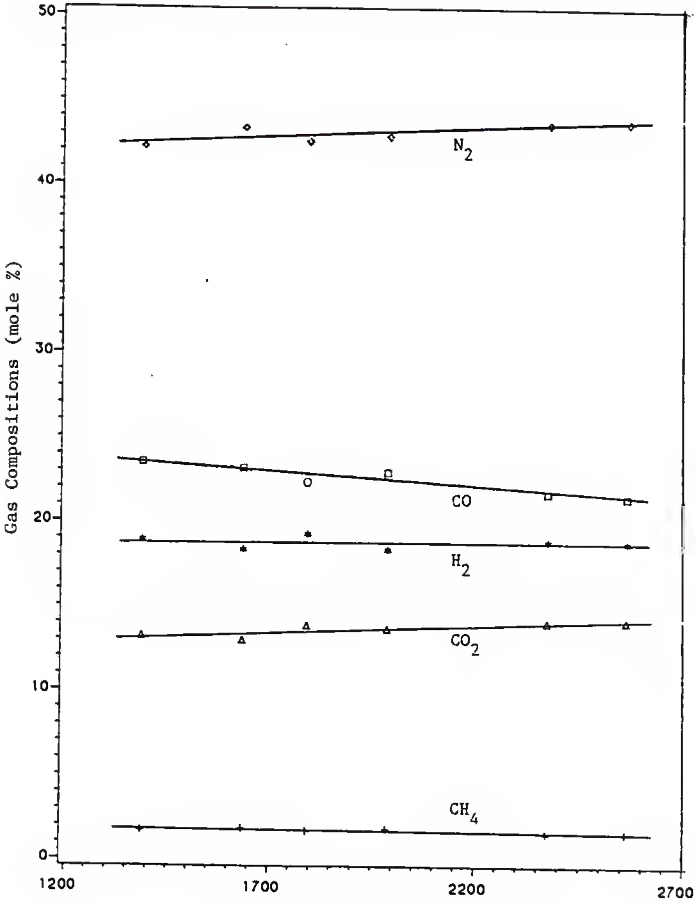

Figure 12. Gas Composition versus Gas Fan Rotation Speed.

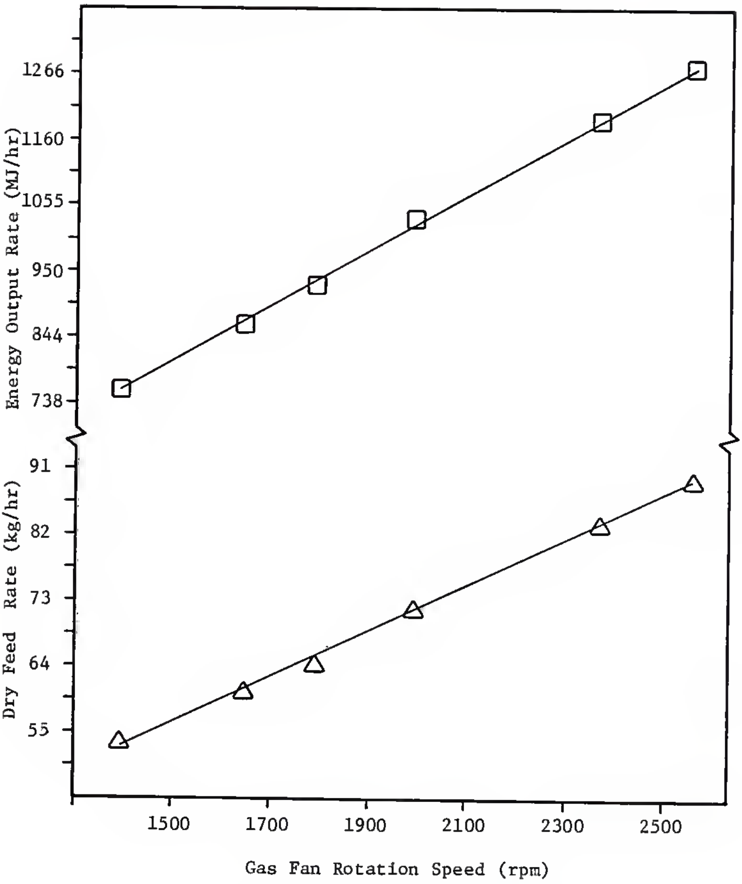

Figure 13. Relationships Between Energy Output Rate and Dry Feed Rate, and Gas Fan Rotation Speed.

CHAPTER 5

INFLUENCE OF CHIP PHYSICAL PROPERTIES ON DOWNDRAFT GASIFIER PERFORMANCE

The preceding chapter discusses the influence of three operating parameters (chip moisture content, grate rotation speed, and gas fan rotation speed) on the performance of a commercial downdraft gasifier. This chapter explores the influence of some of the wood chip physical properties on the performance of the same downdraft gasifier. The physical properties investigated are the chip voidage and the chip bulk density.

Only a few researchers have conducted investigations of the effect of the type of material on downdraft gasifier performance. The work of Walawender et al. (1987) on wood chips and wood pellets illustrated that the form of the feed material had a significant influence on gasifier performance. They found that wood pellets produced more char and less gas than chips. Graham and Huffman (1981) observed that more gas and less char was produced from large chips than from small chips. Their finding suggests that chip voidage may be important while the work of Walawender et al. (1987) indicates that the bulk density may be important.

Voidage cannot be neglected as a feedstock property since the air input to the system would be expected to depend on it. High voidage allows more air input to the gasifier resulting in a faster processing rate. In contrast, low voidage tends to reduce the air input and thus lowers the overall processing rate.

Palmer et al. (1982) have indicated that most gasifier designs contain a slowly moving bed of charcoal through which gases and vapors must flow, and that the performance is highly dependent on the porosity of the bed. However, since it is impractical to measure the bed porosity of the wood char which is located above the gasifier grate, the chip voidage is employed in this work instead.

There are three ways to describe chip density: bulk density, apparent particle density, and skeletal density. They differ from each other in terms of the volume bases. The bulk density includes the actual volume of the solid, the pore volume of the particles, and the void volume among the solid particles. The apparent particle density includes the actual solid volume and pore volume, whereas the skeletal density (true density) considers only the actual solid volume. Due to the convenience of determining the chip bulk density, it is chosen as the measure of the chip density in this study. However, both the apparent particle density and skeletal density are related to the bulk density through the definitions of pore volume (within a solid particle) and void volume (between solid particles).

Since the chip bulk density depends largely on its physical properties which, in turn, is largely determined by the structure that makes up the wood, it is logical to investigate the influence of chip bulk density on the gasifier performance. Graboski and Bain (1980) reported that most hardwoods have higher bulk density than softwoods. They found that the bulk density varied with chip moisture content. To avoid this variation, the chips were maintained at a constant moisture content in the present work.

The objective of this work was to investigate the influence of two chip physical properties, chip voidage and chip bulk density, on the performance of a downdraft gasifier. In the chip voidage variation experiments, the same gasifier operating parameters were used throughout the experiments. In studying the effect of chip bulk density, chips with different bulk densities were gasified over a range of gas fan rotation speed (2 sources of chips) and over a range of grate rotation speed (2 sources of chips). This allowed comparison of the influence of bulk density over ranges of these gasifier operating parameters.

EXPERIMENTAL FACILITIES AND PROCEDURE

Gasifier Description

The gasifier is the same as the gasifier used in studying the influence of the operating parameters presented in Chapter 4. The schematic diagram of the gasifier is shown in Chapter 4 (Figure 1).

Operating Procedure

The complete procedures involving start-up, gas analysis and condensables measurements, feed and char determinations, and shut-down were as outlined in Chapter 4.

Measurements

All measurements were made during steady state operation when temperature readings remained constant. The measurement procedures have been detailed in Chapter 4.

In determining the chip bulk density, chips were filled to the level of a tared box with a known volume. The chip bulk density (wet basis) was calculated from the chip net weight and the box volume. The same box was used for this determination in each experimental run.

The void space among the chips (chip voidage) in the box described above was determined by fine sand with a predetermined packed density. Continuous tapping was necessary in aiding the sand to completely occupy the void volume. The mass of sand in the box was used to calculate the chip voidage.

CHIP PROPERTIES

Chip Voidage Variation

An adequate supply of oak chips was dried to a moisture content range of 12 to 14% (wet basis). These chips consisted of a 50-50 volume percent mixture of white and red oak with unknown age and tree diameter. Six runs were conducted with voidage ranging between 0.33 and 0.56. The raw chips with voidage of 0.48 were separated by screening into coarse and fine cuts. The highest chip voidage, 0.56, comprised chips with no fines. By mixing fines with the original batch of chips in a volume ratio of 1:5, a chip voidage of 0.43 was obtained. A chip voidage of 0.40 was prepared by adding the fines and the original chips in a 2:5 volume proportion, whereas the 0.37 voidage was obtained by using a volume ratio of 3:5 (fines to original chips). The lowest chip voidage, 0.33, consisted only of the fine cut. Even though a wide range of chip voidage was prepared, the blends exhibited a small range of bulk density variation, ±8.0 kg/m^3 from the mean.

In conducting the chip voidage variation runs, the gasifier operating parameters were held constant. The grate rotation speed was maintained at 4.08 rph and the gas fan rotation speed was held at 1388 rpm throughout the course of the experiments. The chip moisture content was maintained between 12 and 14% (wet basis).

Chip Bulk Density Variation

Two different tree species were used as feedstocks in attempt to determine the influence of chip bulk density on downdraft gasifier performance. They were cottonwood and black locust. Even though two tree species were available for the present study, there were actually four sources of chips investigated since three different sources of cottonwood chips were employed. To systematically evaluate the influence of chip bulk density, two distinct sets of experiments were conducted as discussed in the proceeding sections.

(A) Gas Fan Rotation Speed Variation. The chips employed were obtained from black locust and cottonwood trees. The black locust chips were obtained from 5 year old trees with trunk diameters of about 15 cm. Bark and small branches were included in the chips. Cottonwood chips were gathered from dead fall cottonwood limbs with some bark and branches. These cottonwood chips were also used to study the gas fan rotation speed variation in Chapter 4. The black locust chips had a higher wet bulk density (190 kg/m^3) than the cottonwood chips (140 kg/m^3). The gas fan speed was varied from 1400 to 2600 rpm for the cottonwood chips while the gas fan speed was varied from 1400 to 2400 rpm with the black locust chips. Other operating parameters were kept constant (chip moisture content at about 13% and grate rotation speed at 4.08 rph). Both chips had similar voidage (0.48) and showed slight fluctuations in their bulk densities (± 6.8 kg/m^3 for the black locust and ± 2.6 kg/m^3 for the cottonwood).

(B) Grate Rotation Speed Variation. The same tree species, cottonwood, was used for this variation. However, the sources varied for the chips employed. One source, with a higher wet bulk density (185 kg/m^3), was obtained from the trunk of a 40-50 year old dead tree with a base diameter of 0.9m. No bark or branches were included. The other source, which was used to evaluate the grate rotation speed variation in Chapter 4, was obtained from the major limbs of the same cottonwood tree. These chips had a lower wet bulk density (140 kg/m^3). The voidage was approximately the same for both sources of chips. The range of the grate rotation speed was wider for the low bulk density cottonwood (2 to 14 rph) than for the high bulk density cottonwood (2 to 8 rph). Other operating parameters were held constant (chip moisture content at 7.5% and gas fan rotation speed at 1794 rpm). Both chip sources showed nearly constant bulk densities throughout the experiments ($\pm$6.0 kg/m^3 for the high bulk density cottonwood and $\pm$9.3 kg/m^3 for the low bulk density cottonwood).

Chemical and Physical Analyses

The chemical and physical properties determined are identical to those described in Chapter 4. Tables 1 and 2 summarize the chemical properties and physical properties for each chip source. Additional information included in the tables are the chip size distribution and average chip thickness.

TREATMENT OF DATA

Calculations

Similar to Chapter 4, the system performance measures can be classified as either efficiency related or throughput related indicators. The efficiency related indicators measure the efficiency of the gasifier. These include the char yield, dry gas-to-dry feed ratio (G/F), air-to-dry feed ratio (A/F), mass conversion efficiency (MCE), cold gas efficiency (CGE), dry gas heating value (GHHV), and the dry gas composition. The throughput indicators consist of the dry feed rate and the energy output rate. The definitions of the various indicators were presented in Chapter 4.

Statistical Analyses

The Statistical Analysis System software package was employed to fit regression models relating the performance indicators to the chip properties and operating parameters. Significant difference tests of the regression models were compared as outlined by Neter and Wasserman (1974) for the results of the bulk density variation experiments. The validity of the statistical comparisons were based on two important criteria. The regression models under evaluation should be of the same form or same order (same number of parameters) and the data sets should have the same variance.

RESULTS

Chip Voidage Variation

A total of six runs were conducted with oak chips over a voidage range of 0.33 to 0.56. Table 3 summarizes the chip properties, operating parameters, and performance measures. Table 4 shows the major gas compositions for each run. Figures 1-4 present comparisons of the various performance measures and the regression models. Figures 1 through 3 illustrate the relationships between the efficiency indicators (cold gas efficiency, gas-to-feed ratio, air-to-feed ratio, gas heating value, mass conversion efficiency, char yield, and major gas compositions) and chip voidage. Figure 4 shows the relationships between the throughput indicators (the dry feed rate and the energy output rate) and chip voidage. The regression models are summarized in Table 5 along with the correlation coefficients and the significance test probabilities.

Chip Bulk Density Variation

(A) Gas fan rotation speed variation. A total of ten runs were conducted; four runs with black locust chips and six runs with cottonwood chips. The chip properties, operating parameters, performance measures, and major gas compositions are given in Tables 3 and 4. Figures 5-11 show the comparisons of the various performance measures and the regression models for the two chip sources. The relationships of char yield, gas-to-feed ratio, air-to-feed ratio, mass conversion efficiency, cold gas efficiency, gas heating value, and gas compositions, to the gas fan rotation speed are shown in Figures 5-9. Figures 10 and 11 show the relationships of dry feed rate and energy output to the gas fan rotation speed for the two chip sources. The regression models for the cottonwood chips are given in Table 5 (Chapter 4) while the regression models for the black locust chips are given in Table 6.

(B) Grate rotation speed variation. A total of ten runs were conducted; five runs with high bulk density cottonwood and five runs with low bulk density cottonwood. Tables 3 and 4 list the chip properties, operating parameters, performance measures, and major gas compositions. Figures 12-18 graphically illustrate the performance comparisons. The efficiency indicators, the char yield, gas-to-feed, air-to-feed, mass conversion efficiency, cold gas efficiency, gas heating value, and gas compositions, are related to the grate rotation speed in Figures 12-16 for both sources of chips. The throughput indicators, the dry feed rate and energy output rate, are plotted against the grate rotation speed in Figures 17-18. Table 7 gives the regression models for the high bulk density cottonwood whereas Table 8 presents the regression models for the low bulk density cottonwood.

Table 9 presents the results of the significant difference tests of the regression models for both the gas fan speed variation and grate rotation speed variation.

DISCUSSION

Chip Voidage Variation

In the chip voidage variation runs, increasing the chip voidage from 0.33 to 0.56 resulted in only gradual increases in the gas-to-feed ratio, air-to-feed ratio, mass conversion efficiency, cold gas efficiency, dry feed rate, and energy output rate. The gradual increase in gas-to-feed ratio is accompanied by a gradual decrease in the char yield (see Figures 1 and 2). The hexagonal point in Figure 2 was neglected in the regression analysis due to a possible measurement error that resulted in an unreasonably high char yield.

The air-to-feed ratio increases gradually with chip voidage as shown in Figure 1. This implies that at high voidage, more air passes through the chip bed while at low voidage, less air permeates through the chip bed. Suprisingly, the change in the air-to-feed ratio was not profound indicating that the effect of chip voidage on the air input rate is minor with the present gasifier configuration and the flow rate level investigated.

In Figures 1 and 2, the higest values of the cold gas efficiency and mass conversion efficiency occured at the highest chip voidage. This is simply due to the increase in the gas-to-feed ratio with increasing voidage.

The chip voidage variation also has an insignificant effect on the compositions of the major gas components. Figure 3 shows slight increases in N_2 and H_2, slight decreases in CO_2 and CH_4, and no change in CO. The gas compostion changes resulted in a slight decrease in the gas heating value with increasing voidage as shown in Figure 1. The gas heating value dropped from 6.3 MJ/m^3 to 5.9 MJ/m^3 over the chip voidage range.

The increase in the dry feed rate as the voidage increased from 0.33 to 0.56 is due to the increase in the amount of air permeating through the bed (see Figure 4). However, the dry feed rate appears to level off at a voidage of around 0.5. Overall, the change in the dry feed rate with the chip voidage is not appreciable. The maximum increase is about 12 kg/hr while the measurement error in the dry chip feed rate determination is ±8 kg/hr.

Figure 4 shows a gradual increase in the energy output rate with increasing chip voidage. This is directly related to the increase in the gas-to-feed ratio, slight increase in the dry feed rate, and the decrease in the char yield.

The results of preliminary estimations of the pressure drop for the gasifier under investigation suggest that the major controlling resistance to flow is exerted by local regions near the grate openings. For the present gasifier, the grate contains 96 openings which comprise about 20% of the total bed area. With this limited area for flow, the local regions near these openings appear to control the overall bed resistance. Results of calculations with no agitation (zero grate rotation) indicated that the depth of the controlling regions (above each grate opening) is of the order of 6 to 7cm. Other regions of the bed only provide about 1 to 5% of the total resistance. The results also reveal that the local voidage in the controlling zone increases with increasing grate rotation speed. The local voidage appears to be nearly independent of the incoming chip voidage and consequently, only minor effects are observed in the chip voidage variation experiments.

The principal finding from the voidage variation runs is:

(1) the effect of chip voidage on the gasifier performance is minor.

Chip Bulk Density Variation

(A) Gas fan rotation speed variation. From Table 9, the significant difference tests indicate that all the regression models used to describe the performance measures are significantly different except the air-to-feed ratio, gas heating value, and dry feed rate.

Figure 5 suggests that the char yield from cottonwood is lower than that from black locust. This observation is complemented by the gas-to-feed ratio plot (Figure 6) which indicates that cottonwood produces more gas, consequently less char. The higher gas yield also results in a higher mass conversion efficiency and cold gas efficiency for cottonwood (Figure 7).

In Figure 6, the air-to-feed ratio appears to be slightly higher for the low bulk density chips. However, statistical analysis (Table 9) indicates no significant difference between the two regression models for the air-to-feed ratio for the two chip sources. This result might be expected since the voidage is the same for both chip sources.

In Figure 8, even though the regression models suggest that the gas from cottonwood has a lower heating value than the gas from black locust, the significant difference test concludes that the two models are identical (Table 9). This implies that the gases from both chip sources have the same heating value.

The dry gas composition for both chip sources is illustrated in Figure 9. The gas produced from cottonwood contains slightly lower N_2 , CH_4, and CO but slightly higher H_2 and CO_2 than the gas from black locust. The compensating effects between the N_2 and H_2 are responsible for the insignificant change in the gas heating value.

Figure 10 shows the variations of the dry feed rates as functions of the gas fan rotation speed for both chip sources. The significant difference test in Table 9 shows that there is no significant difference in the dry feed rates with respect to chip source.

Figure 11 illustrates that cottonwood produces a higher energy output rate than black locust which indicates that cottonwood has a higher energy yield since the dry feed rates are similar for both chip sources.

The principal findings from the gas fan rotation speed variation runs are:

(1) chips with a low bulk density, give a lower char yield, higher mass conversion efficiency, higher cold gas efficiency, and higher energy yield.

(2) the air-to-feed ratio, gas heating value, and dry feed rate are not significantly affected by the chip bulk density when the voidages are similar.

(B) Grate rotation speed variation. One of the requirements to conduct significant difference tests is that the regression models be of the same order. In Chapter 4, some of the regression models for the low bulk density cottonwood contained expressions such as the exponential and logarithmic terms found in the relationships for the gas-to-feed ratio, air-to-feed ratio, gas heating value, gas compositions, mass conversion efficiency, and cold gas efficiency. In order to permit meaningful statistical comparison, the data for both the high bulk density and low bulk density cottonwood chips were forced to be described by regression models which had the same form. This required the data for the low bulk density cottonwood to be refitted by excluding the extreme points (0 rph and 21.6 rph). Consequently the data for both chip sources were fitted with a statistically comparable second order models.

Figure 12 shows that the low bulk density cottonwood appears to give a lower char yield than the higher bulk density material. However, the significant difference tests in Table 9 indicates that both the low and high bulk density chips produce a similar char yield. This finding is the opposite of the result obtained in the gas fan rotation speed variation experiments.

Figure 13 indicates that the low bulk density cottonwood appears to have a higher gas-to-feed ratio and air-to-feed ratio than the high bulk density material. However, the differences between the regression models are found to be insignificant. Unlike the gas fan rotation speed variation experiments, chips with a low bulk density do not give a higher gas-to-feed ratio. However, as in the results from the gas fan rotation speed variation experiments, both chips show similar air-to-feed ratios due to the same voidage.

The mass conversion efficiency and cold gas efficiency appear to be about the same for both chip sources as suggested in Figure 14. Both chip sources have the same regression models for these performance measures. Unlike the gas fan rotation speed variation experiments, these two performance measures are unaffected by the chip bulk density.

The significant difference test in Table 9 indicates that the two regression models in Figure 15 are identical, suggesting that both chip sources produce gases with similar heating values. This finding is similar to that for the gas fan rotation speed variation experiments indicating that the effect of chip bulk density on the gas heating value is not significant. Figure 16 indicates nearly identical gas compositions for both chip sources.

In Figure 17, the curves used to relate the dry feed rate for both chip sources to the grate rotation speed are statistically identical (Table 9). This finding, coupled with the finding for the dry feed rate from the gas fan rotation speed variation experiments, indicates that the chip bulk density has no influence on the dry feed rate.

Unlike the case of the gas fan rotation speed variation experiments, both chip sources show statistically similar regression models for the energy output rate for the grate rotation speed variation experiments (see Figure 18 and Table 9). This implies that both chip sources produce the same energy yield since the dry feed rate is the same for both.

The principal findings from the grate rotation variation experiments are:

(1) both chip sources produce identical efficiency indicators (char yield, G/F, A/F, mass conversion efficiencies, cold gas efficiencies, gas compositions, and gas heating values),

(2) the chip sources do not significantly influence the gasifier throughput indicators, (dry feed rate and the energy yield).

From the experiments conducted for the chip bulk density variation, it should be reiterated that the chip sources used for the gas fan rotation speed investigation were from different tree species while the chips used for the grate rotation speed experiments were from the same tree species (only differing in source). The variation in the chip bulk density for both cases was about the same. The bulk density of black locust (190 kg/m^3) was 50 kg/m^3 higher than that of cottonwood (140 kg/m^3) whereas the bulk density of the high bulk density cottonwood (185 kg/m^3) was 45 kg/m^3 higher than that of the low bulk density cottonwood (140 kg/m^3). However, the results presented for the two cases showed both consistent and contradictory outcomes.

Comparing the two cases, consistency is shown in the behavior of the air-to-feed ratio, gas heating value, and dry feed rate. Therefore, it is appropriate to conclude that the chip bulk density does not affect the air-to-feed ratio, the gas heating value, and the dry feed rate.

Contradictory results were obtained for the char yield, gas-to-feed ratio, mass conversion efficiency, cold gas efficiency, gas compositions, and energy yield. In conducting the gas fan rotation speed variation experiments, chips from different tree species strongly suggest that low bulk density chips produce a lower char yield, higher gas-to-feed ratio, higher mass conversion efficiency, higher cold gas efficiency, higher energy yield, and statistically significantly different gas compositions. These conclusions were not reached in the grate rotation speed variation experiments using chips from same tree species.

Besides the bulk density of the chips, another source of variation is the wood specific gravity which is defined as the ratio of the density of the wood to the density of water at a specified reference temperature (often 4°C where the density of water is 1.0 gm/cm^3). Graboski and Bain (1980) reported that wood is composed of cells of various sizes and shapes. Hardwoods, such as cottonwood and black locust, normally contains fibers (long pointed cells) of about 1mm in length. However, the dominant features of the hardwood structure are the large open vessels and pores. Vessels as large as 30μm have been observed. The variations in the size of the vessels and the thickness of the cell walls cause some wood species to have more wood substance per unit volume than others and therefore to have higher a specific gravity (difference in internal porosity).

Specific gravity has been used exclusively in wood science as a standard rather than the bulk density. For a 12% (wet basis) chip moisture content, the specific gravity of black locust is 0.69 while the specific gravity of the cottonwood is 0.40 (Panshin and De Zeeum, 1980). The difference is mainly due to the distinct internal porosities found in both chip sources. Higher specific gravity chips have low internal porosity which prevents the easy passage of gas and therefore produce more char. Some of the performance indicators that did not show differences in the grate rotation variation experiments may be a consequence of the same chip internal porosity found in the same tree species.

The results obtained from the chip bulk density variation experiments suggest that factors such as the wood morphology and/or chemical composition may influence the gasifier performance. These features need to be systematically studied to better understand the results obtained in this study.

CONCLUSIONS

The influence of chip voidage and chip bulk density on the performance of a commercial downdraft gasifier has been investigated. Chip voidage variation has only a minor influence on the gasifier performance for the range of variables investigated. The main resistance to flow appears to be the local regions near the grate openings of the gasifier under investigation.

When comparing the chip bulk density variation experiments for chips from different tree species (gas fan rotation speed variation), chips with lower bulk density produce a lower char yield, higher gas-to-feed ratio, higher mass conversion efficiency, higher cold gas efficiency, and higher energy yield. Other performance indicators such as the gas heating value and the dry feed rate are unaffected by the chip bulk density.

In the case of the grate rotation speed variation experiments for chips from the same tree species, the effects of the chip bulk density on both the efficiency indicators and throughput indicators are insignificant.

This chapter has presented the influences of two chip physical properties: chip voidage and chip bulk density. Besides the gasifier operating parameters and the chip physical properties, the tree species is another parameter that needs to be examined in more detail in order to provide additional understanding of the gasifier performance. The chapter to follow will present a preliminary study of the effect of tree species on the gasifier performance.

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Table 1. Chip Chemical Properties.

	CHIP VOIDAGE VARIATION		CHIP BULK DENSITY VARIATION							
			GAS FAN ROTATION SPEED VARIATION				GRATE ROTATION SPEED VARIATION			
Chip Type	Oak		Black Locust		Cottonwood		Cottonwood#		Cottonwood*	
Elemental Analysis (%)	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
C	47.88	0.41	48.62	-	49.44	0.22	48.17	0.32	48.47	0.27
H	5.78	0.13	6.13	-	6.00	0.07	5.91	0.10	5.96	0.10
O	44.31	0.24	39.06	-	42.71	0.10	44.00	0.00	44.19	0.10
N	0.00	0.00	1.15	-	0.04	0.10	0.09	0.10	0.08	0.11
Ash	2.03	0.64	1.61	-	1.81	0.34	2.07	0.29	1.50	0.44
Heat of Combustion (kJ/gm)	20.27	0.16	19.81	0.15	20.00	0.00	19.88	0.23	19.90	0.20
Wet Moisture Percent	12.62	0.63	13.88	0.48	13.37	0.85	7.62	0.16	7.40	0.80
Lignin Percent	26.66		24.73		29.64		24.96		25.95	
Cellulose Percent	44.95		45.92		44.04		50.07		48.66	
Hemi-Cellulose Percent	19.23		17.59		15.72		18.73		14.61	

\# High bulk density cottonwood chips.

* Low bulk density cottonwood chips.

Table 2. Chip Physical Properties.

	CHIP VOIDAGE VARIATION	CHIP BULK DENSITY VARIATION			
		GAS FAN ROTATION SPEED VARIATION		GRATE ROTATION SPEED VARIATION	
Chip Type	Oak	Black Locust	Cottonwood	Cottonwood#	Cottonwood*
Screen Opening (cm)	Weight Percent	Weight Percent	Weight Percent	Weight Percent	Weight Percent
>2.54	3.75	9.32	9.23	7.60	10.22
1.27-2.54	44.15	57.20	58.97	59.69	60.58
0.97-1.27	20.31	13.56	11.28	11.03	10.95
0.33-0.97	28.26	16.95	17.44	19.01	15.33
<0.33	3.53	2.97	3.08	2.66	2.92
Average Thickness (cm)	0.43	0.55	0.56	0.61	0.58
Voidage Percent	48.22	47.63	48.32	44.46	45.11
	Mean Standard Deviation	Mean Standard Deviation	Mean Standard Deviation	Mean Standard Deviation	Mean Standard Deviation
Bulk Density (kg/m^3)	228 8.02	192 6.86	138 2.56	183 6.03	148 9.29

\# High bulk density cottonwood chips.

* Low bulk density cottonwood chips.

Table 3. Summary of Chip Properties, Operating Parameters, and Performance Measures.

Run No.	Chip Wet Moisture Content (%)	Grate Rotation Speed (rph)	Gas Fan Speed (rpm)	Chip Voidage in Fraction	Wet Bulk Density (kg/m^3)	Pressure Drop (cm H_2O)	Temperature above Grate (°C)
CHIP VOIDAGE VARIATION Oak Chips							
501	12.8	4.08	1388	0.32	211	2.8	727
502	12.0	4.08	1388	0.37	228	2.3	732
503	13.5	4.08	1388	0.40	220	1.8	788
504	12.0	4.08	1388	0.43	221	1.4	799
505	12.8	4.08	1388	0.48	226	1.3	820
506	13.5	4.08	1388	0.56	230	1.1	804
CHIP BULK DENSITY VARIATION (A)Gas Fan Rotation Speed Variation Black Locust Chips							
701	14.0	4.08	1388	0.43	194	1.5	827
702	14.5	4.08	1615	0.43	181	2.5	827
703	13.5	4.08	1794	0.43	196	2.8	827
704	13.5	4.08	2360	0.43	194	4.6	827
Cottonwood Chips							
301	13.00	4.08	1389	0.48	138	1.3	721
302	13.00	4.08	1636	0.48	134	2.5	732
303	14.00	4.08	1793	0.48	140	3.3	727
304	12.00	4.08	1987	0.48	138	4.3	743
305	14.20	4.08	2373	0.48	137	5.6	743
306	14.00	4.08	2561	0.48	141	6.3	760
(B)Grate Rotation Speed Variation High Bulk Density Cottonwood Chips							
401	7.5	2.55	1794	0.43	173	3.1	777
402	7.8	3.37	1794	0.43	181	3.1	788
403	7.8	5.00	1794	0.43	186	2.2	782
404	7.5	6.00	1794	0.43	187	2.0	788
405	7.5	7.94	1794	0.43	188	1.9	782
Low Bulk Density Cottonwood Chips							
202	6.0	2.76	1794	0.45	140	3.8	749
203	7.0	3.37	1794	0.45	141	3.3	749
204	8.2	4.08	1794	0.45	157	2.8	749
205	7.2	5.00	1794	0.45	134	2.3	760
206	8.2	13.33	1794	0.45	150	2.0	716

Table 3. (continued).

Run No.	Wet Feed Rate (kg/hr)	Dry Feed Rate (kg/hr)	Char Yield (%)	Gas-to-Feed Ratio	Air-to-Feed Ratio	Condensate-to-Gas Ratio
CHIP VOIDAGE VARIATION Oak Chips						
501	55.91	48.75	10.13	2.12	1.28	0.170
502	55.34	48.70	13.61	1.97	1.18	0.130
503	63.04	54.54	8.72	2.18	1.34	0.050
504	64.07	58.38	8.28	2.19	1.33	0.100
505	65.11	56.78	8.39	2.22	1.36	0.140
506	66.68	57.68	7.24	2.31	1.43	0.050
CHIP BULK DENSITY VARIATION (A)Gas Fan Rotation Speed Variation Black Locust Chips						
701	58.96	50.70	7.77	2.37	1.47	0.060
702	70.08	59.92	8.32	2.45	1.54	0.090
703	75.93	65.68	5.52	2.46	1.55	0.060
704	90.63	78.39	4.17	2.51	1.59	0.040
Cottonwood Chips						
301	61.20	53.30	4.16	2.44	1.50	0.076
302	69.10	60.10	3.52	2.51	1.58	0.066
303	74.20	63.80	3.29	2.54	1.56	0.082
304	81.40	71.60	2.53	2.52	1.56	0.044
305	97.00	83.20	2.84	2.58	1.62	0.071
306	104.1	89.50	3.70	2.57	1.62	0.082
(B)Grate Rotation Speed Variation High Bulk Density Cottonwood Chips						
401	65.54	61.55	3.19	2.54	1.64	0.055
402	74.02	68.24	3.55	2.48	1.58	0.042
403	85.36	78.70	8.42	2.24	1.41	0.073
404	87.21	80.67	8.02	2.49	1.74	0.071
405	93.46	86.45	10.85	2.08	1.28	0.095
Low Bulk Density Cottonwood Chips						
202	59.80	56.20	4.22	2.81	2.03	0.056
203	68.80	64.00	4.21	2.65	1.83	0.071
204	75.60	69.40	5.19	2.64	1.84	0.058
205	77.20	71.60	5.53	2.45	1.59	0.060
206	99.50	91.40	11.71	2.35	1.63	0.083

Table 3. (continued).

Run No.	Mass Conversion Efficiency (MCE)	Cold Gas Efficiency (CGE)	Gas Heating Value (MJ/m^3)	Energy Output Rate (MJ/hr)	Carbon Conversion
CHIP VOIDAGE VARIATION Oak Chips					
501	0.87	0.60	8.20	594	0.85
502	0.85	0.57	6.31	565	0.80
503	0.87	0.63	6.23	895	0.87
504	0.89	0.64	6.23	728	0.88
505	0.89	0.83	6.11	724	0.87
506	0.89	0.64	5.92	749	0.89
CHIP BULK DENSITY VARIATION (A)Gas Fan Rotation Speed Variation Black Locust Chips					
701	0.90	0.70	6.22	899	0.93
702	0.90	0.70	6.04	828	0.94
703	0.91	0.70	6.08	916	0.95
704	0.91	0.71	6.01	1105	0.96
Cottonwood Chips					
301	0.92	0.71	6.15	757	0.94
302	0.92	0.72	6.11	870	0.95
303	0.93	0.73	6.04	926	0.96
304	0.94	0.73	8.11	1037	0.97
305	0.93	0.72	5.89	1190	0.97
306	0.92	0.71	5.89	1275	0.95
(B)Grate Rotation Speed Variation High Bulk Density Cottonwood Chips					
401	0.93	0.71	5.91	874	0.96
402	0.93	0.71	6.06	962	0.95
403	0.90	0.85	6.22	1021	0.89
404	0.88	0.65	5.63	1046	0.87
405	0.88	0.62	6.39	1067	0.83
Low Bulk Denisty Cottonwood Chips					
202	0.91	0.70	5.37	782	0.95
203	0.91	0.69	5.66	884	0.94
204	0.90	0.68	5.55	942	0.92
205	0.92	0.70	6.04	980	0.92
206	0.86	0.61	5.70	1117	0.80

Table 4. Dry Gas Major Component Compositions.

Run No.	Average Mole Percent of Major Gas Components				
	N_2	CO	H_2	CO_2	CH_4
CHIP VOIDAGE VARIATION Oak Chips					
501	42.3	19.2	18.1	16.6	2.8
502	41.7	20.1	18.6	16.0	2.7
503	42.4	21.6	18.5	14.4	2.4
504	41.9	21.2	19.1	14.7	2.3
505	42.3	20.3	19.0	15.3	2.3
506	42.6	20.0	19.7	15.2	1.8
CHIP BULK DENSITY VARIATION (A)Gas Fan Rotation Speed Variation Black Locust Chips					
701	43.5	23.5	17.1	12.9	2.2
702	44.1	22.9	17.2	13.0	2.1
703	44.4	23.9	16.7	12.3	2.0
704	44.4	23.7	17.0	12.4	1.9
Cottonwood Chips					
301	42.1	23.5	18.9	13.2	1.7
302	43.2	23.1	18.3	12.9	1.8
303	42.4	22.3	19.2	13.8	1.6
304	42.7	22.8	18.3	13.6	1.8
305	43.4	21.6	18.8	14.0	1.5
306	43.5	21.4	18.7	14.1	1.6
(B)Grate Rotation Speed Variation High Bulk Density Cottonwood Chips					
401	45.3	25.5	17.6	13.0	1.8
402	44.0	22.9	17.9	12.6	1.9
403	44.4	21.7	17.0	13.6	2.2
404	53.1	17.5	14.5	11.9	2.0
405	43.3	20.7	17.1	14.5	2.7
Low Bulk Density Cottonwood Chips					
202	51.0	20.9	14.7	11.0	1.8
203	48.7	21.4	15.2	11.9	2.0
204	49.0	20.2	16.2	12.1	1.8
205	45.6	22.7	16.1	12.6	2.2
206	49.3	17.7	15.5	13.8	2.5

Table 5. Regression Models for the Oak Chips under the Chip Voidage Variation.

Dependent Variables		Regression Models (V is the chip voidage in fraction)	R^2	PR>F
Dry Feed Rate	=	$-0.9+224(V)-214(V)^2$	0.9843	0.0157
Char Yield	=	$17.3-29.4(V)+20.9(V)^2$	0.9241	0.0759
G/F	=	$2.1-0.4(V)+1.3(V)^2$	0.9783	0.0217
A/F	=	$1.3-0.2(V)+0.87(V)^2$	0.9470	0.0530
MCE	=	$0.9+0.06(V)+0.033(V)^2$	0.7671	0.2329
CGE	=	$0.4+(V)-(V)^2$	0.8635	0.1365
GHHV	=	$4.76+7.69(V)-10(V)^2$	0.9920	0.0080
EOR	=	$-252+3828(V)-3671(V)^2$	0.9628	0.0372
N_2	=	$41.4+1.74(V)$	0.2003	0.3736
CO	=	$19.7+1.6(V)$	0.0239	0.7701
H_2	=	$16.1+6.3(V)$	0.9263	0.0021
CO_2	=	$17.3-4.6(V)$	0.2359	0.3287
CH_4	=	$4-3.9(V)$	0.8986	0.0040

Table 6. Regression Models for the Black Locust Chips under the Gas Fan Rotation Speed Variation-Chip Bulk Density Variation*.

Dependent Variables		Regression Models (Z is the gas fan speed in rpm)	R^2	PR>F
Dry Feed Rate	=	14.31+0.028(Z)	0.9769	0.0116
Char Yield	=	12.22-0.00035(Z)	0.9341	0.0335
G/F	=	2.22+0.00013(Z)	0.8460	0.0802
A/F	=	1.34+0.00011(Z)	0.8309	0.0311
MCE	=	0.88+0.000014(Z)	0.9387	0.0311
CGE	=	0.67+0.000016(Z)	0.9577	0.0214
GHHV	=	6.4-0.00017(Z)	0.5941	0.2293
EOR	=	159+0.41(Z)	0.9806	0.0097
N_2	=	42.67+0.0008(Z)	0.6120	0.2177
CO	=	22.74+0.00043(Z)	0.1680	0.5901
H_2	=	17.26-0.00015(Z)	0.0806	0.7161
CO_2	=	13.71-0.0006(Z)	0.4882	0.3013
CH_4	=	2.59-0.0003(Z)	0.9261	0.0376

* The regression models for the cottonwood chips are given in Chapter 4 (Table 5).

Table 7. Regression Models for the High Bulk Density Cottonwood Chips under the Grate Rotation Speed Variation-Chip Bulk Density Variation.

Dependent Variables		Regression Models (Y is the grate rotation speed in rph)	R^2	PR>F
Dry Feed Rate	=	$33.36+13.09(Y)-0.81(Y)^2$	1.0000	0.0053
Char Yield	=	$-5.53+3.7(Y)-0.21(Y)^2$	0.9564	0.2088
G/F	=	$3.02-0.21(Y)+0.011(Y)^2$	0.9850	0.1224
A/F	=	$2.00-0.18(Y)+0.0088(Y)^2$	0.9933	0.0817
MCE	=	$0.99-0.025(Y)+0.0014(Y)^2$	0.9594	0.2016
CGE	=	$0.81-0.04(Y)+0.002(Y)^2$	0.9610	0.1974
GHHV	=	$5.4+0.23(Y)-0.01(Y)^2$	0.9961	0.0624
EOR	=	$611+130(Y)-9.17(Y)^2$	0.9760	0.1550
N_2	=	$48.23-0.55(Y)+0.023(Y)^2$	0.7258	0.5237
CO	=	$32.11-3.36(Y)+0.24(Y)^2$	0.9428	0.2391
H_2	=	$19.13-0.62(Y)+0.05(Y)^2$	0.8862	0.5602
CO_2	=	$12.45+0.06(Y)+0.02(Y)^2$	0.9008	0.3149
CH_4	=	$1.25+0.20(Y)-0.002(Y)^2$	0.9916	0.0917

Table 8. Regression Models for the Low Bulk Density Cottonwood Chips under the Grate Rotation Speed Variation-Chip 8ulk Density Variation.

Dependent Variables		Regression Models (Y is the grate rotation speed in rph)	R^2	PR>F
Dry Feed Rate	=	$32.72+10.35(Y)-0.45(Y)^2$	0.9833	0.0167
Char Yield	=	$2.38+0.6(Y)+0.01(Y)^2$	0.9962	0.0038
G/F	=	$3.37-0.24(Y)+0.01(Y)^2$	0.9602	0.0398
A/F	=	$2.73-0.31(Y)+0.017(Y)^2$	0.9141	0.0859
MCE	=	$0.89+0.01(Y)-0.001(Y)^2$	0.9128	0.0872
CGE	=	$0.69+0.005(Y)-0.001(Y)^2$	0.9468	0.0534
GHHV	=	$4.29+0.47(Y)-0.027(Y)^2$	0.7642	0.2358
EOR	=	$467+141(Y)-6.89(Y)^2$	0.9782	0.0238
N_2	=	$60.15-3.99(Y)+0.24(Y)^2$	0.8588	0.1412
CO	=	$17.82+1.38(Y)-0.10(Y)^2$	0.8170	0.1830
H_2	=	$11.84+1.27(Y)-0.08(Y)^2$	0.8488	0.1512
CO_2	=	$8.63+1.06(Y)-0.05(Y)^2$	0.9746	0.0254
CH_4	=	$1.31+0.20(Y)-0.008(Y)^2$	0.8385	0.1615

Table 9. Significant Difference Tests on Regression Models.

Performance Measures	Conclusions of Significant Difference Tests Based on Significance Level of 0.05	
	CHIP BULK DENSITY VARIATION	
	(1) Gas Fan Rotation Speed Variation	(2) Grate Rotation Speed Variation
Char Yield	Different Models	Identical Model
G/F	Different Models	Identical Model
A/F	Identical Model	Identical Model
CGE	Different Models	Identical Model
MCE	Different Models	Identical Model
GHHV	Identical Model	Identical Model
N_2	Different Models	Identical Model
CO	Different Models	Identical Model
H_2	Different Models	Identical Model
CO_2	Different Models	Identical Model
CH_4	Different Models	Identical Model
EOR	Different Models	Identical Model
Dry Feed Rate	Identical Model	Identical Model

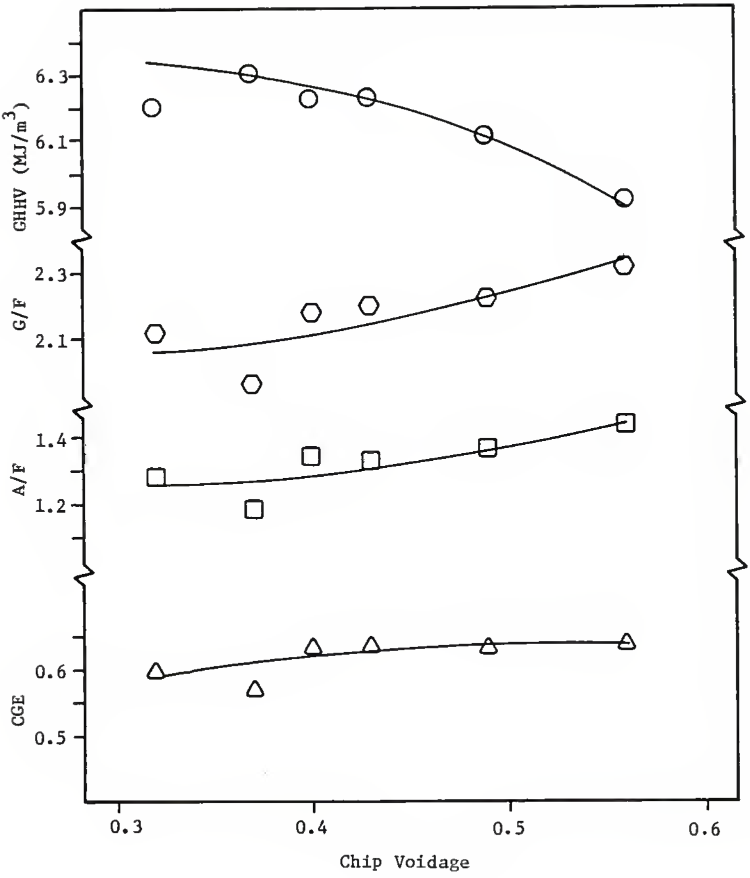

Figure 1. Relationships Between Gas Heating Value (GHHV), Gas-to-Feed Ratio (G/F), Air-to-Feed Ratio (A/F), and Cold Gas Efficiency (CGE), and Chip Voidage.

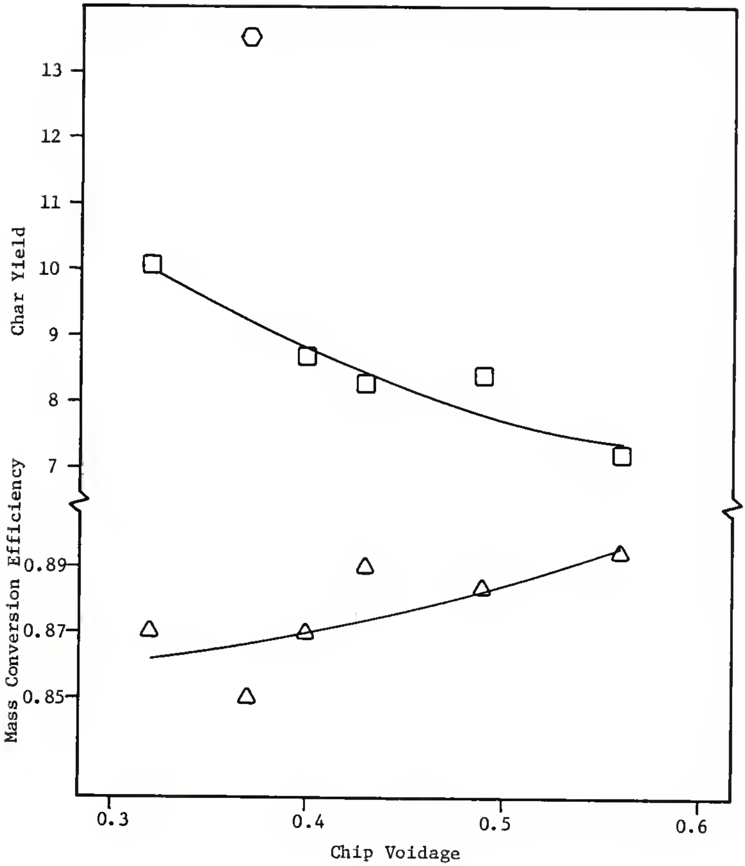

Figure 2. Relationships Between Char Yield and Mass Conversion Efficiency, and Chip Voidage.

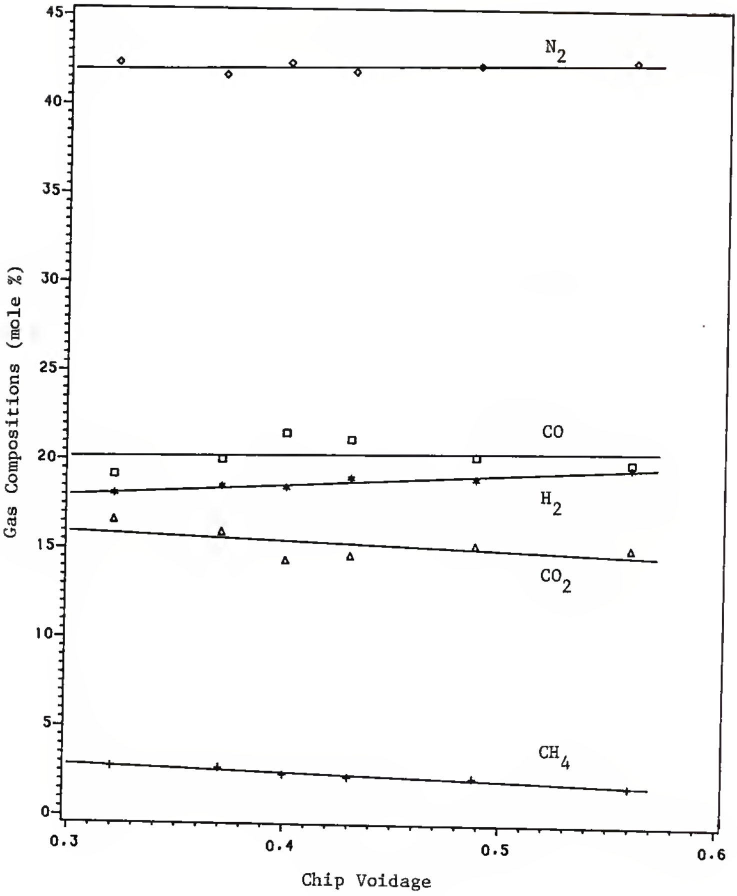

Figure 3. Gas Compositions versus Chip Voidage.

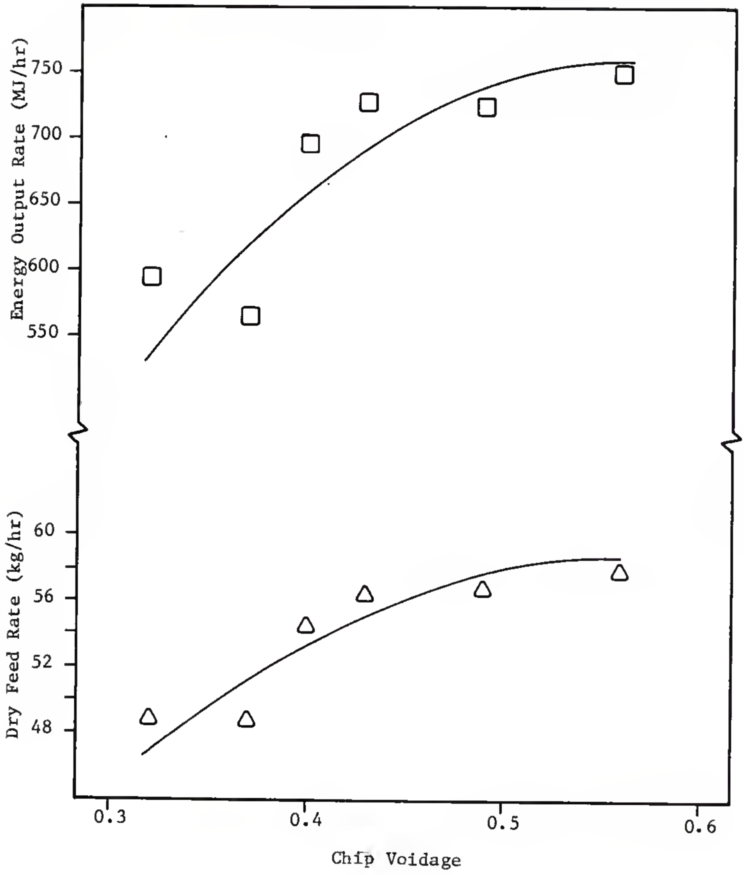

Figure 4. Relationships Between Energy Output Rate and Dry Feed Rate, and Chip Voidage.

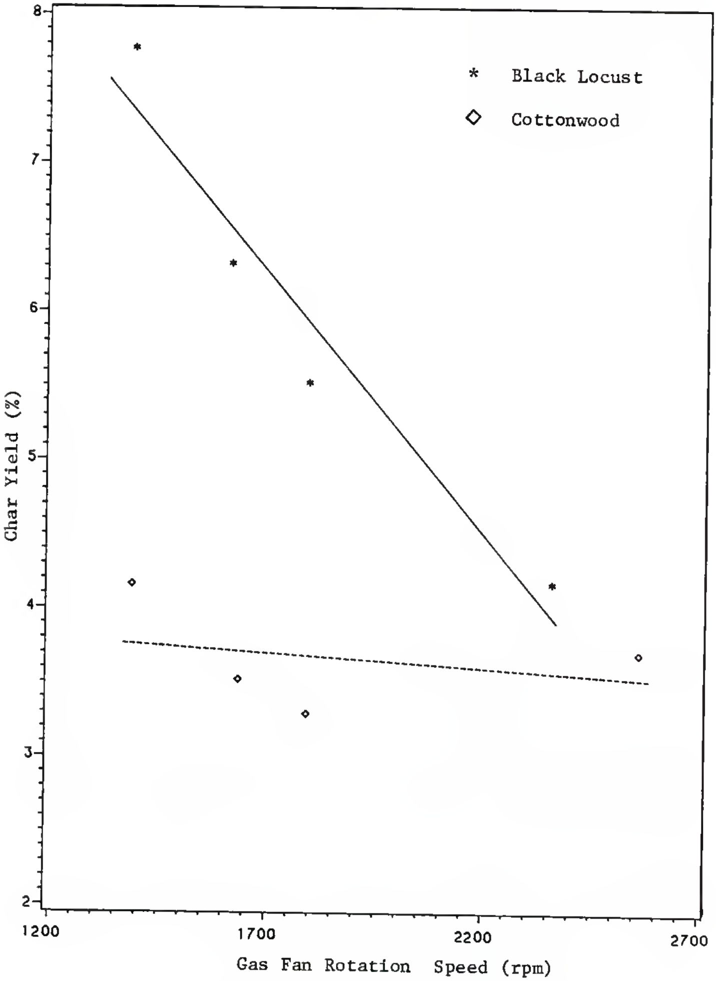

Figure 5. The Relationship Between Char Yield and Gas Fan Rotation Speed.

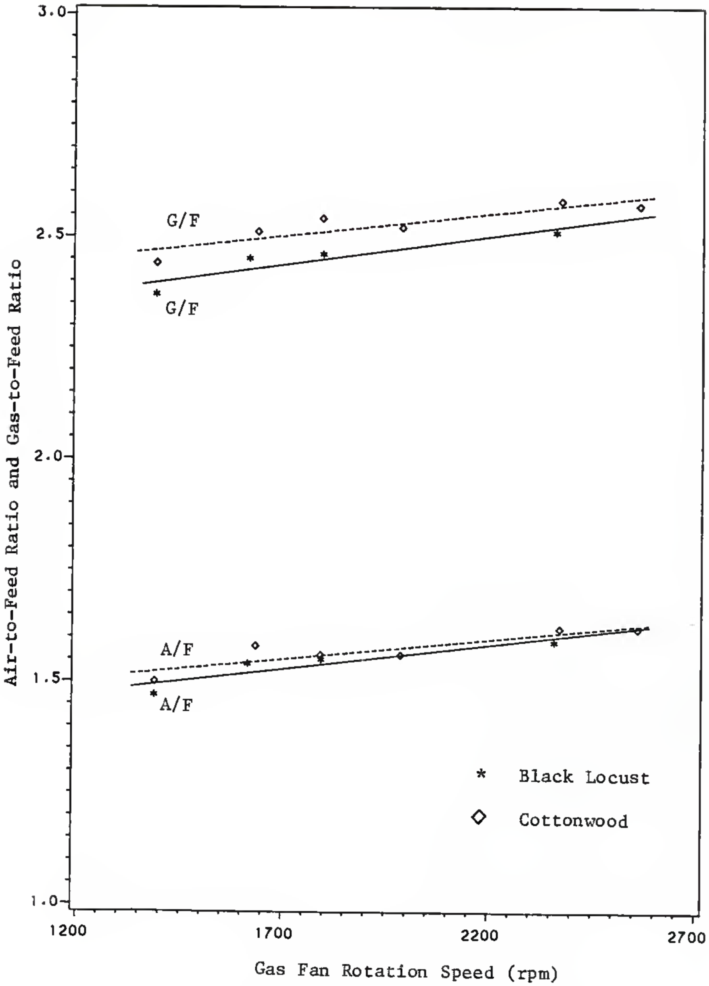

Figure 6. Relationships Between Gas-to-Feed Ratio (G/F) and Air-to-Feed Ratio (A/F), and Gas Fan Rotation Speed.

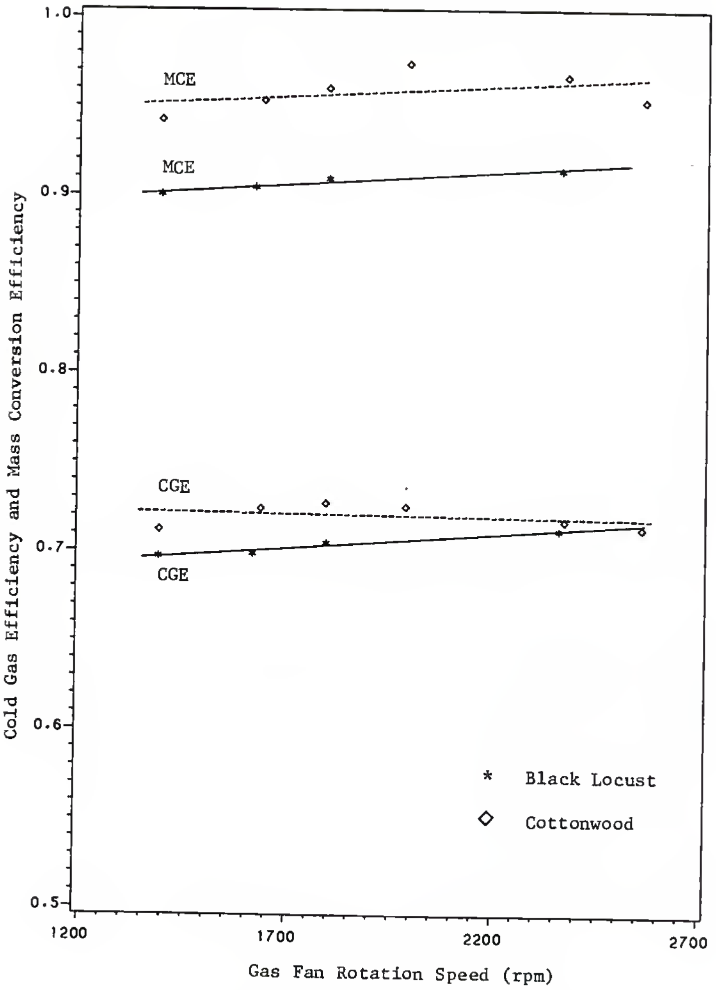

Figure 7. Relationships Between Mass Conversion Efficiency (MCE) and Cold Gas Efficiency (CGE), and Gas Fan Rotation Speed.

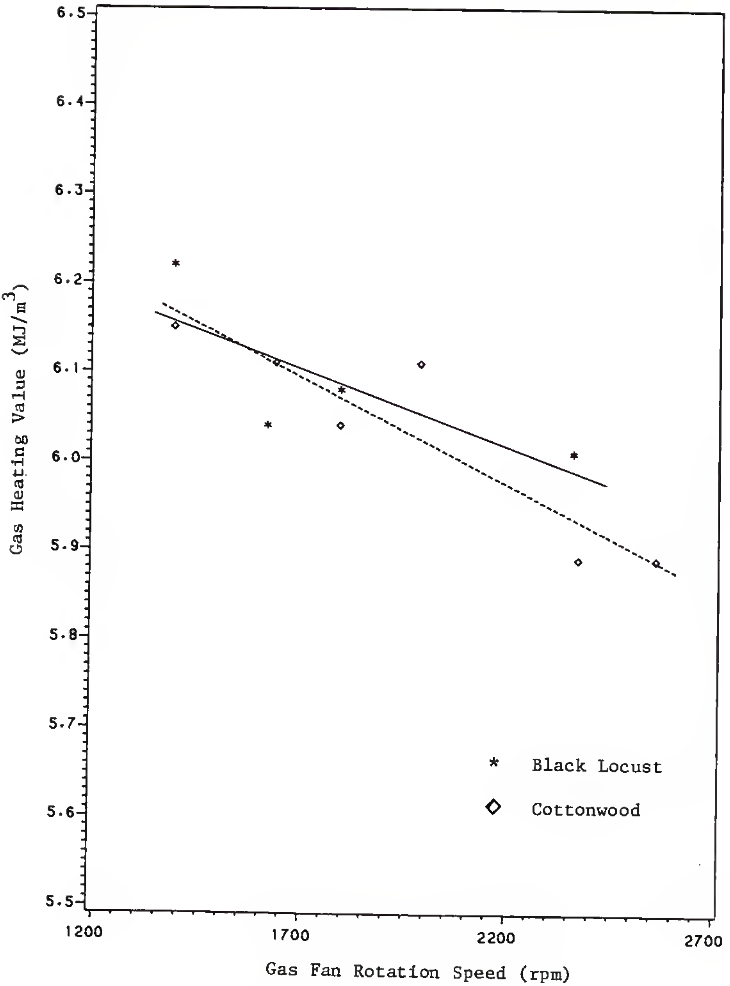

Figure 8. The Relationship Between Gas Heating Value and Gas Fan Rotation Speed.

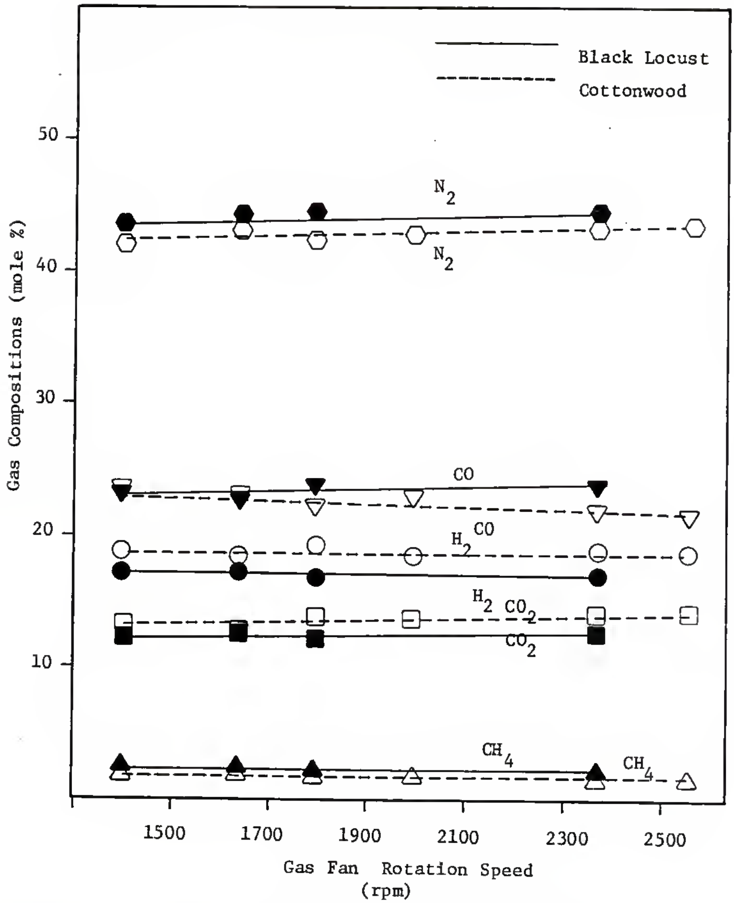

Figure 9. Gas Composition versus Gas Fan Rotation Speed.

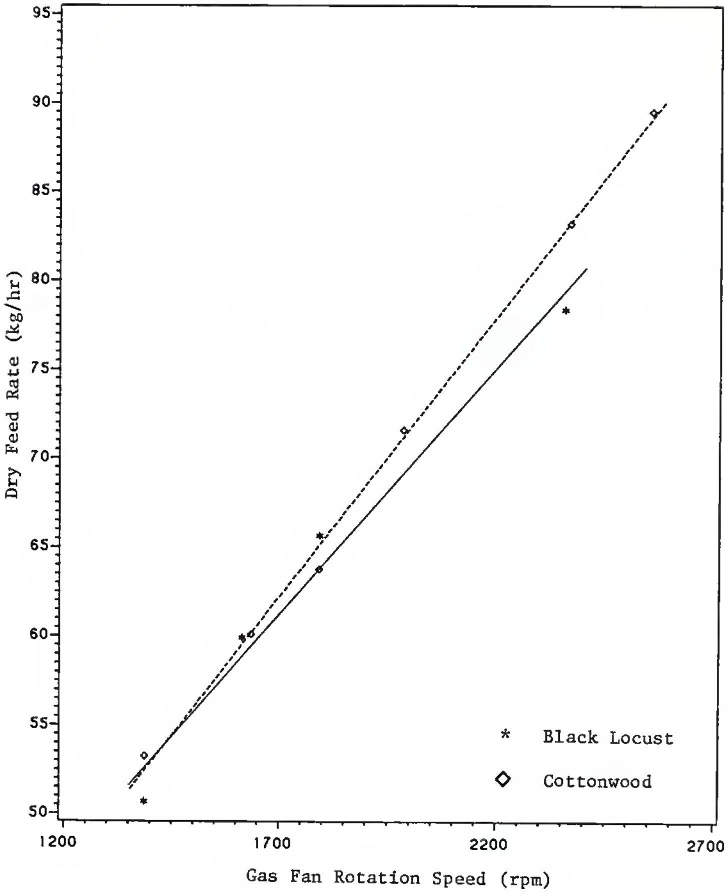

Figure 10. The Relationship Between Dry Feed Rate and Gas Fan Rotation Speed.

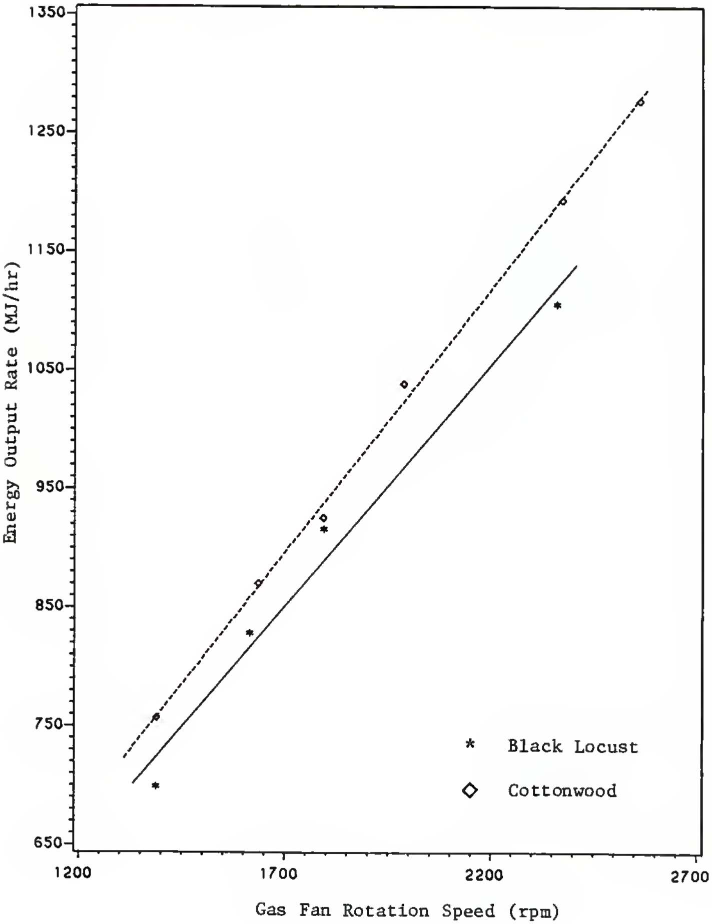

Figure 11. The Relationship Between Energy Output Rate and Gas Fan Rotation Speed.

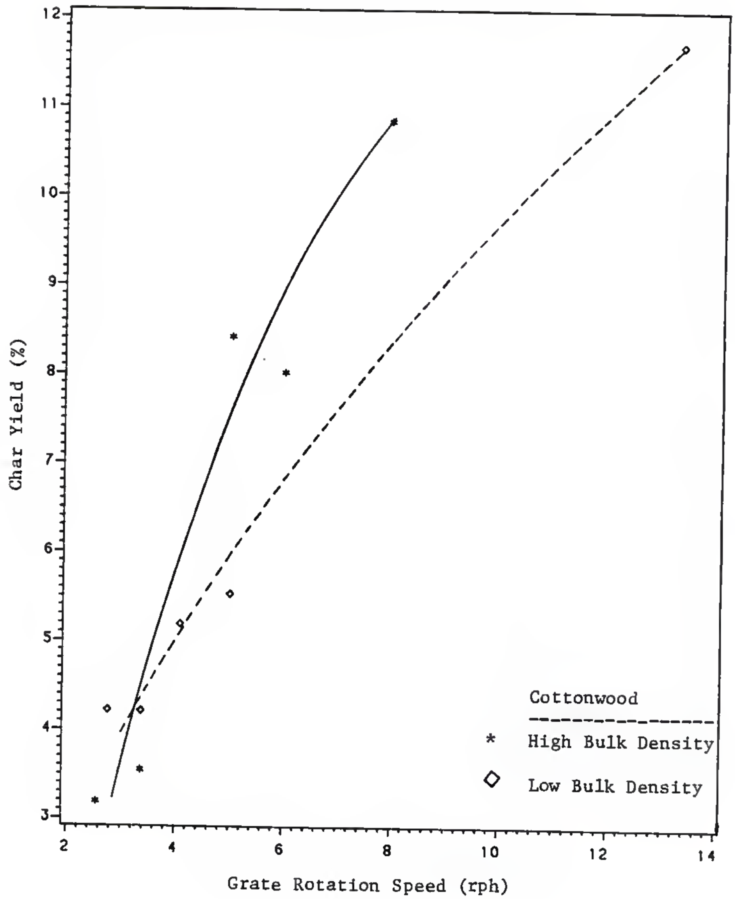

Figure 12. The Relationship Between Char Yield and Grate Rotation Speed.

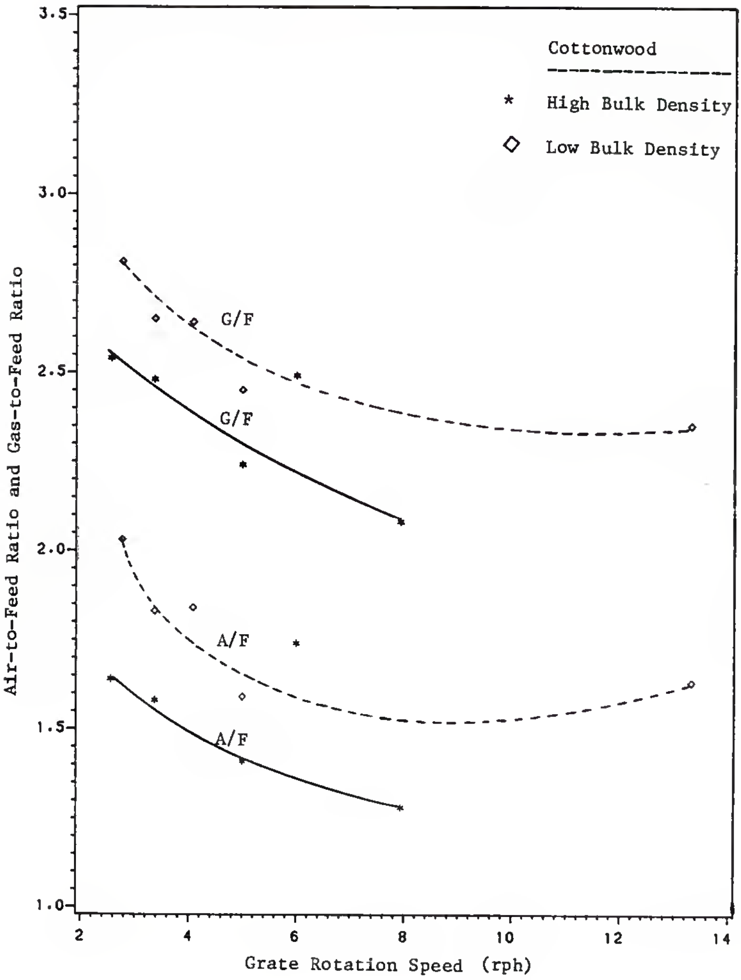

Figure 13. Relationships Between Gas-to-Feed Ratio (G/F) and Air-to-Feed Ratio (A/F), and Grate Rotation Speed.

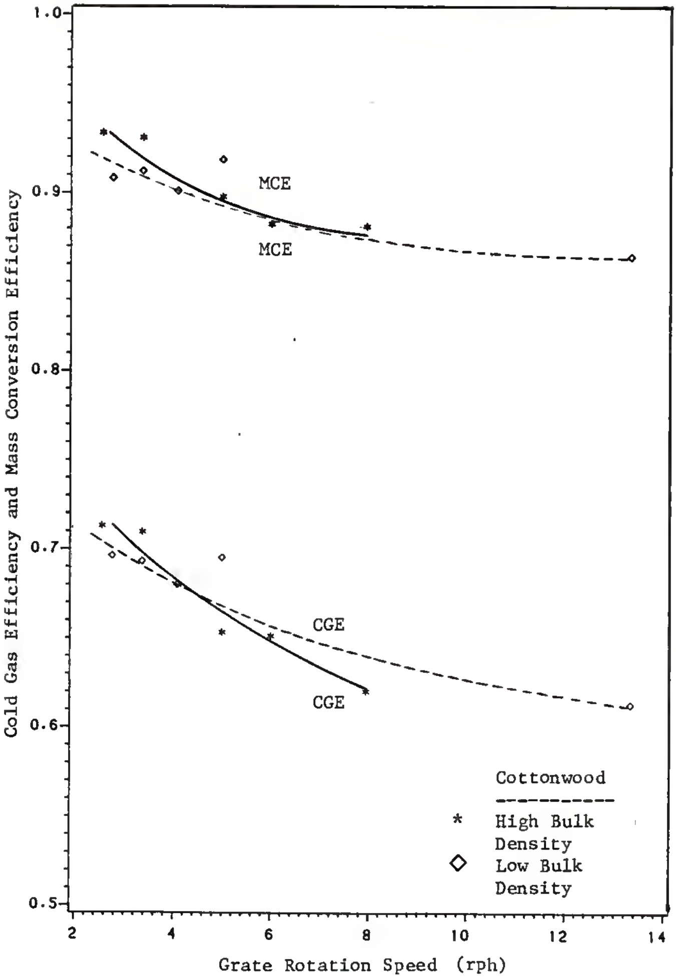

Figure 14. Relationships Between Mass Conversion Efficiency (MCE) and Cold Gas Efficiency (CGE), and Grate Rotation Speed.

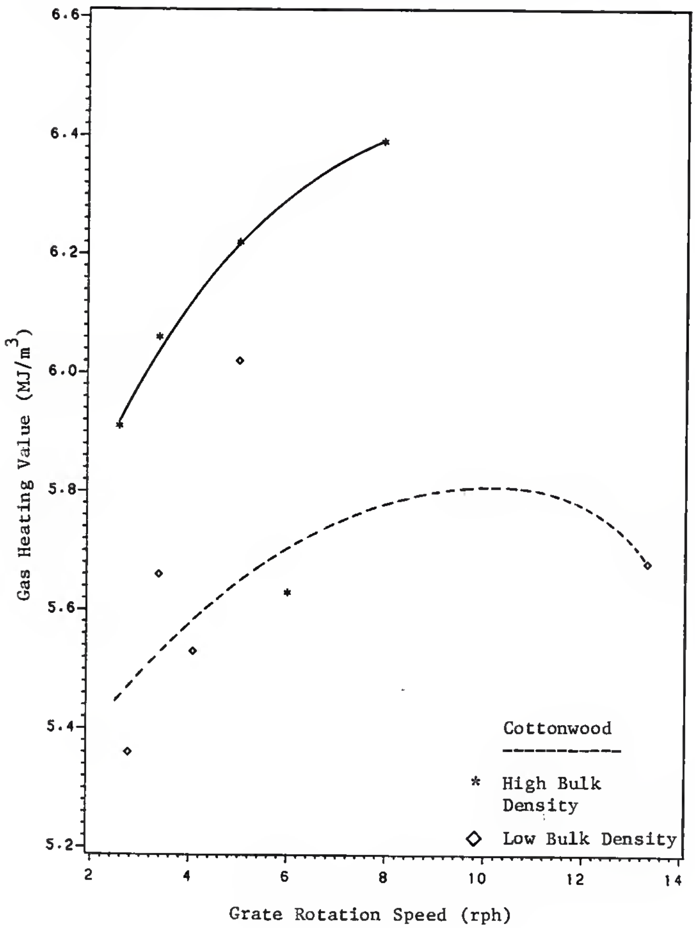

Figure 15. The Relationship Between Gas Heating Value and Grate Rotation Speed.

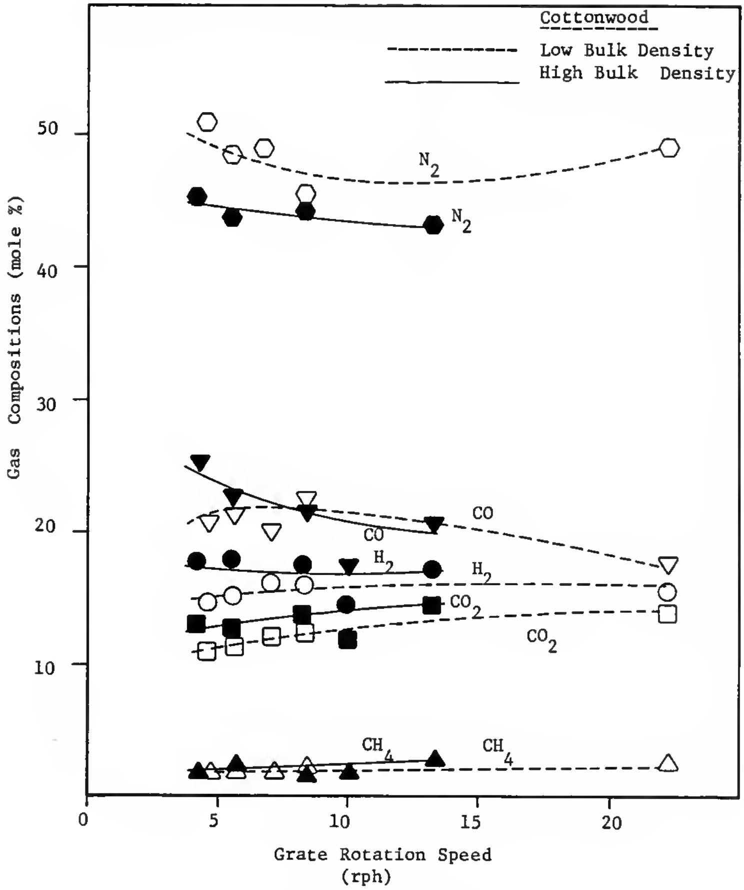

Figure 16. Gas Composition versus Grate Rotation Speed.

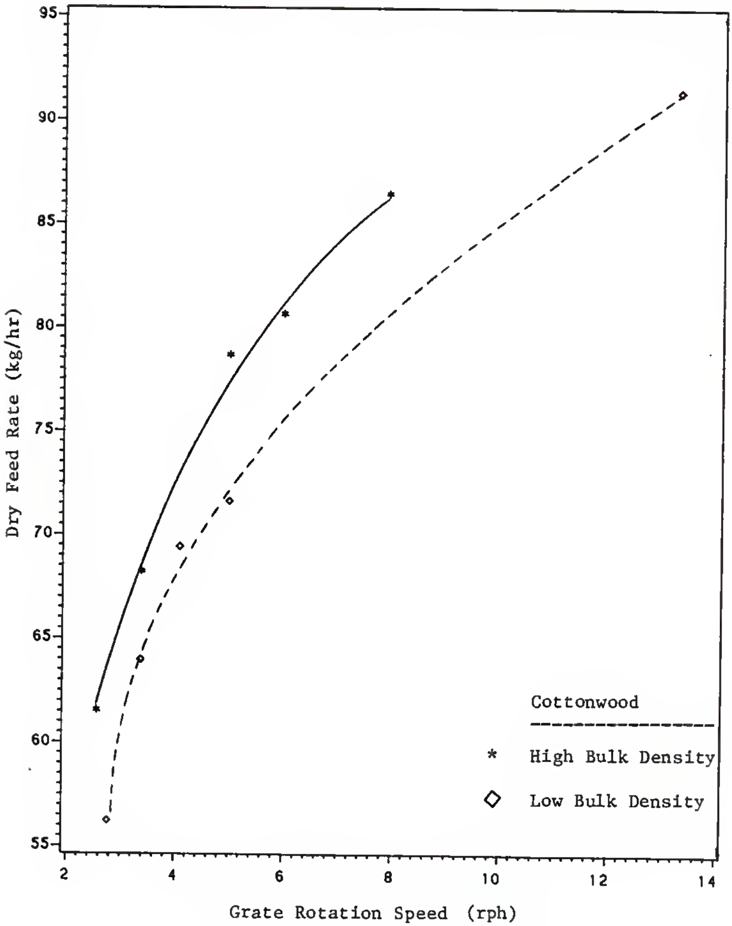

Figure 17. The Relationship Between Dry Feed Rate and Grate Rotation Speed.

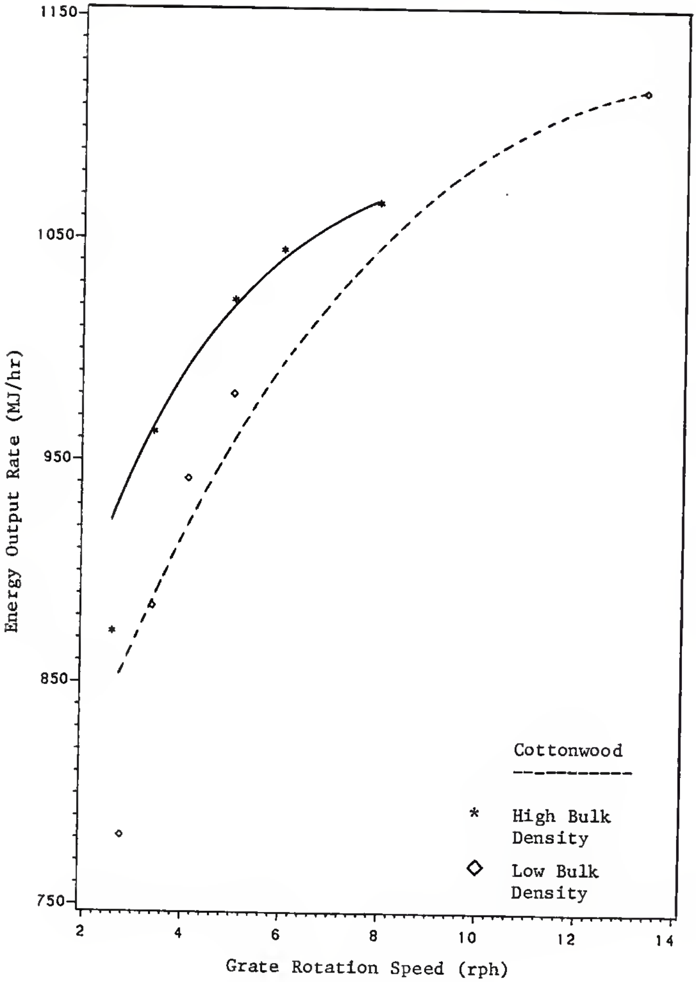

Figure 18. The Relationship Between Energy Output Rate and Grate Rotation Speed.

CHAPTER 6

INFLUENCE OF TREE SPECIES ON DOWNDRAFT GASIFIER PERFORMANCE

The gasifier operating parameters (Chapter 4) and chip physical properties (Chapter 5) may not be the only factors that influence the wood chip-air gasification process. Since some wood properties vary between tree species, it is appropriate to investigate the influence of tree species on downdraft gasifier performance.

Prior to the present work, Graham and Huffman (1981) conducted two experiments with two wood species, poplar and pine in a commercial downdraft gasifier. However, the data reported by them could not be used to make a conclusion on the effect of tree species due to the fact that they failed to hold all of the operating parameters constant for the two runs. Graboski and Brogan (1987) conducted downdraft gasification experiments with pine and cedar, but they did not offer any discussion on the influences of tree species.

This chapter is concerned with a preliminary investigation of the influence of tree species on the performance of a commercial downdraft gasifier. Four different hardwood tree species were used to provide sources of chips that were gasified under similar operating conditions.

EXPERIMENTAL FACILITIES AND PROCEDURE

Gasifier Description

The downdraft gasifier employed is the same as that used in Chapter 4 (operating parameter variation runs) and Chapter 5 (chip physical property variation runs). A schematic diagram is shown in Chapter 4 (Figure 1).

Operating Procedure

The operating procedure is as outlined in Chapter 4.

Measurements

Measurements of the feed rate, char output rate, gas compositions, condensables, temperature and pressure, chip moisture content, chip wet bulk density, dry gas production rate, and air input rate are as outlined in Chapter 4.

Tree Species Variation

Four different hardwood tree species were used to provide wood chips for the preliminary evaluation. They were cottonwood, maple, black locust, and oak. The chips were gasifier under similar operating conditions to systematically study the influence of tree species on gasifier performance. The chip moisture content was maintained at 12 to 14% wet basis. The grate rotation speed was held at 4.1 rph and the gas fan rotation speed was fixed at 1793 rpm.

The cottonwood chips were obtained from dead fall, mature cottonwood limbs which contained some bark and branches. Maple chips were obtained from 5 year old trees with trunk diameters ranging from 5 to 15cm. Since the chips were exposed to the elements for almost 2 years, they were highly deteriorated. Black locust chips were obtained from 5 year old trees with trunk diameters of about 15cm. Bark and small branches were included. Oak chips were comprised of a 50-50 volume percent mixture of white and red oak. Age and diameter of the trees were unknown.

Chemical and Physical Analyses

The chemical and physical properties of the four chip sources are presented in Table 1 and Table 2. The chemical properties reported include the elemental analysis, the heat of combustion, the moisture content, the lignin percent, the cellulose percent, and the hemicellulose percent. The physical properties include the size distribution, the average chip thickness, the voidage percent, and the bulk density.

TREATMENT OF DATA

Calculations

The gasifier performance measures can be classified into two categories: efficiency related indicators and throughput related indicators, as defined in Chapter 4. The performance measures grouped under the efficiency indicators consist of the char yield, dry gas-to-dry feed ratio, air-to-dry feed ratio, cold gas efficiency, mass conversion efficiency, and dry gas compositions. The dry feed rate and energy output rate are the throughput indicators. The details of calculation are presented in Chapter 4.

RESULTS

Four runs were conducted with four different tree species. Table 3 summarizes the operating parameters, performance measures, dry gas compositions, pressure drop, above grate temperature, condensate-to-dry gas mass ratio, carbon conversion, and char ash content. Figures 1 through 3 present qualitative relationships between the efficiency indicators and tree species. In Figure 1, the cold gas efficiency (CGE), gas-to-dry feed ratio (G/F), air-to-dry feed ratio (A/F), and gas high heating value (GHHV), are plotted against the tree species. The plots between char yield and mass conversion efficiency, and tree species are shown in Figure 2 and the dry gas compositions for the different tree species are graphically illustrated in Figure 3. Figure 4 presents qualitative relationships between the throughput indicators, the energy output rate and dry feed rate, and the tree species.

DISCUSSION

The results obtained can be discussed in terms of both the chemical and physical structure of the tree species. The bulk of the mass of wood comprises two components, lignin and holocellulose (cellulose and hemicellulose). Lignin occurs in wood largely as an intercellular material. Generally, hardwoods contain 16 to 25% of lignin. As a chemical species, lignin is an intractable, insoluble material. To remove it from wood on a commercial scale requires vigorous reagents, high temperatures, and high pressures. Cellulose, the major constituent, comprises approximately 45% of the wood substance by weight. It is a high-molecular weight linear polymer of glucose that can be degraded readily. The average percent of hemicellulose in hardwoods is about 20 to 30 percent. Like cellulose, it is a polymer of simple sugar molecules. The sugar components are of potential interest for conversion into chemical products.

Each species used for the present study shows some fluctuations in both the chemical and physical properties. The influence of these different properties on downdraft gasification is discussed below.

Since the condition of the maple chips was significantly different from the other chip sources due to biological deterioration, it is appropriate to discuss the differences in both chemical and physical properties between aged and fresh chips.

Table 1 shows that the deteriorated maple chips contain the highest ash percent. However, work with fresh maple chips indicated that the normal ash percent in maple chips is about 1.4%. The high ash content in the decayed maple is due to the deteriorated condition, since the wood volume has been greatly reduced through shrinkage. From Table 2, it can be seen that the average chip thickness of maple is about 55% smaller than those of cottonwood and black locust. All three sources of chips were obtained from the same wood chipper. Ash consists of inorganic materials and is unaffected by the deterioration. Consequently, its percentage increases due to the loss of chip mass. The ash content of the other chips is in the range of 1.6 to 2.0%.

All of the chip species show nearly the same heat of combustion as indicated in Table 1. Bomb calorimetry with both fresh and deteriorated maple chips has shown that both sources give similar heats of combustion. The same result was obtained with both fresh and decayed black locust chips. While studying a 5 year old pile of white oak sawdust, Cutter and Ostmeyer (1983) found that the energy potential of the deteriorated sawdust was reduced to about 86% of the heat potential of fresh white oak. This strongly suggests that wood, regardless of condition (fresh or decayed), yields similar heat of combustion if its storage duration is less than 5 years. The data in Table 1 indicate that wood, regardless of tree species, has approximately the same heat of combustion.

The lignin content in the decayed maple is about 60% higher than that in cottonwood, black locust, and oak (see Table 1). However, the cellulose content in the decayed maple is about 40% lower while its hemicellulose content is about 60% lower than in the other chip sources. The biological degradation of wood reduces the holocellulose constituents. Lignin, on the other hand, survives the deteriorating because of its stable molecular structure. Cottonwood, black locust, and oak contain about the same contents of lignin, cellulose, and hemicellulose.

Table 2 shows that the bulk density of maple is higher than that of cottonwood. This is due in part to the smaller size of the maple chips which gives rise to more efficient packing of the chips. Similarly, oak (with a slightly lower average chip thickness) shows a higher bulk density than black locust even though wood handbooks report that the specific gravity of oak is slightly lower than that of black locust.

Based on the experimental data for cottonwood, black locust, and oak, the influence of tree species on gasifier performance can be assessed. Figure 1 shows that the gas-to-feed ratio declines with tree species arranged in ascending order of chip bulk density. Cottonwood, the lowest bulk density chip among the sources, gives the highest gas-to-feed ratio indicating that it produces more gas than the others. Oak gives the lowest gas-to-feed ratio. In Chapter 5, the significant difference tests have concluded that high bulk density chips yield a lower gas-to-feed ratio when compared to low bulk density chips from a different tree species. This finding can be assessed based on the difference in the internal porosity found among tree species. Generally, chips with lower specific gravity contain larger internal pores that allow gas to escape more readily than high specific gravity chips.

The comparison of gas heating values in Figure 1 shows that all tree species produce gases with similar heating values. Cottonwood gives the highest cold gas efficiency as shown in Figure 1. This is compatible with the high gas-to-feed ratio obtained from the cottonwood. Oak shows a low cold gas efficiency due to the low gas-to-feed ratio. This observation is consistent with the finding in Chapter 5 which indicates that high bulk density chips give a significantly lower cold gas efficiency than low bulk density chips from a different tree species.

Among the cottonwood, black locust, and oak, cottonwood gives rise to the lowest char yield whereas oak gives rise to the highest char yield. The low char yield obtained with cottonwood is compatible with the high gas-to-feed ratio for this type of wood. The low gas-to-feed ratio with oak is related to the high char yield for this type of wood. The significant difference tests in Chapter 5 showed that high bulk density chips give rise to higher char yield than low bulk density chips from a different tree species due to the low internal porosity contained in high specific gravity chips that prevents the production of more gas (high char yield).

Figure 4 shows that the tree species has a minor effect on the dry feed rate since the maximum difference between the feed rates is about 9 kg/hr and the measurement error in the feed rate is ±7 kg/hr. This finding agrees with the conclusion drawn in Chapter 5, that chips from different tree species do not have a significant effect on the system throughput.

As for the deteriorated maple, it yields the lowest cold gas efficiency and gas heating value as shown in Figure 1. These observations are expected since the partially decayed chips have a high lignin and ash content. These factors are responsible for the high char yield shown in Figure 2.

The principal findings from this preliminary study are:

(1) different tree species do not significantly affect the dry feed rate and the gas heating value,

(2) high bulk density chips produce a higher char yield, lower gas-to-feed ratio, and lower cold gas efficiency than low bulk density chips from a different tree species,

(3) deteriorated chips have undesirable characteristics such as high ash and lignin content, and low volatile content which result in a lower gas yield and a higher char yield.

CONCLUSION

This chapter has presented a preliminary study of the influence of four different tree species on the performance of a downdraft gasifier. The results indicate that the system throughput and gas heating value are unaffected by tree species while increasing the wood chip bulk density through tree species variation results in a higher char yield, lower gas-to-feed ratio, and lower cold gas efficiency. Observations reveal that the chip deterioration influences chip characteristics. Long-term storage in the elements cause the chips to loose their volatile constituents which reduces gasifier efficiency. The next chapter will outline the major conclusions and recommendations from this thesis.

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Table 1. Chip Chemical Properties.

	TREE SPECIES VARIATION							
Chip Type	Cottonwood		Maple		Black Locust		Oak	
Elemental Analysis (%)	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
C	49.44	0.22	49.71	-	48.62	-	47.88	0.41
H	6.00	0.07	5.42	-	6.13	-	5.78	0.13
O	42.71	0.01	37.61	-	42.49	-	44.31	0.24
N	0.04	0.10	1.15	-	1.15	-	0.00	0.00
Ash	1.81	0.34	6.11	0.45	1.61	0.15	2.03	0.64
Heat of Combustion (kJ/gm)	20.00	0.00	20.07	0.10	19.88	0.23	20.27	0.16
Wet Moisture Percent	13.37	0.85	13.25	0.87	13.88	0.48	12.62	0.63
Lignin Percent	29.64		40.18		24.73		26.66	
Cellulose Percent	44.04		27.80		45.92		44.95	
Hemi-Cellulose Percent	15.72		7.15		17.59		19.23	

Table 2. Chip Physical Properties.

	TREE SPECIES VARIATION			
Chip Type	Cottonwood	Maple	Black Locust	Oak
		Size Distribution Analysis		
Screen Opening (cm)	Weight Percent	Weight Percent	Weight Percent	Weight Percent
>2.54	9.23	2.09	9.32	3.75
1.27-2.54	58.97	24.69	57.20	44.15
0.97-1.27	11.28	12.55	13.56	20.13
0.33-0.97	17.44	44.35	16.95	28.26
<0.33	3.08	18.23	2.66	3.53
Average Thickness (cm)	0.58	0.25	0.55	0.43
Voidage Percent	48.32	38.41	47.63	48.22

	Cottonwood		Maple		Black Locust		Oak	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Bulk Density (kg/m^3)	140	2.56	148	8.65	192	6.88	219	8.02

Table 3. Summary of Operating Parameters, Performance Measures, and Gas Composition.

Run No.	Chip Type	Chip Wet Moisture Content (%)	Grate Rotation Speed (rph)	Gas Fan Speed (rpm))	Pressure Drop (cm H_2O)	Temperature above Grate (°C)
			TREE SPECIES VARIATION			
801	Cottonwood	14.0	4.08	1793	3.3	793
802	Maple	12.0	4.08	1793	4.6	760
803	Black Locust	13.5	4.08	1793	2.8	827
804	Oak	13.8	4.08	1793	3.6	799

Run No.	Wet Feed Rate (kg/hr)	Dry Feed Rate (kg/hr)	Char Yield (%)	Gas-to-Feed Ratio	Air-to-Feed Ratio	Condensate-to-Gas Ratio
801	74.16	63.78	3.29	2.54	1.56	0.082
802	69.65	61.30	12.40	2.50	1.62	0.041
803	75.93	65.68	5.52	2.46	1.55	0.060
804	81.46	70.22	6.13	2.30	1.42	0.087

Run No.	Mass Conversion Efficiency (MCE)	Cold Gas Efficiency (CGE)	Gas Heating Value (MJ/m^3)	Energy Output Rate (MJ/hr)	Carbon Conversion	Ash in Char (%)
801	0.93	0.73	6.04	925	0.98	34.04
802	0.91	0.65	5.55	798	0.89	82.00
803	0.91	0.68	6.08	916	0.95	28.88
804	0.89	0.65	6.12	931	0.91	24.69

Run No.	Average Mole Percent of Major Gas Components				
	N_2	CO	H_2	CO_2	CH_4
801	42.4	22.3	19.2	13.8	1.6
802	45.2	21.5	18.3	13.5	0.9
803	44.4	23.9	16.7	12.3	2.0
804	42.7	21.8	18.5	14.1	2.1

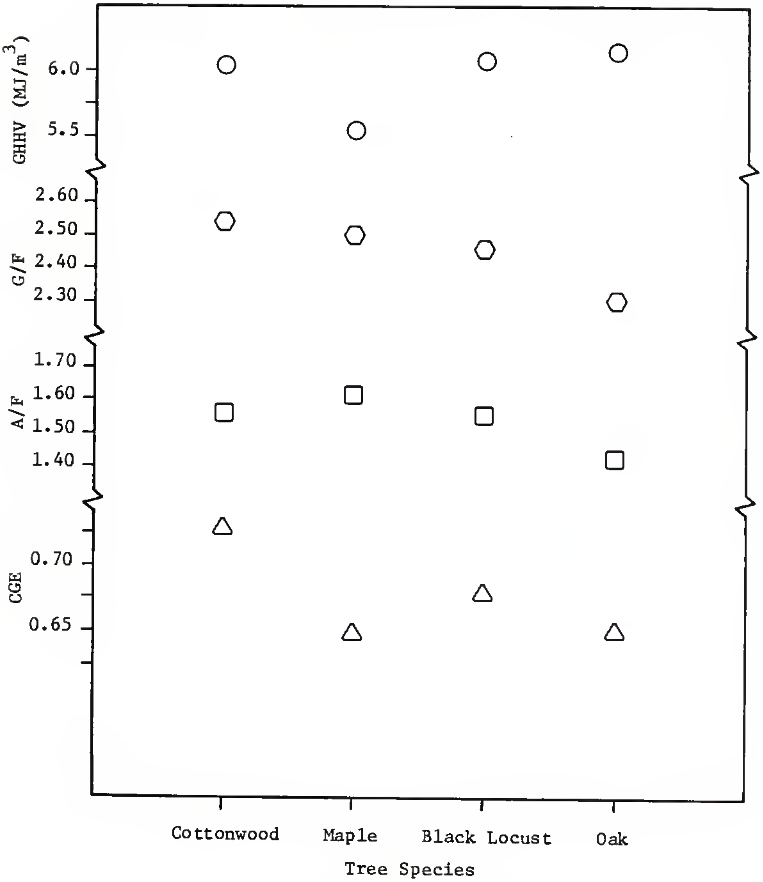

Figure 1. Relationships Between Gas Heating Value (GHHV), Gas-to-Feed Ratio (G/F), Air-to-Feed Ratio (A/F), and Cold Gas Efficiency (CGE), and Tree Species.

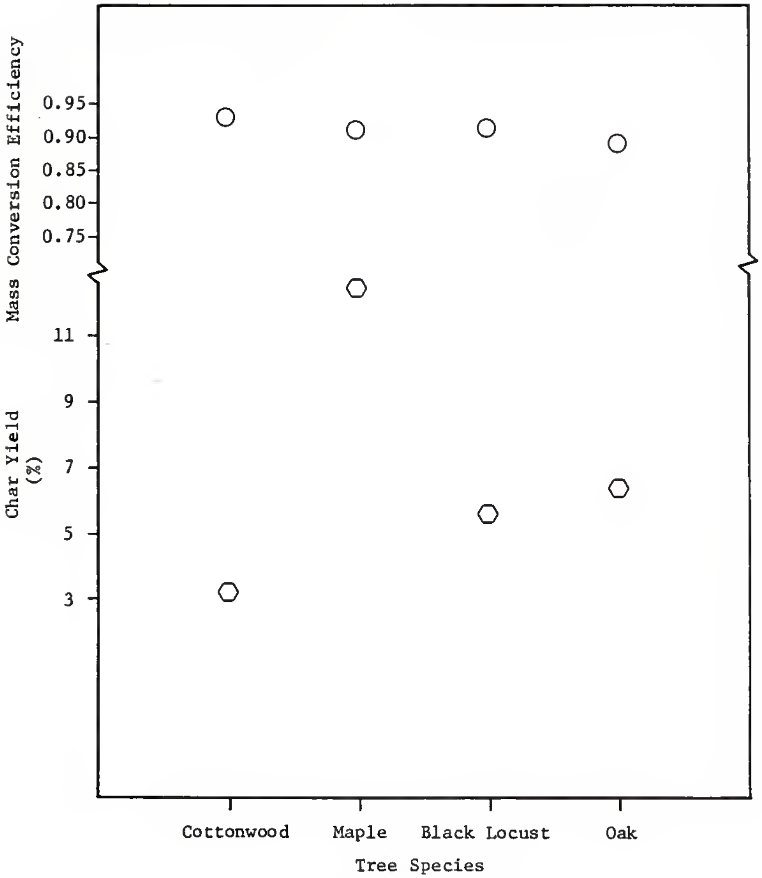

Figure 2. Relationships Between Char Yield and Mass Conversion Efficiency, and Tree Species.

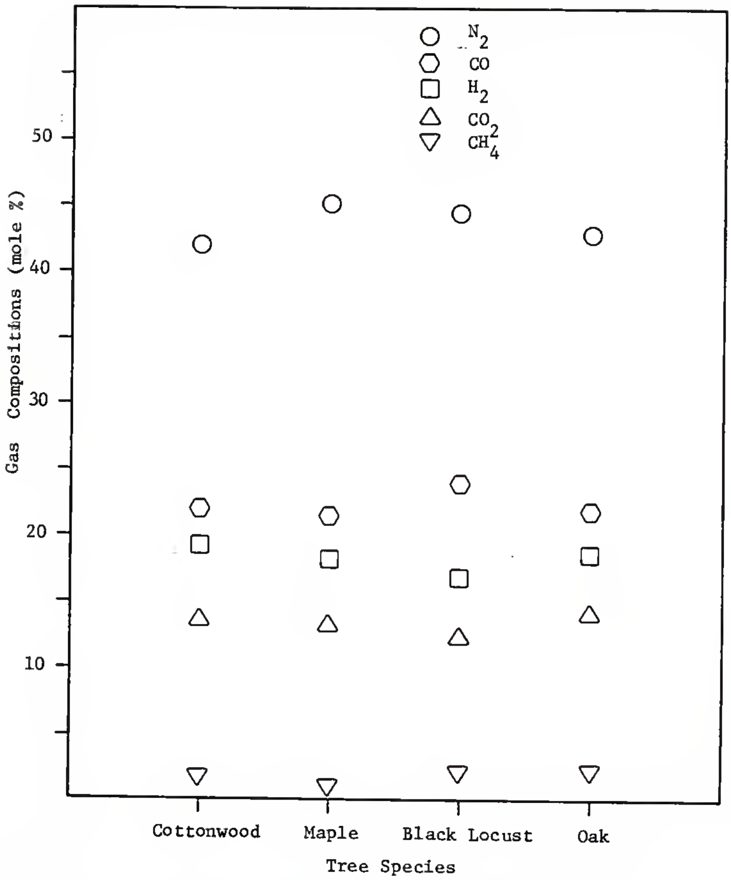

Figure 3. Gas Compositions versus Tree Species.

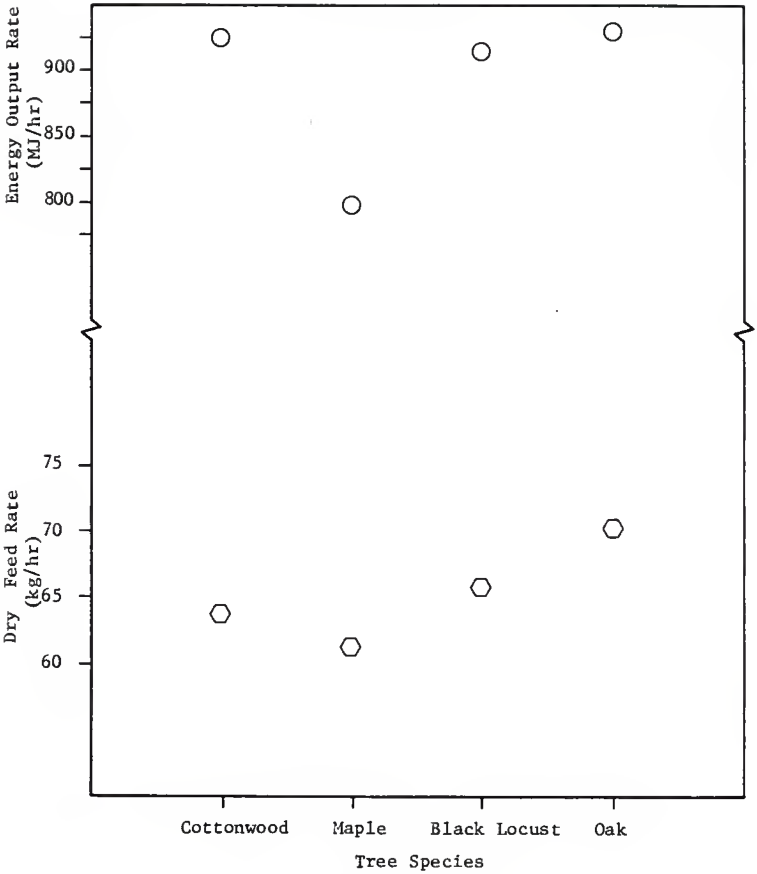

Figure 4. Relationships Between Energy Output Rate and Dry Feed Rate, and Tree Species.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Several conclusions have been reached from the present study of the air gasification of wood chips. They are summarized below.

Material Balance Procedures

The selected material balance procedure, involving both the measured wood chip input rate and char output rate which forces perfect closures on the overall, nitrogen, and carbon balances, is sufficient to describe all stream flow rates for downdraft gasifier investigated in this work. The procedure was selected due to its ability to predict stream magnitudes with reasonable precision and its insensitivity to the measurement errors and system fluctuations. The reliability of this method was further established by application to the data from previous studies.

Influence of Operating Parameters

The conclusions concerning the influence of gasifier operating parameters include the following.

(1) Increasing the chip moisture content results in a linear decrease in both the gasifier throughput (dry feed rate and energy output rate) and the gasifier efficiency (gas-to-feed ratio, air-to-feed ratio, mass conversion

efficiency, cold gas efficiency, and gas heating value). The optimum operating conditions can be achieved by gasifying drier chips. However, the cost involved in drying the chips should also be considered.

(2) Increasing the grate rotation speed gives rise to gradual increases in the dry feed rate and energy output rate. As for the gasifier efficiency indicators, the maximum values are attained at a grate rotation speed of about 4 rph.

(3) Increasing the gas fan speed has insignificant effects on the gasifier efficiency. However, a higher gas fan rotation speed results in higher system throughput.

Influence of Chip Physical Properties

The principal conclusions for the variation of chip voidage and chip bulk density are outlined as follow.

(1) The effect of chip voidage on the gasifier performance measures is insignificant for the gasifier configuration and the range of variables studied.

(2) Over the range of gas fan rotation speed for chips obtained from different tree species, chips with lower bulk densities produce a higher gas-to-feed ratio, lower char yield, higher mass conversion efficiency, higher cold gas efficiency, and higher energy yield. The air-to-feed ratio,

gas heating value, and dry feed rate are unaffected by the chip bulk density.

(3) Over the range of grate rotation speed for chips obtained from the same tree species, but with different bulk density, the efficiency indicators and throughput indicators were not significantly affected by the chip bulk density.

Influence of Tree Species

Using 4 different tree species, the conclusions can be outlined as follow.

(1) Cottonwood chips (low specific gravity chips) produce a higher gas-to-feed ratio, lower char yield, and higher cold gas efficiency than black locust or oak chips (high specific gravity chips). This is due to the large internal pores which permit the volatile to readily escape the wood structure in the low specific gravity wood.

(2) Tree species does not affect the gas heating value and system throughput.

(3) Deteriorated chips are high in ash and lignin contents and consequently give rise to reduce the gasifier efficiency.

RECOMMENDATIONS

Several recommendations are proposed for future study of the air gasification of wood chips in the downdraft gasifier. They are outlined in the proceeding paragraphs.

The wood chip size in a potentially important factor that may influence the downdraft gasifier performance. Thus, future investigation of this variable should be conducted. It is evident that chip thickness plays an important role in determining the char yield and other gasifier performance measures. When the chip size is changed, it will also change the voidage of the chip bed. A variety of chip sizes can be prepared by using hogger and different sizes of chippers.

As mentioned in Chapter 3, the reliability of some of material balance procedures is very sensitive to the measurement of the water contained in the gaseous product. Part of the problem in the present work is suspected to be caused by the partial condensation in the filters prior to the condensers. Thus, it may be benificial to use heating tapes on the filters to avoid possible condensation and improve the water determination.

It may be possible to gain additional insight into the downdraft gasifier performance if the compositions of transition metals in the wood chip are determined. These metallic elements possess catalytic properties and have been reported to influence the char gasification process even when present at low levels. Different types of transition metals yield different colors of condensate collected. The condensate color should be noted in future studies to aid in metal element identification. Additionally, neutron activation analysis should be used to identify the elements and inorganic compounds present in the wood char.

The temperatures recorded during steady state operation period may provide valuable information for gasifier modeling. A more extensive temperature distribution may be required for this purpose. Several thermocouples should be mounted along the two reaction zones: the pyrolysis and char gasification zones. A computer will be needed to provide rapid sampling of the thermocouple readings and easy manipulation of data in future analysis.

Besides the temperature, the porosity of the char gasification zone is another crutial factor required for future modeling. Unfortunately, no techniques are currently available to measure this parameter due to the high temperatures and the difficult accessibility of the char gasification zone. More pressure readings should be recorded during the course of an experiment to provide a better understanding of the pressure drops across the different zones in the gasifier.

Since the air gasification of wood chips is a complicated phenomena involving a number of independent variables such as the grate rotation speed, the gas fan rotation speed, the chip moisture content, the chip voidage, and the tree species, there is a need for better techniques to handle this complexity. The statistical analysis approach employed in this study gives satisfactory single parameter models. For more detail analysis, the Fuzzy Logical Method is recommended. This developing technique permits the development of qualitative models with multiple parameters based on semantic intervals. This technique can probably be coupled with a self-learning algorithm making it more attractive. The approach should be attempted in future studies.

THE AIR GASIFICATION OF
WOOD CHIPS IN A DOWNDRAFT GASIFIER

by

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The air gasification of wood chips was systematically investigated in a 0.6m ID commercial downdraft gasifier to evaluate the influences of the gasifier operating parameters, chip physical properties, and tree species on its performance. In addition, a detailed analysis of material balance options for the evaluation of gasifier performance was conducted.

The gasifier operating parameters consisted of the chip moisture content (5-23% wet basis), grate rotation speed (0-21 rph), and gas fan rotation speed (1400-2600 rpm). The chip physical properties consisted of the chip voidage (0.30 to 0.56) and the chip bulk density (140, 185, and 190 kg/m^3). Four sources of chips from different tree species, cottonwood, maple, black locust, and oak, were used to evaluate the influence of tree species. Measures for the gasifier performance measures included the dry feed rate, char yield, gas compositions, and gas yield.

The results from the gasifer operating parameter variation experiments showed the following.

(1) Increasing the chip moisture content resulted in linear decreases in both the dry feed rate and gas yield, a minimum char yield at 12-15% moisture, and increases in the CO_2 and H_2 in the gas coupled with a decrease in CO.

(2) Increasing the grate rotation speed resulted in gradual increases in the dry feed rate, gas yield, and char yield, and sharp variations in the gas composition.

(3) Increasing the fan rotation speed resulted in linear increases in both the dry feed rate and gas yield, little effect on the gas composition, and a declining char yield.

The results from the chip physical property variation experiments showed the following.

(1) Varying the chip voidage resulted in insignificant changes in the dry feed rate, gas yield, char yield, and gas composition.

(2) Using chips from different tree species showed that low bulk density chips produced a lower char yield, higher gas yield, and similar dry feed rate when compared to the high bulk density chips. Chips with different bulk density, but from the same tree species, showed statistically identical behavior.

The results from the tree species variation experiments showed that an increase in chip density resulted in an increase in the char yield and a decrease in the gas yield.

The results of the parametric studies provide basic quantitative information which will aid in understanding some of the factors that control downdraft gasifier performance and can be used to provide guidelines for adjusting these parameters to obtain the optimum operating performance. The results of the material balance procedure analysis identify the most accurate and least sensitive method.