Gas cleaning strategies for the operation of a wood-chip gasifier coupled to an internal combustion engine

by

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A_p = specific particle surface area (area/mass)

C = total gas concentration (mole/volume)

C_{Bi} = concentration of component i in the bulk (mole/volume)

C_{Si} = concentration of component i near the surface (mole/volume)

C_p = heat capacity (energy/mass/temperature)

C_p* = molar heat capacity (energy/mole/temperature)

D = film diffusivity ($length^2$/time)

D_c = combined diffusivity ($length^2$/time)

D_p = particle diameter (length)

h = heat transfer rate coefficient (energy/time/area/temperature)

h_{Bi} = enthalpy of component i in the bulk (energy/mole)

h_{Si} = enthalpy of component i on the particle surface (energy/mole)

j = Colburn j factor (dimensionless)

k" = first order area reaction rate constant ($time^{-1}area^{-1}$)

K_{eff-ms} = first order effective reaction rate constant on a per mass solid basis (volume/time/mass)

K''_{eff-ms} = first order effective reaction rate constant on a per mass solid and catalyst specific particle surface area basis (length/time)

k_m = mass transfer coefficient (length/time)

k_{ms} = first order chemical reaction rate constant on a per mass solid basis (volume/time/mass)

k_T = thermal conductivity (energy/time/length/temperature)

Pr = $C_p\mu/k_T$, Prandtl number (dimensionless)

$\dot{q}$ = heat transfer rate to the gas per particle mass (energy/time/mass)

r_{ms} = reaction rate on a per mass solid basis (Mole/time/mass)

Sc = $\mu/\rho/D$, Schmidt number (dimensionless)

scf = standard cubic foot (volume)

S_{ex} = particle area (area)

S_g = specific particle and particle pore surface area (area/mass)

S_x = particle area (area)

T_B = bulk temperature (temperature)

T_S = particle surface temperature (temperature)

V = superficial gas velocity based on an empty tube (length/time)

V_{ex} = particle volume (volume)

V_g = specific pore volume (volume/mass)

V_p = particle volume (volume)

W_i = transfer rate of component i (mole/time/solid mass)

Y_{Bi} = bulk gas mole fraction of component i (mole/mole)

Y_{Si} = surface gas mole fraction of component i (mole/mole)

η = effectiveness factor (dimensionless)

μ = absolute viscosity (mass/length/time)

ρ = density (mass/volume)

$\rho*$ = molar density (mole/volume)

ϕ_T = Theile modulus (dimensionless)

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CHAPTER 1

INTRODUCTION

History of Gasification

The phenomenon of gasifying solid fuel has been known for almost 200 years. Murdock in 1792 generated gas from coal to light his house (1). Prior to the advent of low cost natural gas and petroleum products, gasification provided fuel for engines and processes that could not use coal. After the development of liquid and gas products from petroleum, gasification of coal or biomass became useful when crisis or geography made the petroleum products scarce or unavailable. During World War II many parts of Europe relied on gasification to meet homefront energy needs (1). However, once the crisis that precipitated the petroleum scarcity had past, gasification ceased in favor of using more economical and convenient petroleum products. When gasification fell into disuse some of the associated technology and most of the operator skill disappeared. As a result, each time gasification was resurrected, such as in the early 1970's, many of the previous lessons learned about gasification had to be relearned. One of the benefits of this project will be to help keep viable the use of biomass gasification technology as a renewable energy resource to remove dependence on non-renewable fossil fuel resources.

Objectives

The goal of this project is to modify a commercial downdraft gasifier to achieve a gas quality acceptable for an internal combustion engine. The contaminant limits for most internal combustion engines are 10-50 mg/m^3 tar and 10-50 mg/m^3 particulate (2). I also wanted the gas clean up strategy to be simple enough for local manufacture in rural Iowa. It was particularly desirable to try a filter media that could be consumed in the gasifier. This would greatly reduce one of the waste streams from the gasifier. Previous work indicated that the use of a rice husk filter to clean the gas from a rice husk gasifier had been successful (3). Therefore, I attempted to extend this principle to wood chip gasification. I also wanted to add limestone to the feedstock as a catalyst for cracking of tars similiar to the methods used in coal pyrolysis (4).

The gasifier used was a fixed bed downdraft design manufactered by Buck Rodgers Company Incorporated (BRCI) of Olathe, Kansas (Figure 1), now a part of Olathe Manufacturing of Olathe, Kansas. Although the only documentation on this specific unit is the name plate data, it is suspected that this unit was manufactured in 1982 or 1983. The gasifier was obtained in early 1991 from a farm in Missouri where it had been idle for several years.

Figure 1. Buck Rodger's wood chip gasifier (feed auger side). Arrow 1 indentifies the feed auger. Arrow 2 indentifies the gas flare.

CHAPTER 2

GASIFICATION THEORY

Discussion of Pyrolytic Processes

Gasification is a complex combination of reactions. The overall gasification process can be described as an initial pyrolysis of the feedstock followed by the high temperature reduction of pyrolysis products to low molecular weight gases (5). Thus, gasification can be treated as a special type of pyrolysis. In understanding gasification, it is useful to consider pyrolysis of carbonaceous materials in general. The pyrolytic processes can be categorized by their dependence on oxygen (5). The major processes occuring with the complete absence of oxygen are slow pyrolysis, fast pyrolysis, hydrogen gasification and steam gasification. The processes requiring a reduced oxygen environment are oxygen gasification and air gasification.

Slow pyrolysis

Slow pyrolysis is probably the most common and most studied of the pyrolytic processes (5). Slow pyrolysis generally occurs with larger feedstock particles and slower heating rates. These conditions allow the pyrolytic reactions to go to equilibrium (5). The pyrolytic behavior of cellulose is the most documented of all the biomass materials. Since the other major constituents of biomass, namely hemicellulose and lignin, are difficult to isolate in their natural form, there is little definitive information on the pyrolysis of these substances (5). Studies indicate that under slow pyrolysis conditions cellulose is first dehydrated and then forms char and lighter gas species (5). This is in contrast to the fast pyrolysis where the cellulose is broken into tar and volatiles at the expense of the char and lighter gases (5). Hemicellulose is speculated to pyrolyze similarly to cellulose (5). Due to the increased complexity of lignin and the inability to isolate lignin without chemical structural modification, there is no consensus on its pyrolysis mechanism (5).

Fast pyrolysis

Fast pyrolysis is characterized by rapid heating rates, high temperatures and short residence times (5). The fast pyrolysis products are dominated by heavier hydrocarbon species instead of the light molecular weight gases. The olefins are the most significant type of hydrocarbon produced in fast pyrolysis (5). Other valuable products such as benzene, toluene and acetylene have been observed in fast pyrolysis experiments (5). Fast pyrolysis may be useful in producing valuable chemicals from biomass or liquid fuels.

Hydrogen gasification

Hydrogen gasification utilizes hydrogen gas to increase the amount of hydrocarbons produced from the biomass. Since many of the hydrocarbons produced in other pyrolytic processes are unsaturated, the presence of hydrogen allows for more saturated hydrocarbons to be formed. All the other pyrolytic processes rely on water to supply additional hydrogen for the formation of hydrocarbon species. It appears that rapid heating rates and high hydrogen gas pressures are required for the hydrogen to interact with freshly formed char in the biomass (5).

Steam gasification

Steam gasification is primarily used in coal gasification. However, since most biomass feedstocks contain some water, steam gasification is important in all biomass pyrolysis and gasification processes. Steam gasification requires hot incandescent char to interact with the steam to produce hydrogen and carbon monoxide. However, since this reaction is very endothermic the steam addition is usually intermittent to prevent cooling the chemical system too much (6). The most widely used coal gasifiers were based on a "blow and make" configuration. Initially, air would be blown into the gas generator to produce a hot char bed. Next, the air injection would cease and steam admitted into the oxygen deficient char bed to produce gas. This produces a medium energy gas of 270 BTU/scf (6).

Air gasification

Air gasification is the simplest of the gasification processes. The biomass is partially combusted to provide heat for the gasification reactions which are endothermic. The chemical energy of the fuel is greatest when only 28% theoretical oxygen is permitted to interact with the biomass. The energy content of the gas from an air gasifier is typically 120-180 BTU/scf (5). One of the causes of the low energy value is due to the dilution of the combustible products by nitrogen.

Oxygen gasification

Oxygen gasification yields a gas with a much higher heating value of 300-400 BTU/scf (5). Since the nitrogen is no longer diluting the combustible gases, the gas flow rates for a given reaction rate are lower thus making gas cleaning easier (5). The chief disadvantage of oxygen gasification is the expense of procuring and handling oxygen. However, bulk oxygen is readily available since it is required in large volumes for other industries.

Fundamental Thermodynamics of Gasification

The four basic processes in biomass gasification are drying, oxidation, pyrolysis and reduction. For a downdraft gasifier these processes occur in the above order. For other gasifier configurations the order of the processes may be varied. In a downdraft gasifier the biomass particle is first dried driving off water and some combustible volatiles. Next, pyrolysis occurs tranforming some of the wood structure into char, hydrocarbons and gases. The char and some of the volatiles are then oxidized, releasing heat. The heat from combustion can be used for drying, pyrolysis or reduction. Finally, in reduction, the char and some the hydrocarbons are formed into gas (5). Although a multitude of species are formed in gasification, five major reactions have been identified to help describe most of the products at equilibrium (5). These reactions are listed in Table 1.

The combination of the highly endothermic and exothermic reactions allows for the development of a thermally stable system. In general, the exothermic oxidation of carbon (the fifth reaction in Table 1) provides the heat for the highly endothermic reduction reactions. As the system temperature increases, the reduction reactions (third and fourth reactions in Table 1) proceed at a greater rate and remove more heat from the chemical system. Likewise, as the temperature decreases, the rate of oxidation (the fifth reaction in Table 1) increases, thus adding heat to the system. This temperature stabilization phenomena is what makes gasification so easy to control once the char bed is established (5).

Table 1. Gasification reactions (Reed, 1981 p.120)

	Reaction	Heat of reaction (KJ/gmole) 298°K	Heat of reaction (KJ/gmole) 1000°K
(1)	$CO + H_2O \rightarrow CO_2 + H_2$	-41.2	-34.77
(2)	$C + 2H_2 \rightarrow CH_4$	-74.93	-89.95
(3)	$C + H_2O \rightarrow CO + H_2$	131.4	136.0
(4)	$C + CO_2 \rightarrow 2CO$	172.6	170.7
(5)	$C + O_2 \rightarrow CO_2$	-393.8	-394.9

Reaction Kinetics of Gasification

The overall kinetics of gasification are very dependent on the mass transport of species, both inter-particle and intra-particle. For air gasification, the presence of nitrogen will dilute the partial pressure of hydrogen and severely limit the amount of methane produced at atmospheric conditions. Additionally, even though water can be consumed in the water-carbon reaction (reaction 3 Table 1), the highly endothermic nature of the reaction will cool the char so much that the water-carbon reaction ceases with excessive additions of moisture or steam (5). Another important effect is the change in char reactivity after the char is formed. Newly formed char is highly reactive and in the presence of hydrogen will form methane. However, the char quickly becomes stablilized as graphite and the methane production thereafter is minimal. Rapid heating rates and high hydrogen pressures are needed to facilitate methane production.

Mass Transport Phenomena in Gasification

For most gasification processes the transport phenomena of the reactants and products in and out of the char particle will dictate the behavior of the gasifier, thus making many gasifiers sensitive to the sizing and type of feedstock used.

Boundary layer diffusion

Diffusion from the bulk to the particle surface is weakly dependent on temperature. The transport across the boundary layer is most affected by the gas flow rate and the particle size. At steady state the mass transport across the layer can be expressed as equation 1 (5).

$$W_i = k_m A_p C(Y_{Bi}-Y_{Si}) = k_m A_p (C_{Bi}-C_{Si}) \qquad (1)$$

The convective heat transfer across the boundary layer is described by equations 2 and 3. The chemical energy produced or consumed is expressed by equation 3 while the movement of energy across the boundary layer is expressed by equation 2. Since most analyses ignore the radiant and conductive heat exchanges across the boundary layer, equations 2 and 3 should be equal to each other.

$$\dot{q} = -hA_p(T_B - T_S) \tag{2}$$

$$\dot{q} = -\Sigma\, W_i(h_{Bi} - h_{Si}) \tag{3}$$

The negative sign in equations 2 and 3 conforms to the convention of heat transfer from the particle to the bulk as being positive.

For fixed bed gasifiers Satterfield (5) recommends a Colburn j factor in equation 4 for relating the heat and mass transfer phenomena.

$$j = \frac{k_m\ (Sc)^{2/3}}{V} = \frac{h\ (Pr)^{2/3}}{C_p * \rho * V} \tag{4}$$

However, a correlation is needed to calculate the j factor. By quantifying the flow over the particles in the fixed bed, the j-factor can be calculated with equation 5 (5).

$$j = 0.357/Re^{0.359} \tag{5}$$

Next using equations 4 and 5, a relationship for the mass transfer or heat transfer coefficients can be expressed by equation 6 (5).

$$k_m \text{ or } h = f(V^{0.641}) \qquad (6)$$

The mass transfer coefficient's temperature dependency is the same as that of the diffusion coefficient. Equation 7 relates the mass transfer coefficient to temperature as a pair of ratios.

$$\left(\frac{k_{m2}}{k_{m1}}\right) = \left(\frac{T_2}{T_1}\right)^{1.75} \qquad (7)$$

Assuming an Arrhenius behavior can be assigned to the mass transfer coefficient in the temperature range of 1100°K to 1300°K, an activation energy of about 4 kcal is calculated (5). This low activation energy indicates that the mass transfer rate is not strongly dependent on temperature.

To consider the overall kinetic effect, assume the chemical reaction of gasification is first order and the gasification rate is equal to the mass transfer rate. This relation is expressed on a per mass solid basis in equation 8 (5).

$$k_{ms}C_{si} = k_m A_p (C_{Bi} - C_{Si}) \qquad (8)$$

But, rearrange equation 8 to solve for the reactant concentration on the particle surface (equation 9) (5).

$$C_{si} = \frac{k_m A_p C_{Bi}}{k_{ms} + k_m A_p} \qquad (9)$$

Now note that if equation 9 is substituted into the chemical reaction rate expression on a per mass basis, equation 10, a kinetic gasification rate can be obtained (equation 11)(5).

$$r_{ms} = -k_{ms} C_{Si} \qquad (10)$$

$$r_{ms} = \frac{-k_{ms} k_m A_p C_{Bi}}{k_{ms} + k_m A_p} \qquad (11)$$

Next, consider the system behavior in the limiting cases for low temperatures and high temperatures. At low temperatures (< 900°K) the mass transfer coefficient is larger than the chemical reaction coefficient. Thus, equation 11 reduces to equation 12 implying that the effective low temperature gasification rate is a function of the bulk reactant concentration (5).

$$r_{ms} = -K_{eff-ms} C_{Bi} \qquad (12)$$

At high temperatures (> 1600°K) the chemical reaction rate is much greater than the mass transfer rate. Thus, equation 11 reduces to equation 13 implying that the effective high temperature gasification rate is limited by diffusion (5).

$$r_{ms} = -K''_{eff-ms}A_pC_{Bi} \tag{13}$$

Pore diffusion

Gasification occurs primarily within the pores of the char particle. The reaction within the pores can be quantified with the use of an effectiveness factor, equation 14, relating the actual reaction rate to the reaction rate at the particle surface (7).

$$\eta = \frac{\text{rate(actual)}}{\text{rate(entire available surface)}} \tag{14}$$

An expression for the effectiveness factor can be derived based on a pore geometry and reaction rate order. A non-dimensional term within the expression has been identified as the Thiele modulus (7). Based on first-order gas-solid reactions and cylindrical pores, equation 15 quantifies the Theile modulus (7).

$$\phi_T = \frac{V_p}{S_x}\sqrt{\frac{k''S_g}{D_cV_g}} \tag{15}$$

The solution for the effectiveness factor in the first order case yields equation 16.

$$\eta = \frac{\tanh \phi_T}{\phi_T} \qquad (16)$$

For small values of the Theile modulus the effectiveness factor approaches one. This is the case of fast diffusion and slow chemical reaction where the reaction can occur on all of the particle surfaces. For values of Theile modulus greater than 2 the effectiveness factor can be approximated by equation 17 (7).

$$\eta = \frac{1}{\phi_T} \qquad (17)$$

Approximations can also be made in the case where slow diffusion and fast chemical reaction occurs. When diffusion is limiting, a low effectiveness factor is assigned. Thus, the apparent reaction rate constant is proportional to the inverse Theile modulus (equation 18) (7).

$$k_{apparent} \quad \alpha \quad \frac{k_{true}}{\phi_T} \qquad (18)$$

or

$$k_{apparent} \quad \alpha \quad \frac{k_{true}}{\sqrt{k_{true}/D_c}}$$

If the diffusivity can be assigned an Arrhenius relation, as in equation 19, the apparent activation energy can be expressed as equation 20.

$$D_c = A\ e^{-Ediff/RT} \tag{19}$$

$$E_{apparent} = 1/2(E_{diffusion} + E_{true}) \tag{20}$$

However, since the true activation energy is much greater than the diffusion activation energy, equation 20 can be approximated by equation 21 (7).

$$E_{apparent} \approx 1/2\ E_{true} \tag{21}$$

The end result is that at low temperatures (<1100°K) the effectiveness factor is high and the chemical kinetics are rate limiting. At higher temperatures (1100°K to 1600°K) the pore diffusion starts to limit the process and effectively cuts the apparent activation energy in half. Finally, at very high temperatures (>1600°K) the process becomes limited by the mass transfer across the boundary layer (5).

Discussion of Potential Gasification Feedstocks

Both coal and biomass are suitable feedstocks for gasification. Coal's chief advantage is that it is much denser than biomass, which reduces the handling and transportation costs. However, in other aspects biomass is superior to coal. These advantages include the absence of sulphur, higher volatile content and the presence of water already incorporated in the biomass material. With the ever increasing stringency in air quality standards, biomass can become a more economical gasification feedstock (5).

Composition of Wood Biomass

The composition of wood varies considerably even within a single specie. The nature of the wood in a particular tree is a function of the growing environment in addition to its genetic origin. Due to the cellular structure of the wood, its properties also vary among the directional axes.

The chemical composition of wood can be broken into primary compounds and secondary modifying compounds (8). The primary compounds in wood are cellulose (40-50%), hemicellulose (20-35%) and lignin (15-35%). The secondary compounds are substances that greatly effect the properties of the wood even though they constitute a small fraction of the wood cell structure. Some of the secondary compounds found in wood are tannins, oils, resins, gums, latex, alkaloids, dyes and ash. The majority of the secondary compounds are in the living cell and are sometimes referred to as extractables (5).

Cellulose

The most significant compound in wood is cellulose (8). Cellulose is a very stable long chain polymer. It resists decomposition from many acidic and basic substances. The monomer that forms the chain in the cellulose polymer is anhydro-d-glucose ($C_6H_{10}O_5$) (8). The cellulose polymer has been estimated to be 5,000 to 10,000 monomers long resulting in a molecule 2.5 to 5 microns in length (8). The cellulose polymer is very stiff and readily forms hydrogen bonds with adjacent cellulose polymers (5) thus making cellulose fiber durable.

Hemicellulose

Hemicelluloses are identified as those polysaccharides which are soluble with mildly basic treatments (8). The exact definition of hemicellulose is difficult to determine since the processes to extract the hemicellulose from the cellulose alters its chemical structure (8). Hemicellulose polymers are much shorter than cellulose (50 to 200 polymer units) and have a branched structure rather than a long straight chain (5). The two major types of hemicellulose are xylans and mannans. Xylans are polymers of pentose sugars called anhydro-d-xylose ($C_5H_{10}O_4$) (5). Xylans are the major hemicellulose constituent. Mannans are polymers of hexose sugars. The primary hexose monomers found in mannans are anhydro-d-glucose ($C_6H_{10}O_5$), anhydro-d-mannose ($C_6H_{12}O_5$) and anhydro-d-galactose ($C_6H_{12}O_5$). Mannans are more prevalent in softwood hemicellulose than hardwood hemicellulose (5).

Lignin

Lignin is the most insoluble of the cell wall substances and is very stiff. The exact chemical structure of lignin is unknown since the extraction process probably modifies the natural structure inside the cell wall (5). It is assumed that the basic monomers are various forms of the phenyl propane unit (8). The lignin polymers are interspersed among the cellulose polymers and bonded to the cellulose by ether bonds (5). The lignin is very important in adding rigidity to the cell walls. Additionally, when lignin is pyrolyzed, it yields a large amount of char (5).

Types of Gasifiers

There are many gasifier configurations that have been used over the years. Most of the designs can be classified as either updraft, downdraft, crossdraft or fluidized bed. Each group has its own advantages with respect to a certain application (5).

Updraft

The updraft gasifiers are counter flow reactors. The feedstock enters the reactor from the top while air is admitted at the bottom. The fuel gas exits at the top. The primary advantage of the updraft gasifier is its simplicity. As the air meets the feedstock a hot combustion zone is formed at the bottom. The hot gases travel upward to pryrolyze and dry the downward traveling biomass. However, the fuel gases do not have an opportunity to pass over a hot char bed, thus, the product gas is heavily laden with tars and oils. The best application of an updraft gasifier is a close coupled furnace so that the tar laden gas can be immediately combusted. (5)

Downdraft

The downdraft gasifiers are parallel flow reactors. Both the feedstock and air are admitted to the top of the gasifier. As the feed stock moves down, it is dried and pyrolyzed before experiencing combustion. The hot char resulting from combustion and reduction resides at the bottom of the bed, thus providing a site for cracking of tar in the product gas. To facilitate tar cracking, some gasifiers have a narrow throat at the bottom of the chamber to concentrate the heat in the char bed. Other designs admit air to the lower portion of the bed to develop combustion zones to keep the char bed temperature high for tar cracking. Both strategies are intended to keep the char bed temperature around 1800°F (1000°C) so that the tars are reduced. The lower tar levels produced by the downdraft gasifiers allow the powering of internal combustion engines (5).

Crossdraft

Crossdraft gasifiers rely on a horizontal vortex to suspend fine biomass particles in hot air. The gases driven off of the particles are combusted in close proximity to the gasification chamber to heat the incoming feedstock. The crossdraft gasifier is well suited for fine feedstocks such as sawdust which would bridge in a fixed bed gasifier (5).

Fluidized bed

Fluidized bed gasifiers are reactors containing fine grained inert or catalyzing solids mixed with the feedstock particles. The entire mixture is then fluidized with an upward gas flow. The suspension of the solids in the gas allows for very high heat transfer rates between the particles and surfaces of the reactor. The exact behavior of a particle of feedstock in the fluidized bed is not as specifically defined as in the fixed bed gasifiers. However, fluidized bed gasifiers with a means to recirculate the product gas back into the bed have produced good results (5).

Products of Gasification

The gasifier products can be segregated into gases, condensible tars and chars. Inside the gas and tar groups are a wide variety of species, not all of which are useful.

Gases

The composition of the gas from a properly operating fixed bed biomass gasifier primarily consists of nitrogen, carbon monoxide, carbon dioxide, and hydrogen. There are some light hydrocarbon species formed, such as methane, propane and butane, but, these gases constitute a very small fraction of the product gas. Additionally, water vapor will be present in the gas as a diluent. The most useful gases for energy conversion are hydrogen and carbon monoxide.

Tar

The tar is made of a multitude of hydrocarbon compounds. The most significant compound identified is levoglucosan. Many of the compounds can be reduced to the gaseous components when the tars pass through a hot char bed. This effect is used in downdraft gasifiers as a means to control the production of tar. If the gas is immediately burned, the tars add heating value and illuminants to the flame.

However, if the gas is used in an engine, the tars can condense on the engine surfaces and damage the engine.

Char

The char is mostly carbon from the lignin structure of the wood. The char is very porous and when at high temperatures is useful in providing sites to crack tars. The char particles entrained in the gas are normally treated as a contaminant, but, they can provide heating value if the gas is burned directly. Fine char particles by themselves may not be as damaging as dust or sand in the engine. However, the char mixed with the tar can rapidly gum up engine parts and cause damage. As a result, most clean up strategies aim to reduce char as well as tar in the product gas.

CHAPTER 3

EXPERIMENTAL

Feedstock

Feedstock source

The feedstock for the majority of the test program came from the Iowa State University (ISU) poplar test site south of Colo, Iowa. Most of the trees used had been harvested during 1990. The trees were approximately 5 years old with trunk diameters of 4 to 6 inches (10.2 to 15.2 cm). The gasifier requires that the feed stock contain less than 15% moisture by weight. Due to the very wet weather during the spring of 1991, I had to dry the feedstock that had been stored outdoors.

Chipping of wood

The trees were chipped using a power-take-off driven wood chipper. The chips produced were 1.5 inch (3.8 cm) square and .25 to .5 inch thick (0.64-1.3 cm) (Figure 2). I chipped the poplar trees in two different manners. The first method was to strip the trunk of twigs and small branches before chipping. This yielded a high quality feedstock due to the lack of twigs and shredded bark. The second method was to chip the whole tree. This method saved some labor but

Figure 2. Wood chip feedstock (poplar).

resulted in more bark fibers and twigs in the feedstock. However, the lower feedstock quality did not degrade gasifier performance.

I also examined the use of very young poplar trees as a feedstock. The ISU Forestry Department has modified a two--row corn picker to harvest one-year-old poplar trees which are about 1/2 inch (1.27 cm) in diameter. The picker discharges the chipped product into a grain trailer. I harvested some of these small trees at the Hines Research farm north of Ames, Iowa during July 1991. However, due to the large amount of wet leaf mass and shredded bark mixed with the wood, it was ascertained that it would not be a good feedstock for the gasifier. The wet leafy biomass might be a useful feedstock for an indirectly heated gasifier which is not as sensitive to moisture in the biomass.

However, I did have a small amount of the young poplar wood chips left over from the previous year for examination. This sample was harvested after the leaves had fallen and was about one-half wood and one-half bark shreds by volume (Figure 3). If these young poplar trees were harvested in the winter and the product sifted to remove bark fibers, this type of feed stock might be usable in the gasifier. But, this extra processing starts to diminish the great saving in manpower realized by the one step harvesting technique devised by the ISU Forestry Department.

Figure 3. Sifted poplar chips harvested with a modified two row corn picker.

Early in the test program the gasifier was operated on chipped oak that had been stored indoors (Figure 4). The very wet spring had made all the cut poplar trees very damp. Due to the density and toughness of the oak wood, it did not chip easily. Some of the oak wood splintered instead of cleaving off in a chip. The resulting oak splinters and fibers would get bound up in the chipping flywheel and plug the chipper. The chipper would then need to be dismantled and the wood mass chiseled out of the flywheel cutting blade.

Feedstock drying techniques

For small amounts of wood, less than 100 pounds (45.5 kg), I bagged the wet chips in burlap bags and dried them in the ISU Agronomy Department grain dryer. This method dries the chips quickly but is very labor intensive. For amounts of 1000-1500 pounds (454-680 kg), I spread the chips 4-6 inches (10.2-15.2 cm) deep on an indoor concrete floor. Warm building air was then circulated by fan. This method was not as labor intensive as bagging, but was still another feedstock handling process. Drying inside a heated building on a concrete floor was very good when the weather was cold and damp. Even when the chips were covered outdoors in a grain trailer, the wood chips absorbed enough moisture in cool damp weather to render them unusable in the gasifier.

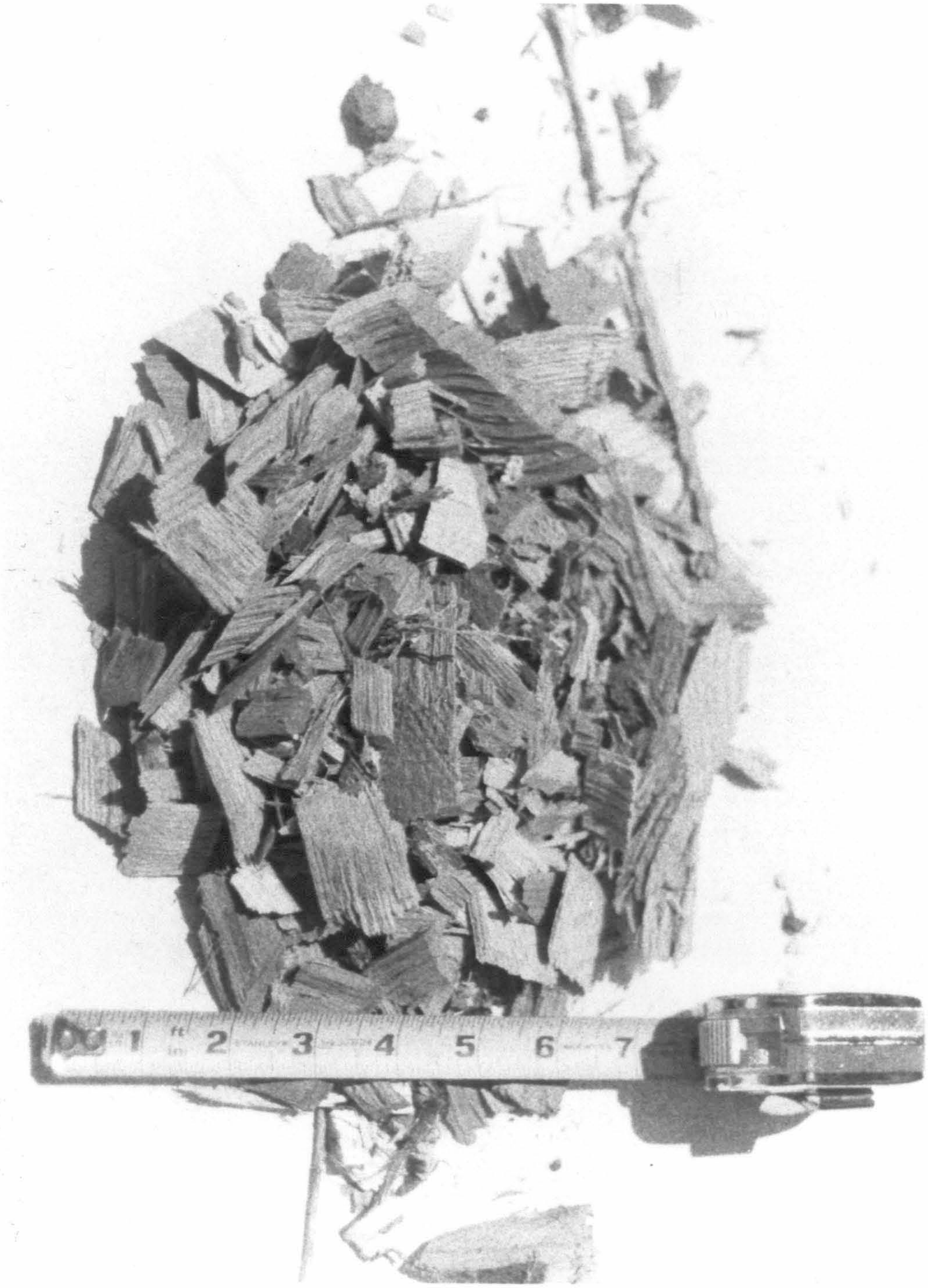

Figure 4. Wood chip feedstock (oak).

The least troublesome method of reducing the moisture was to pile the cut poplar trees and cover them with a waterproof tarpaulin during the summer season. The hot, dry weather drove the moisture from the wood while the waterproof cover minimized moisture absorption during the infrequent rainstorms. This method may not have been as effective during a cool wet summer. After several weeks of hot dry weather, the wood could be chipped and used without any further processing.

Feedstock storage and moisture control

I spent considerable effort drying the wood and keeping it dry since the moisture content could adversely affect the gasifier. To keep the wood dry, I used a covered grain trailer to store my chips. As long as the weather was warm and the trailer cover maintained watertight integrity, the trailer kept the wood adequately dry. As the weather became colder and damper the trailer was less effective in keeping the wood dry. I suspected that the hot weather assisted in drying out the wood if moisture entered the feedstock. When the weather became colder, moisture reentered the wood. The easiest solution to this moisture problem was to bring the trailer into a heated building. Within several weeks, the wood dried out in the trailer with a minimum amount of stirring and effort. Proper biomass storage is a key factor in successful gasification.

The moisture content was determined by measuring the chip sample weight reduction after drying the sample with microwave heating. I departed from ASTM Standard E 1358-90 in that my sample sizes were not 50 grams and the radiation periods were not identical to the standard procedure.

Equipment

Gasifier

Two views of the gasifier are shown in Figures 1 and 5. The wood is fed into the gasification chamber by the wood chip feed auger. The gasifier required pre-heating to prevent tar condensing on the gas fan. With the gas fan discharge damper in the low flow position, a 400,000 BTU (421,900 KJ) propane torch is inserted into a hand hole in the gasification chamber (Figure 5). Care should be taken to ensure that the torch is clear of the gasification chamber rotating tuyres (Figure 6). After approximately 20 minutes of heat up, the fan metal temperature should be greater than 500°F (260°C), the dew point of tar. Once the pre-heating is complete, wood could be fed to the gasifier while the torch is still in the gasifier. It is important to slowly add wood to the chamber so that the bed is kept burning as the bed depth increases.

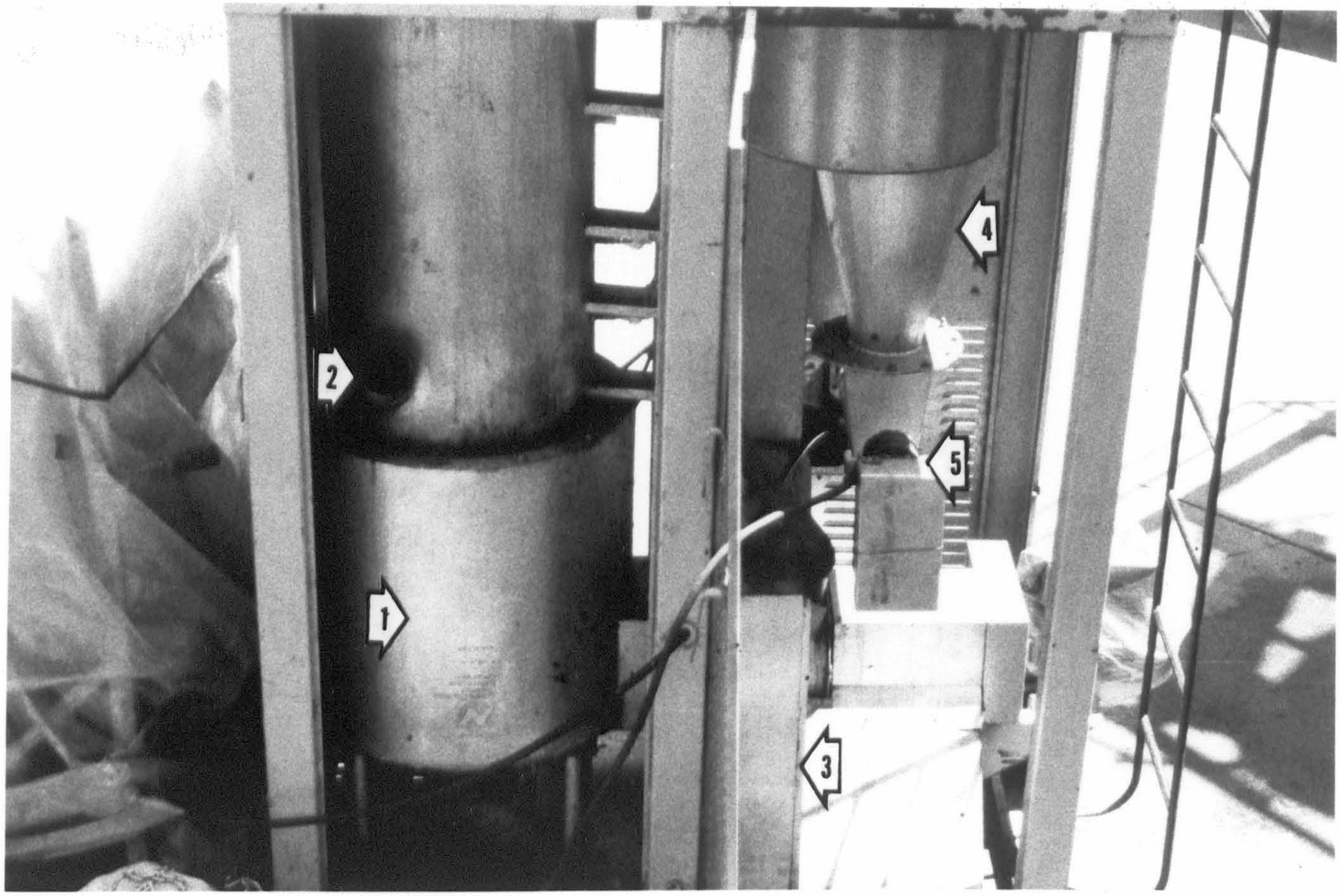

Figure 5. Buck Rodger's Wood Chip Gasifier (Access Port Side). The following numbered arrows identify gasifier components: 1-Gasification chamber, 2-Access port, 3-Gas fan, 4-Cyclone separator, 5-Char auger and motor.

Figure 6. Gasification chamber. The arrow points to one of the tuyres through which air is injected into the gasification chamber. The entire stirrer assembly rotates clockwise.

This will enable establishment of a good char bed to help crack some of the tars formed. The bed will produce combustible gas very quickly, but it will be heavily laden with tar. The gas should be diverted to the stack on the gasifier and burned with a propane torch if a flame can not be sustained. Once the burning bed is 15 to 18 inches (38 to 46 cm) deep, additional wood chips are added to increase the bed depth to 30 to 36 inches (76.2 to 91.4 cm). As the char bed becomes deeper and hotter, the tar levels will decrease and the diverting valve can be operated to allow the product gases to pass into the heat exchanger and filter. It normally takes about 30 minutes of operation to get the char bed fully developed. When the gasifier is operating properly, the fan inlet temperature should be about 1100°F (593°C) and the fan suction should be 1 inch (254 mm) water column vacuum. After the biomass char bed is established, the rotation rate of the stirrer inside the gasification chamber should be adjusted to 3-5 minutes per rotation. (The rotation rate can be set between 3 to 20 minutes per rotation.)

To move air and product gases through the gasification bed, a gas fan pulls suction on the bottom of the gasification chamber and blows the gas stream into a cyclone separator. The larger char particles trapped by the cyclone are removed by a hydraulically-driven auger attached to the bottom of the cyclone. The remaining gas and char exit the cyclone to a flare or end-use system (Figure 7). During early tests of the gasifier, gas leaks around the char auger were discovered. To prevent this leakage I fabricated a steel tube elbow to seal a 55 gallon drum to the char auger.

The biomass bed level control system operated erratically and was not able to maintain proper bed height. I opted for visual and manual control of the wood chip bed for these series of tests. Additionally, the feed auger deposited the wood chips toward the outer edge of the chamber resulting in an unlevel bed. This was corrected by modifiying the auger to deposit the wood chips toward the center of the bed.

Heat exchanger

To cool the gases before use in an internal combustion engine, I designed a heat exchanger placed downstream of the gasifier (Figure 7). The heat exchanger was constructed of 5 inch (12.7 cm) steel tubing. To size the piping I assumed a 1/4 inch (0.6 cm) carbon deposit on the inner surface inhibiting heat transfer. The required tube length for a temperature drop of 1100°F to 440°F (593-226°C) was 7 to 36 feet (2.1-11 m), depending on the gas flow which was assumed to be between 87 and 400 ft^3/min ($2.4-11.5\ m^3/min$).

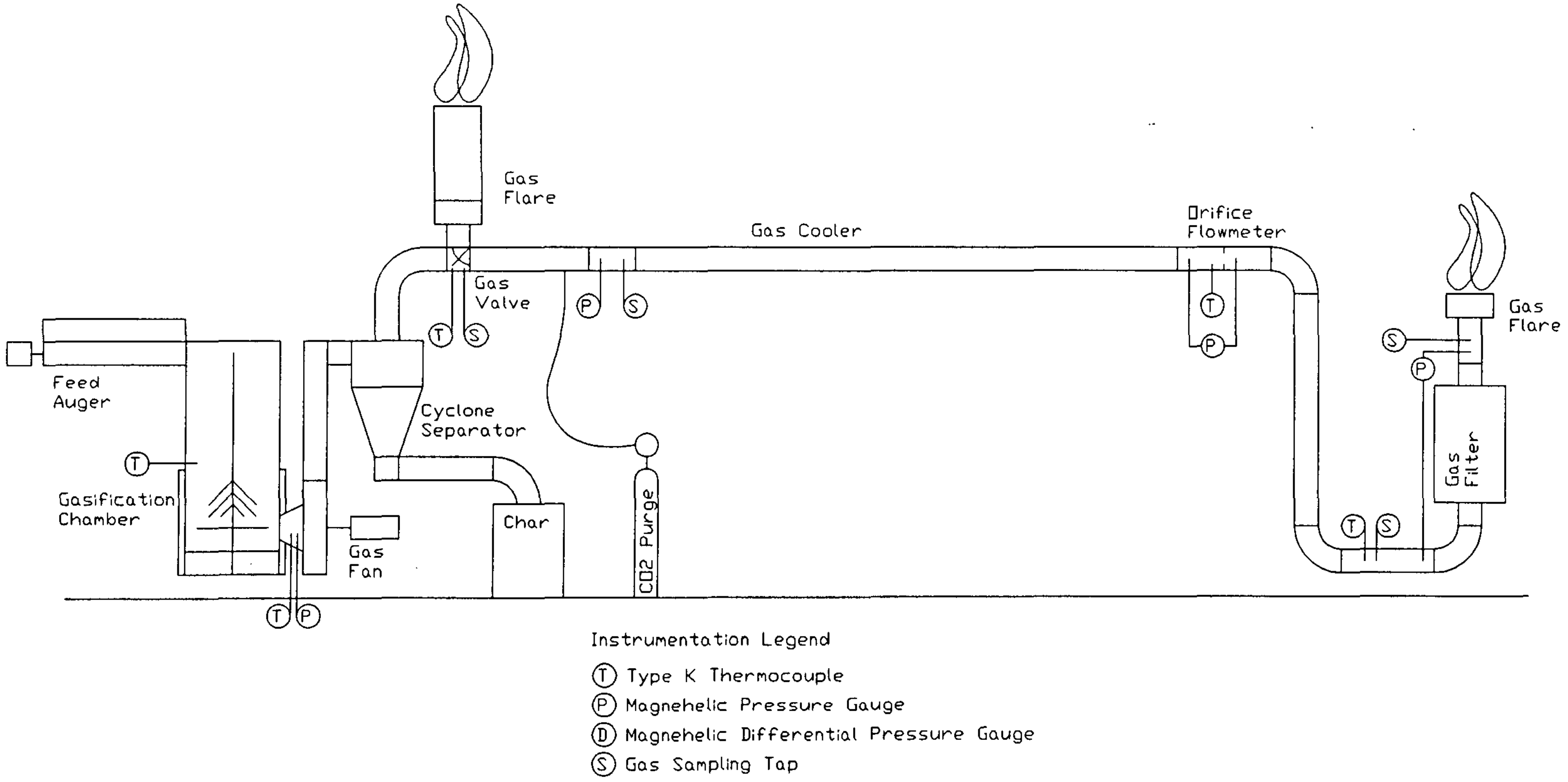

Figure 7. Gasifier, gas cooler, gas filter and system instrumentation.

The actual piping length installed was 26 feet (8.3 m) long. These calculations are based on stagnant air in the surroundings at 100°F (38°C) and no heat transfer by conduction in the direction of the flow. I observed exchanger exit temperatures of 450°F (232°C) during high flow conditions without a filter attached and 250-300°F (121-148°C) during low flow conditions caused by filter backpressure.

Carbon dioxide purging system

Based on accounts of explosions due to gas build up in improperly ventilated gasifiers (1), I added a CO_2 purging system to remove pockets of producer gas from the cooling and filtering system after shutdown (Figure 7). By purging with CO_2 I hoped to minimize the possibility of an explosive mixture being present within the confines of the cooling and filtering system when starting up the next day.

Gas filtering

The gas should contain less than 10-50 mg/m^3 contaminants for use in an internal combustion engine (2). To reduce the char and tar, I opted to first test a filter before relying on more complex strategies such as scrubbing or electrostatic precipitation. I chose a design that could be fabricated with the tools and supplies available in most small machine shops.

The basic design consists of a 55 gallon DOT class 17C shipping barrel with a 9-gauge, 3/4 inch (1.9 cm) mesh, expanded metal filter media basket inside the barrel (Figure 8). The gases pass through the filter element from the outside radius to the center plenum where the gases exit out the top of the filter. The only element of the filter with sensitive tolerances is the mating of the filter discharge to the piping downstream of the filter. This portion of the filter is sealed with a pair of O-rings to prevent gases bypassing the filter (Figure 9).

I tested two types of filter media. Originally I wanted to use finely ground wood chips which were 1/8 to 1/4 inch (0.32-0.64 cm) long to trap the tar and char. However, the gas temperature was still too high for the poplar wood chips and the filter media started to pyrolyze (Figure 10). I then switched to fiberglass media to determine if the filter was large enough for my system. The fiberglass was packed in two different manners. In the first method the fiberglass was torn into hand sized pieces and packed uniformly in the filter retainer element. In the second method the fiberglass batting was cut and placed in the element such that a 3 inch (7.62 cm) layer thickness was toward the outside of the

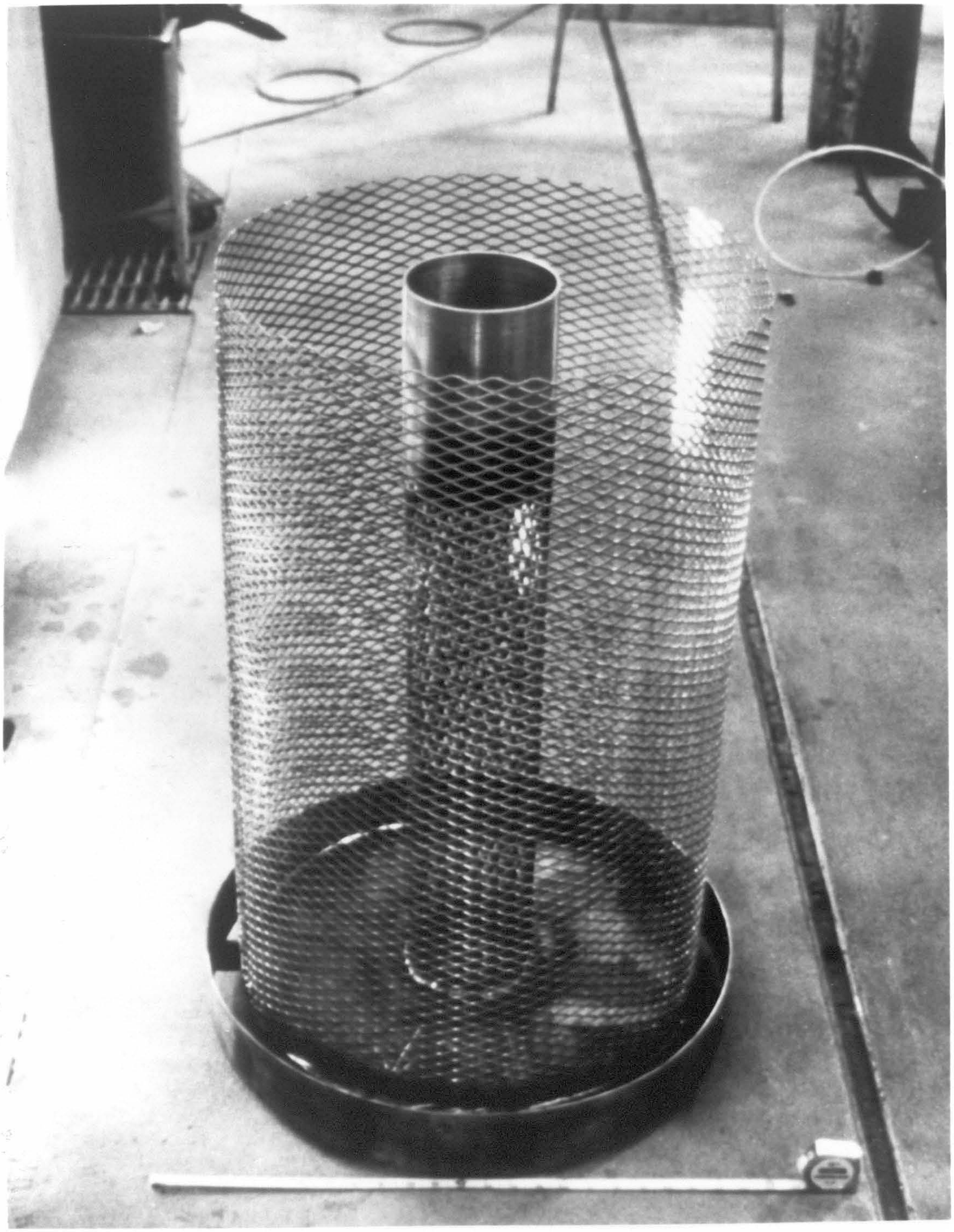

Figure 8. Filter media basket.

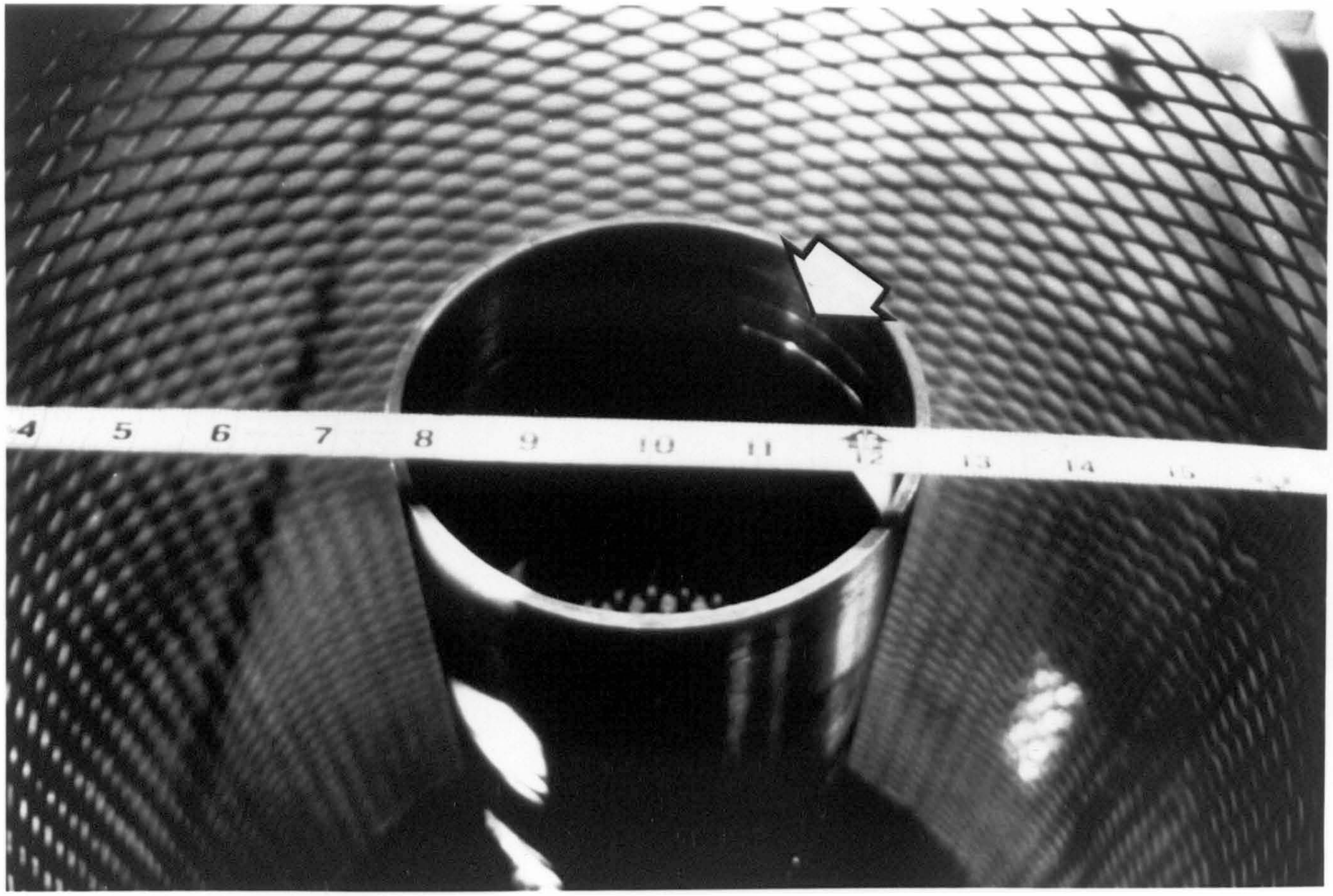

Figure 9. Filter outlet. The arrow indentifies the location of the O-ring seals.

Figure 10. Wood chip filter media. The arrow indentifies a pocket of pyrolyzed filter media.

element and a 3 inch (7.62 cm) layer was toward the inside of the element with a 1 to 2 inch (2.54 to 5.1 cm) gap between the fiberglass layers. I did not note any difference in the two different fiberglass filters.

Instrumentation

To measure the contaminant levels I used a dual-element sampling system (Figure 11). The gas first entered a 4 inch long plastic tube packed with fiberglass to capture the solids and tar. Downstream of the filter tube was placed a cold trap to remove the water vapor and low dew-point tars. A vacuum pump provided suction to draw the sample through the filter and trap. After an average of 1 scf (.028 m^3) of gas had been drawn through the filter, the filter and trap assembly was removed and sealed. The filter and the trap were then weighed and the weight gain recorded. To remove the moisture from the sample filters, the filters were split open and allowed to dry for 5 to 7 days at 80°F (27°C) until no weight loss was noted. The sampling was not isokinetic so the particulate measurement may be lower or higher than actual.

The composition of gas produced by the Buck Rodgers gasifier has been documented by earlier work and is typical of a downdraft type gasifier (Table 2) (9,10).

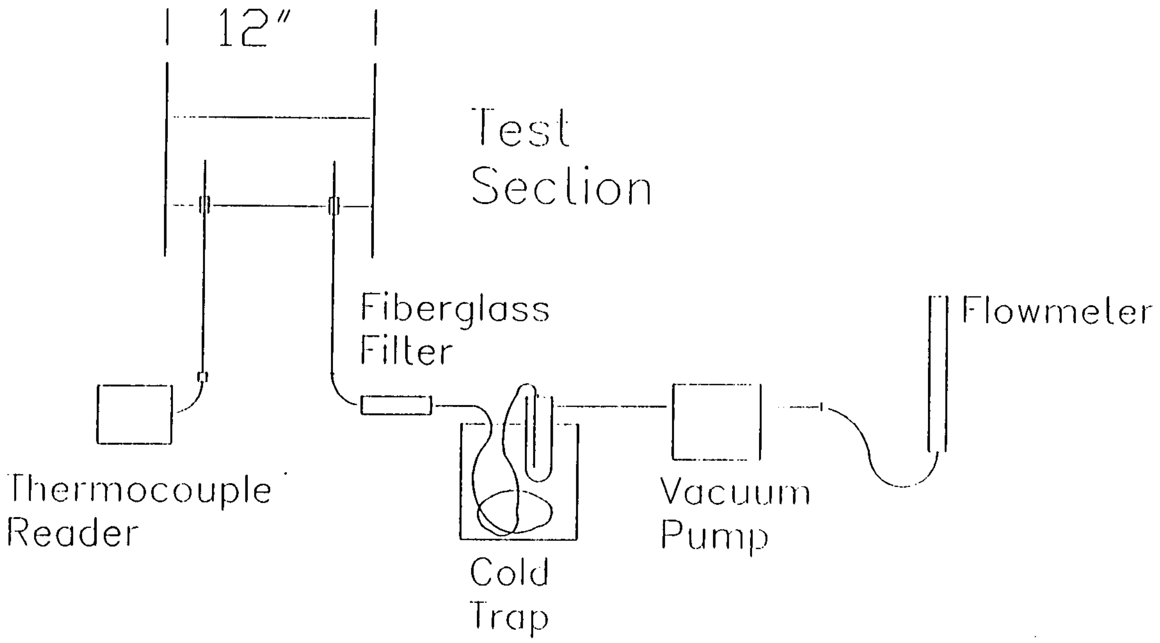

Figure 11. Gas sampling apparatus.

The research emphasis was the reduction of char and tar levels in the gas for use in an internal combustion engine. Therefore, sampling was limited to particulate and tar measurements.

Table 2. Downdraft gasifier gas composition (Walawender, et.al., 1986, p.619)

Gas Specie	Percent Volume
N_2	46 %
CO	20 %
H_2	15 %
CO_2	15 %
CH_4	3 %
Other Hydrocarbons	1 %

The gasifier was instrumented with Type K thermocouples. I monitored the top of the bed, gas fan inlet, cyclone outlet, gas cooler inlet, orifice plate entrance and gas cooler outlet (Figure 7). The thermocouples were read with a hand held reader (Omega HH-71 K2) and a multiplexing switch. The pressures were measured with Magnehelic pressure gauges. I monitored gas fan suction, gas fan pressure, orifice differential pressure and filter differential pressure.

The gas flow rate was calculated by measuring the pressure drop across a 3 inch (7.62 cm) diameter sharp edge orifice 15 feet (4.6 m) downstream of the gasifier (Figure 7). This sized orifice developed a measurable pressure drop for the range of gas flows I experienced. I assumed fully developed turbulent flow due to the high Reynolds number for the expected flow.

CHAPTER 4

RESULTS AND DISCUSSION

Flame Observations

The burning gas flame color provides a qualitative measure of gasifier gas quality and filter performance. I noted a bright orange flame color for most of my unfiltered runs. The orange flame color indicated the presence of tar and char in the product gas. Several times while shutting down the gasifier I noted a blue flame in the gas flare. The blue flame was observed as the gas fan was slowing down in speed after the fan motor was de-energized. The free wheeling fan would draw a reduced gas flow through the char bed. It is suspect that the lower gas flows through the bed increased the gas residence time in the hot char bed, facilitating tar cracking. The gas residence time in the char bed at full fan speed was approximately 0.5 second. Based on an estimated free wheeling fan speed of 10% of the energized fan speed, the gas residence time would increase to as much as 5 seconds.

Wood Consumption

I calculated wood chip feed rates based on the volume of wood fed into the gasifier. Once the char bed was established I calculated feed rates of 100 pounds/hour (45.4 kg/hr). When this feed rate was used the gasifier produced about 60-90 scf/min (1.7-2.5 m^3/min) of gas. This concurs with the gas production rates reported on a similar Buck Rodgers Gasifier (9).

Filter Performance

The orange flame color downstream of the filter indicated that the wood chip filter was not effective. The gas entering the filter was about 300-400°F (148-204°C) which was high enough to partially pyrolyze the wood. The fiberglass filter performed much better, resulting in a blue flame in the gas flare. However, the head loss due to the plugging of the fiberglass filter media reduced the flow rate, thus the flame was much smaller than the unfiltered flame. One of the sources of the high filter back pressure was the caking of tar and char on the outside surface of the filter media (Figure 12). The caking effect, when combined with the high contamination levels, resulted in a short filter life. The presence of tar in gas samples upstream of the filter suggest that the primary mechanism for removing the tar was the filter and not enhanced tar cracking from increased residence time in the char bed at the reduced flow rates.

Figure 12. Outer layer of fiberglass filter media. Arrow 1 indentifies the char and tar cake on the outside of the filter. Gas flow is in the direction of arrow 2.

Char and Tar Contamination Levels

The sampling system trapped char and tar in the fiberglass filter. The majority of the water vapor in the gas was condensed in the liquid trap. After I dried the fiberglass sample filter I calculated the reduction in weight of the filter and added that value to the liquid weight condensed in the trap. Therefore, the contaminants were grouped as solids (tar, char and limestone) and liquids at 90-100°F (32-38°C). The liquid trapped was primarily water. The results are in Table 3 and Figure 13.

Table 3. Average solid contamination (tar and char) in producer gas.

Sample Location	Solid Contaminant* (mg/m3)
Upstream of Filter	$4.3 \times 10^4 \pm 0.96 \times 10^4$
Downstream of Filter	670 ± 390

* to the 95% confidence level

When comparing to previous downdraft gasifier performances in Table 4 (2) and Figure 13, I noted contamination levels for this single-cyclone gasifier exceeding values for other downdraft gasifiers whether or not cyclone separation was employed. These results suggest both

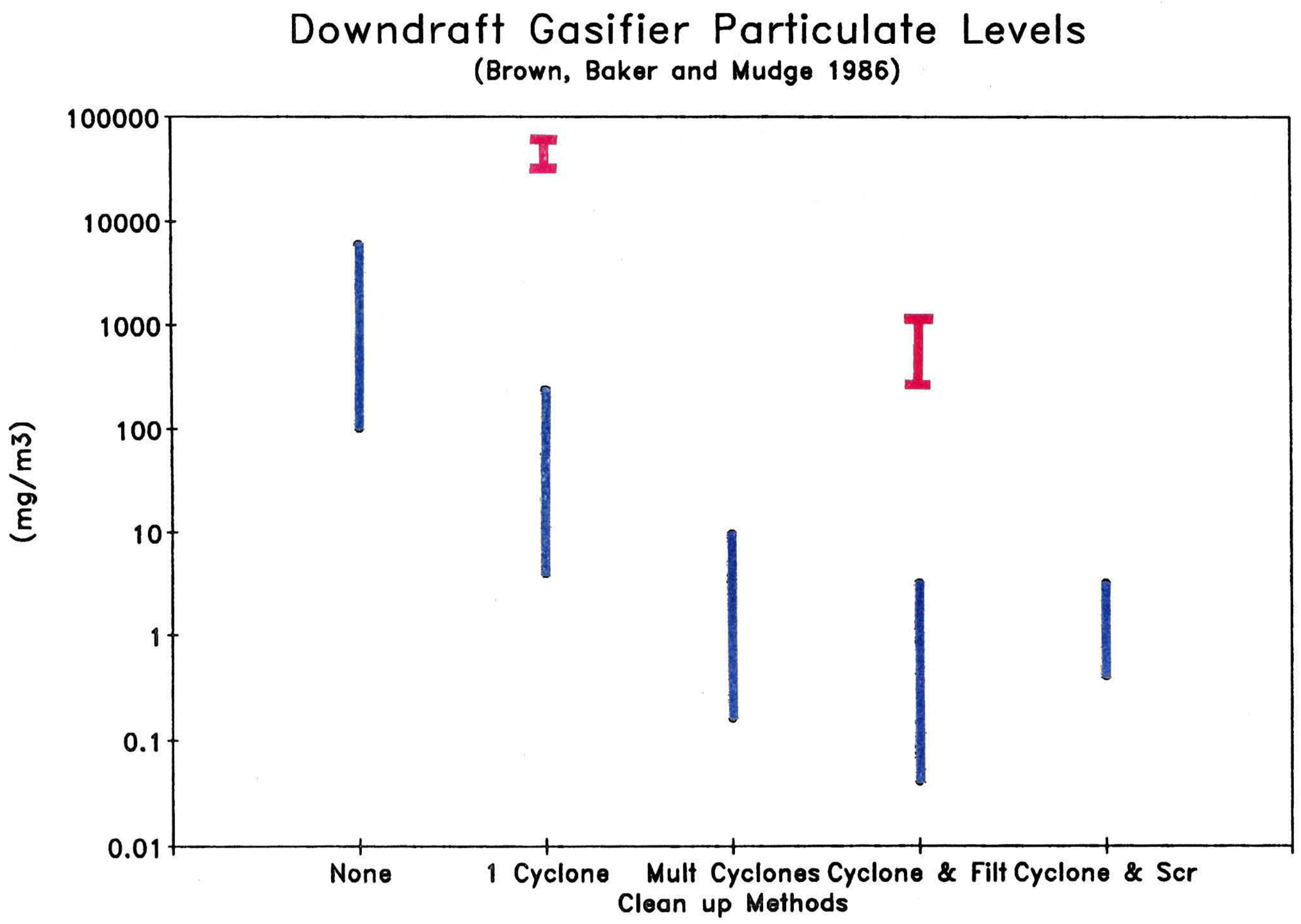

Figure 13. Downdraft gasifier contamination. Buck Rodgers gasifier data are indicated in red to the 95% confidence interval. Brown et. al. 1986 study data are indicated in blue.

gas bypassing the char bed and poor particulate separation efficiency for the cyclone.

The fiberglass reduced the char and tar levels about 2 orders of magnitude but created an excessive back pressure on the gasifier after 1 hour of operation (Figure 14).

Table 4. Particulate contamination of downdraft gasifiers with various cleanup methods (Brown, et. al., 1986, p.671)

Cleanup System	Contamination Level (mg/m3)
None	100-6000
Single Cyclone	4-240
Series Cyclones	0.16-9.6
Cyclone and Filter	0.04-3.2
Cyclone and Wet Scrubber	0.4-3.2

Looser packing of filter media might extend filter life and reduce the pressure drop; however, the effluent contamination levels are still two orders of magnitude above engine limits (2).

Tar Solubility Test

To consider additional scrubbing and cleaning strategies I conducted simple solubility tests of tar in diesel fuel and

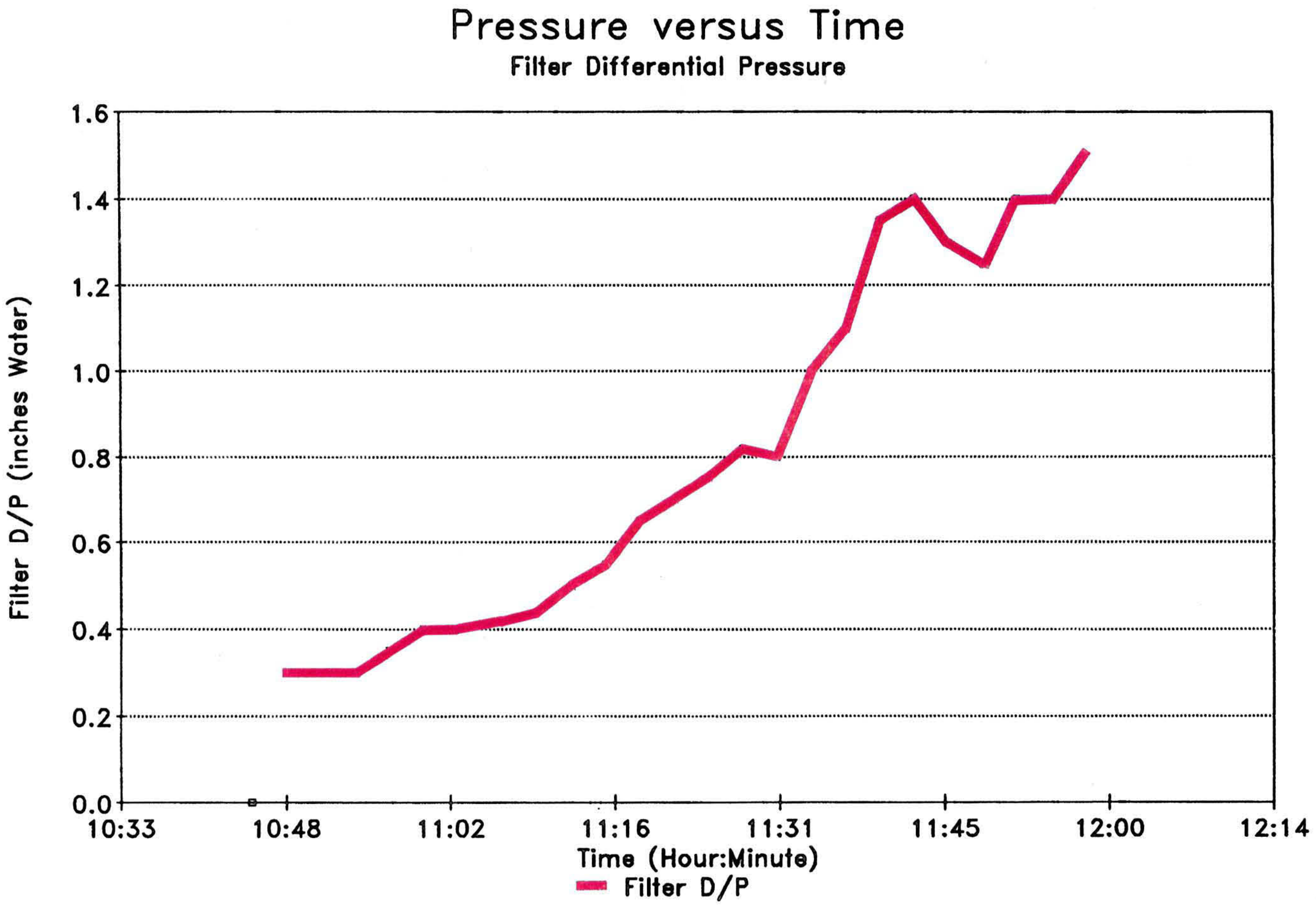

Figure 14. Filter differential pressure versus clock time, October 26, 1991.

methyl alcohol. At 70°F (21°C) the tar was insoluble in diesel fuel but readily dissolved in methyl alcohol. The ability of methyl alcohol to dissolve the tar may assist in suppressing the deposition of tar on internal combustion engine manifold and valve assemblies.

Methyl alcohol was also used to separate the tar from the other solids in the samples. When a solid contaminant sample was washed, the undissolved solids were trapped by a medium porosity filter. The results of the sample washing are in Table 5. The major contaminant is tar.

Limestone Effects

For one test run I added finely ground limestone (agricultural lime) procured from the ISU Physical Plant. I wanted to see if limestone would be a good catalyst for cracking tar in the gasifier. I added 2 pounds (.91 kg) of lime for every 5 pounds (2.3 kg) of wood chips. The lime was added to the wood prior to feeding the biomass to the gasifier. After subjecting the solid contaminants to methyl alcohol washing, only 25% by weight was found to be tar (Table 5). However, some of the reduction in the percent weight of tar is due to the weight of the limestone appearing in the undissolved solids. After the weight of the limestone was accounted for and an error analysis was applied, no change in the average tar level could be attributed to the limestone addition (Figure 15). The statistical error in the data does not allow the rejection of the null hypothesis. (The null hypothesis being that there is not a change in tar level due to limestone addition.) Therefore, the limestone can not be credited with reducing tar by thermal cracking in the gasifier. I did note that the solid contaminant was markedly less sticky when limestone was added. It is possible the limestone provided a condensation site for the tars. This result suggests that limestone could serve as a dry scrubber media to remove tar from the product gas. The resulting solid, if efficiently collected in a cyclone, could be returned to the gasifier for consumption rather than disposal.

Table 5. Solid contaminant composition

Contaminant Type	Contaminant Level* (mg/m3)
No limestone added	
Char	$1.1 \times 10^4 \pm 0.75 \times 10^4$ (25%)
Tar	$3.2 \times 10^4 \pm 1.6 \times 10^4$ (75%)
Total	$4.3 \times 10^4 \pm 0.96 \times 10^4$
Limestone added	
Char/Limestone	$8.7 \times 10^3 \pm 19.6 \times 10^3$ (75%)
Tar	$2.9 \times 10^3 \pm 7.4 \times 10^3$ (25%)
Total	$11.6 \times 10^3 \pm 25.1 \times 10^3$

* to the 95% confidence level

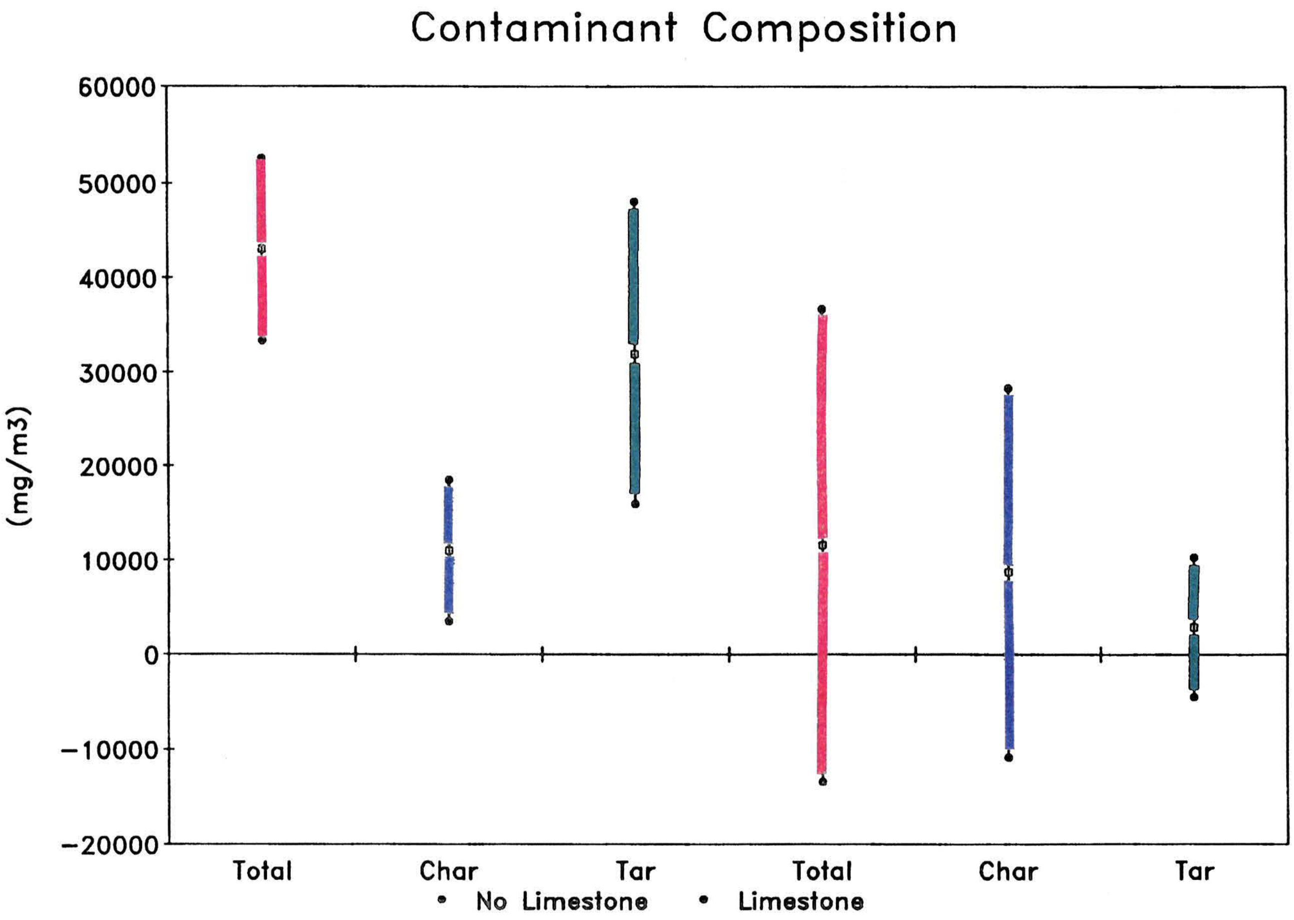

Figure 15. Effect of limestone on contamination composition. Non-limestone data are indicated by the left three data bars. Limestone data are indicated by the right three data bars. Data bars around the mean are to the 95% confidence interval.

Conclusions

The char and tar levels were measured to be higher than downdraft gasifiers of other designs. The higher contamination levels may be due to gas bypassing the char bed and an under-sized cyclone separator. The wood chip filter media is not effective with the present configuration. Much lower gas temperatures are required for the wood media filter. The filter size and type is insufficient for sustained operation with the current gas contamination levels. I will need to continue development of the gas cleanup system to meet engine requirements for longer durations of time. A secondary cyclone and a scrubber may be necessary to meet the engine requirements. The limestone could not be credited with reducing tar levels by catalytic destruction of tar in the gasifier. However, the limestone may be a useful getter in a dry scrubber to trap tar for subsequent removal from the gas stream using a cyclone separator.

CHAPTER 5

RECOMMENDATIONS FOR FURTHER RESEARCH

Secondary Cyclone

The filter system became clogged so quickly that it is impractical for sustained operations. For this particular gasifier it may be necessary to add a secondary cyclone to remove additional solids before filtering or scrubbing.

Methanol Injection

The ability of methyl alcohol to readily dissolve the tar may help suppress the detrimental effect of condensible tar on the internal engine manifold and valve assembly. One of the issues to be resolved is whether methyl alcohol can keep the tars dissolved on the engine parts when the gas temperature is below 500°F (260°C), the dew point of tar, and above 147°F (64°C), the boiling point of alcohol.

Hot Limestone Reactor

The catalytic effect of limestone to help crack tars at an elevated temperature may still be possible if the gases and tar are kept hot and the majority of char is removed. Limestone has been proven to crack the tars in the gas produced from a peat gasifier when the reactor temperature is kept above 1700°F (900°C) (11). A reactor placed in close proximity to the combustion zone of the gasification chamber may achieve those high temperatures.

Char Filter

Char particles have a large pore area for the trapping of contaminants. It may be feasible to use the char by-product as a condensing filter media. By keeping the gas temperature elevated until passing through the char filter, the tar vapor will condense in the pore sites in the char. When the filter media life has expired, the char media could be disposed of in the gasifier or burned as a light weight solid fuel.

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