Optimizing Synthesis Gas Yield from the Cross Draft Gasification of Woody Biomass

Paper # 535

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ABSTRACT

Biomass can be gasified to yield synthesis gas, tars, and ash. The process is governed by a number of parameters such as the temperature of the gasifying medium (in this case air), and the moisture content of the feedstock. Synthesis gas from gasifying wood pellets was collected and analyzed as a function of inlet air temperature and feedstock moisture content. The air was introduced at temperatures ranging from 630 to 730 °C and the moisture content of the feedstock ranged from 8 to 20%. The data collected was used to establish the relationship between the outcome of gasification and these two parameters, and then to determine optimal operating parameters for maximizing the fuel value (maximizing the concentrations of flammable gases in the synthesis gas) while minimizing the production of gasification tars.

INTRODUCTION

Gasification is an endothermic conversion of the energy stored in biomass into a form that is more suitable for various applications. In gasification, thermal energy is used to facilitate the breakdown of the organic content of biomass into its gaseous components by thermo-chemically converting solid biomass-like bio-residues into a synthesis gas that can be burned in engines to generate power. Renewable energy can be obtained from synthesis gas generated by the gasification of a low-cost biomass feedstock, making biomass a renewable energy source and gasification is a means of exploiting this resource. When a gasifier is operating in a sustainable manner, a fraction of the synthesis gas is combusted to provide the heat needed for the endothermic gasification reactions. The gasification process in general is the result of a combination of biomass and heat, in the presence of a gasifying medium like steam or oxygen, to yield synthesis gas, pyrolysis oils or “tars” in gasification jargon, char, ash and steam.

Heat + Biomass = Synthesis gas + pyrolysis oils (tars) + char + ash + steam *(1)*

Equations have been designed to depict the various reactions during gasification such as

The Boudouard reaction:

$$C + CO_2 \rightarrow 2CO \quad (2)$$

The Water Gas Shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (3)$$

The Carbon Steam reaction:

$$C + H_2O \rightarrow CO + H_2 \quad (4)$$

These reactions may apply in the instance of charcoal gasification, however as a previous author noted they may not necessarily apply as accurately to other types of biomass depending on the amounts of charcoal present [1].

Biomass gasifiers have been classified into three major categories based on how feedstock and gasifying medium are fed in relation to one another [1]. These categories are countercurrent (updraft), co-current (further divided into downdraft and cross draft), and fluidized beds. Distinctions are also made between fixed-bed and moving-bed gasifiers within the categories. All categories of gasifiers are plagued with the production of tars that tend to condense at the most inopportune moments during the end use of synthesis gas, making tar reduction or elimination one of the priorities in the research and development of gasification technology.

The relationship between synthesis gas composition and gasification conditions has been extensively investigated. Evans et al. reported an increase in the H_2 and CO content of the synthesis gas as average temperature increased from 700 to 980 °C [2]. The experimentation was done with fluidized bed gasification of woody biomass and an increase in the CO_2 content of the synthesis gas was observed when moisture increased. Bingyan et al. in 1992 investigated the gas yield of woody biomass in a thermo gravimetric analyzer (TGA) with temperatures ranging from 400 to 900 °C .They reported a direct relationship between temperature and yield for temperatures ranging between 500 and 800 °C, and a reduction in the effect of temperature on yield after 800 °C [3]. Narváez et al. in 1996 reported a direct relationship between synthesis gas H_2 and CO composition and temperature over a temperature range of 750 to 850 °C in a fluidized bed reactor. They also reported that increasing the amount of available air decreased the heating value of the synthesis gas produced due to the nitrogen in air [4]. Devi et al. in 2003 reviewed the primary measures for tar reduction and found operating parameters such as temperature and equivalence ratio to have a discernible effect on tar formation. They deemed the use of these factors being among the primary methods of tar reduction [5]. The effect of temperature on synthesis gas yield in the fluidized bed gasification of woody

biomass was modeled by Li et al. as reported in 2004. This study indicated that the amounts of available air considerably influenced the quality of the synthesis gas produced [6].

In reviewing gasification-related literature a problem common to all gasification technologies is the formation of tars. The problems related to tars in conventional synthesis gas applications are predominantly a result of their tendency to condense at the most inopportune points within the processes such as in fuel injectors, nozzles, gasifier air blowers, and producer gas cooling systems. Hassler and Nussbaumer in 1999 looked at various means of removing tars from synthesis gas so it could be used in an internal combustion engine (ICE). They found that no current technologies could consistently clean synthesis gas sufficiently for ICE applications. However the report indicates that more research needs to be conducted on other end use applications for synthesis gas such as gas turbines [7]. Due in part to the diversity of gasification systems, research on various aspects of tars is somewhat unique to each system. Nearly every type of gasification system has been investigated to various degrees for tars. Milne et al. in a book published in 1998, reviewed some of the tar-related investigations of several gasification systems and compiled a helpful bibliography. They also reported that the nature and formation of tars is characteristic of the type of gasification technology used [8]. Baker et al. in 1988 studied the characterization and treatment of tars in a variety of gasifier systems, and described tar yield as a function of temperature exposure. They found that at lower temperatures (400 to 500 °C) tar yield was generally within the range of 10% wt and higher for dry wood, and the yield reduced as temperatures increased up to 1000 °C [9].

Building upon the experiences of others in the biomass gasification field, this study aimed to determine the optimal conditions for gasification of wood pellets using fixed bed, cross draft gasification technology. The goal was to use gasification conditions to maximize the fuel value of the synthesis gas obtained, while minimizing the amounts of tars produced. The results obtained were used to indicate possible trends within the limits imposed for establishing statistical significance. The number of tests conducted was sufficient for observing possible trends and patterns in synthesis gas production and composition as gasification parameters were varied.

EXPERIMENTAL METHODS

Experimental Apparatus

The bench-scale fixed bed, cross-draft batch-mode (2.0 kg/charge) gasification system used in this study consisted of the following:

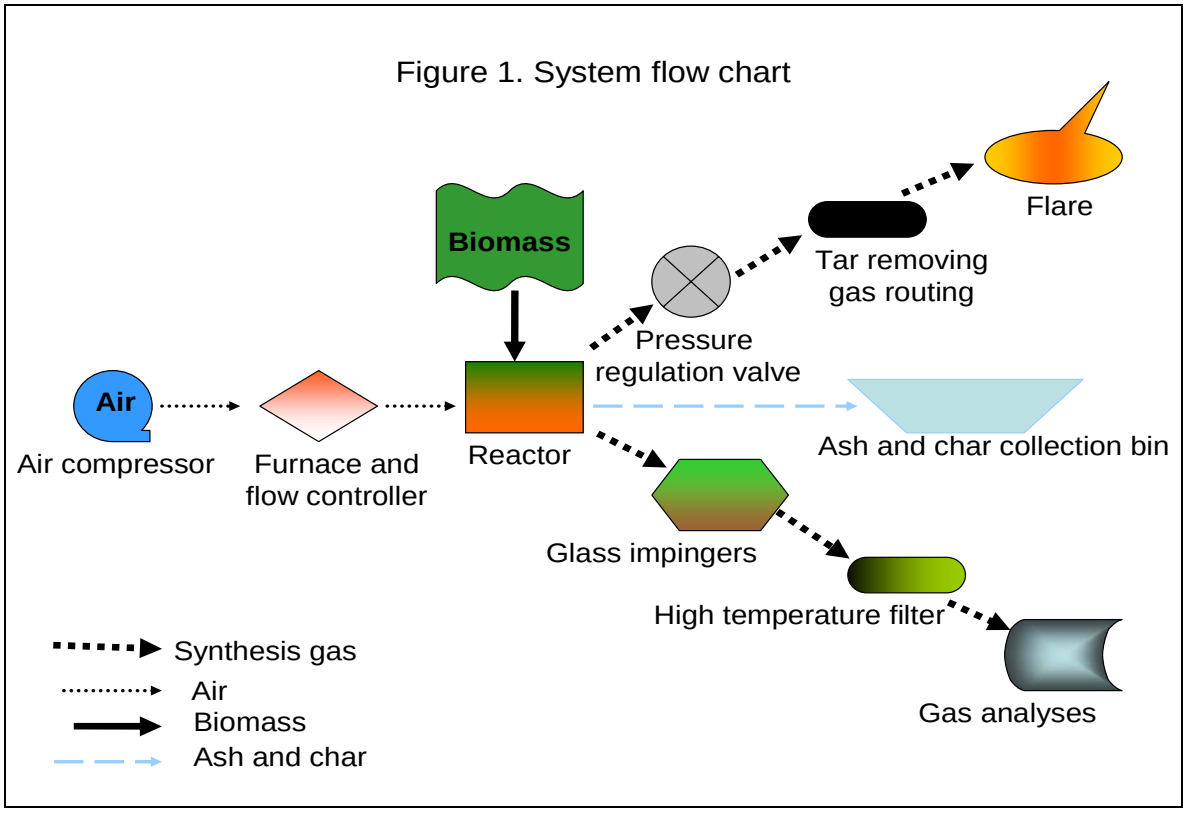
- An air compressor, a coalescing filter, a moisture removal device filled with silica gel and a pressure regulator to feed air into the system
- An electronic mass flow controller to control the air flow rate
- A 400 W in-line T-type air heating coil coupled with a multi-pass steel tubing in a Thermcraft electronically controlled furnace
- A ball valve between the reactor and the flare vent
- An insulated stainless steel reactor equipped with:

- Holes for air inlet, pressure and temperature monitoring and synthesis gas sampling
- A detachable grill with 3 mm diameter holes
- A grate and an ash collection bin
- A pulsating pneumatic vibrator

- A sampling and analysis train that comprised:
  - Four 500 ml glass impingers each filled with roughly 2 g glass wool and placed in a cold bath maintained at a temperature below 0 °C, and a high-temperature filter to remove particulate matter with a diameter greater than 2 µm
  - A continuous emissions monitoring (CEM) system to analyze product gas composition by measuring the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), total hydrocarbons (THC) and nitrogen oxides (NO_X)
  - A gas chromatograph (GC) equipped with a Hayesep DB packed column and thermal conductivity detection (TCD);
- Magnehelic pressure gages and an electronic pressure transducer to indicate any leaks or clogs within the rector
- Type K thermocouples in the reactor and after the gas cooling stage

Figure 1 is a schematic representation of the flow of materials within the system.

Figure 1. System flow chart



Feedstock preparation and test matrix

Table 1 depicts the findings of a proximate and ultimate analysis — to include heating value information — that was conducted on the wood pellets used as biomass feedstock.

Table 1. Wood Pellets Analysis Results

Proximate Analysis		
	As Received	Dry Basis
% Moisture	8.32	
% Ash	0.64	0.70
% Volatiles	62.25	67.90
% Fixed Carbon	28.79	31.40
Btu / lb	8067	8799
% Sulfur	0.07	0.08
Moisture ash free Btu / lb		8861
Ultimate Analysis		
	As Received	Dry Basis
% Moisture	8.32	
% Carbon	46.39	50.60
% Hydrogen	5.87	6.40
% Nitrogen	0.10	0.11
% Sulfur	0.07	0.08
% Ash	0.64	0.70
% Oxygen (difference)	38.61	42.11

The reported percent moisture content was used as a baseline from which the amounts of de-ionized water that would be needed to raise the percent moisture content by weight to the desired levels for a given mass of wood pellet sample were determined. The estimated amount of de-ionized water was sprayed unto the wood pellets which were then sealed in a plastic Ziploc bag for at least 30 minutes to equilibrate. The feedstock moisture content and inlet air temperature were varied as shown in Table 2.

Table 2. Test Matrix

Run number	Charge Mass (g)	Inlet Air Temperature (°C)	Moisture Content (wt %)
1	1500	730	20
2	1500	730	14
3	980	730	8
4	1500	680	14
5	1500	680	8
6	1000	680	14
7	1000	680	20
8	1000	680	8
9	1000	630	8
10	1000	630	20
11	1000	630	14

Experimental Procedures

A known mass of feedstock was loaded in the reactor. Air flow into the reactor was controlled and metered by the mass flow controller, and heated to achieve the desired reactor temperature by the air heating coil and Thermcraft furnace. The air flow rate was set at 30 l/min. The temperature and pressure of the reactor were monitored throughout each run and system pressure was maintained below 0.49 kPa by venting the reactor whenever it exceeded this threshold. Gasification reactions occurred in the reactor, and the reactor temperature was monitored using type K thermocouples and an IOtech cube data acquisition system (DAS) with PdaqView software. Temperature measurements were made every 60 seconds and logged to a spreadsheet.

A sample of the synthesis gas produced was rapidly cooled to encourage the condensation of tars and moisture, and filtered to remove particulate matter with aerodynamic diameter greater than 2 μm. The temperature of the filtered and cooled sample was monitored via the DAS, and the synthesis gas was analyzed for its percent composition of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), total hydrocarbons (THC) - reported as methane (CH_4) - and oxygen (O_2).

The cooled and filtered synthesis gas was pulled through the CEM systems to measure the percent composition of CO, CO_2, and O_2. A flame ionization detector (FID) based CEM system was used to measure the amounts of total hydrocarbons (THC) displaying the results in equivalent concentration of methane (CH_4). A gas chromatograph (GC) with a 30′ packed column and thermal conductivity detector (TCD) was used to measure the percent amounts of H_2, CO, CH_4, and CO_2 in the synthesis gas from a 0.5 ml sample loop. Details on the operation of the GC are found in Table 3. The CEM measurements were made every 60 seconds. The GC measurements were made in three to seven minute intervals. One liter Tedlar bags were filled with cooled and filtered synthesis gas at the time of interest, and the contents were manually injected into the sample loop. Using HP Chemstation software, the gas chromatograms were recorded. The Chemstation software was also used to find the areas under peaks of interest, which was representative of the amounts of these target compounds in the synthesis gas sample.

Table 3. Gas chromatography parameters

GC	HP 5890 Series II GC
Oven	isothermal at 110°C
Carrier	26 ml/min helium
Reference gas	49 ml/min helium
Elution order	H_2, N_2, CO, CH_4, and CO_2
Detector	TCD
Column	Hayesep DB 30 120/100 mesh
Column Pressure	90 psig
Sample Loop size	0.5 ml

The impingers were weighed at the beginning and end of each run, and the mass of condensate (tars and water) was obtained by subtracting initial mass of impingers from mass of impingers at the end of the run. The ash collection bin was emptied and the contents weighed to determine the mass of ash and char produced.

RESULTS AND DISCUSSION

CEM traces and GC chromatograms were integrated and converted into the basis of moles per kg of feed. Heating values of the combustible components of the synthesis gas (H_2, CO and THC reported as equivalent moles of CH_4) and their concentrations were used to estimate the synthesis gas heating value (HV) in kJ per kg feed used. This information was plotted against the inlet air temperature with moisture held constant. Figure 2 depicts the trends observed at 8% feedstock moisture content. THC yield drops by close to 0.005 moles per kg feedstock, while an increase in H_2 amounts is observed. Heating value and CO yield appear to decrease, but they display considerable variability within the moisture setting.

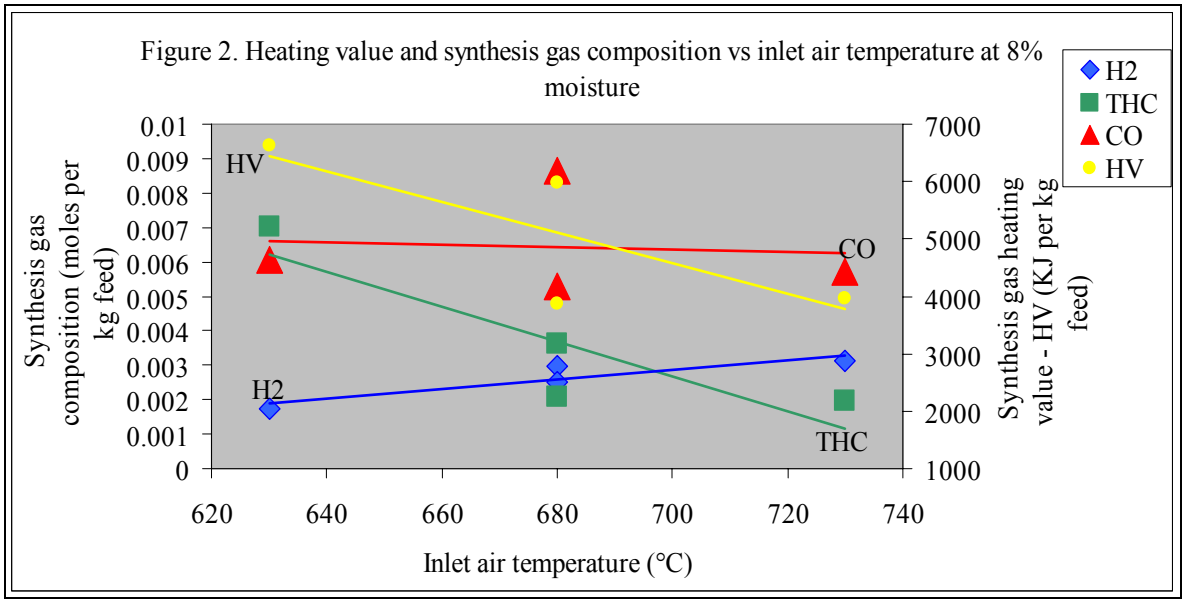


Figure 3 depicts the trends in synthesis gas composition and heating value observed when inlet air temperature is varied and moisture is held constant at 14%. An increase in THC yield was observed with increasing temperature, concurrently with an increase in H_2. The heating value did not show an obvious trend, and neither did CO.

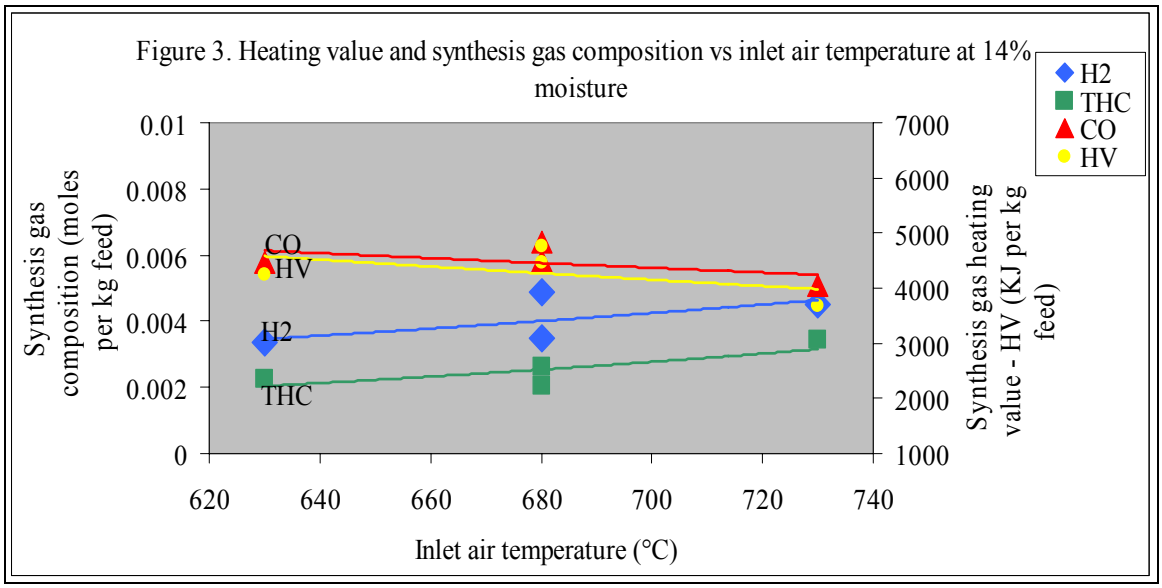
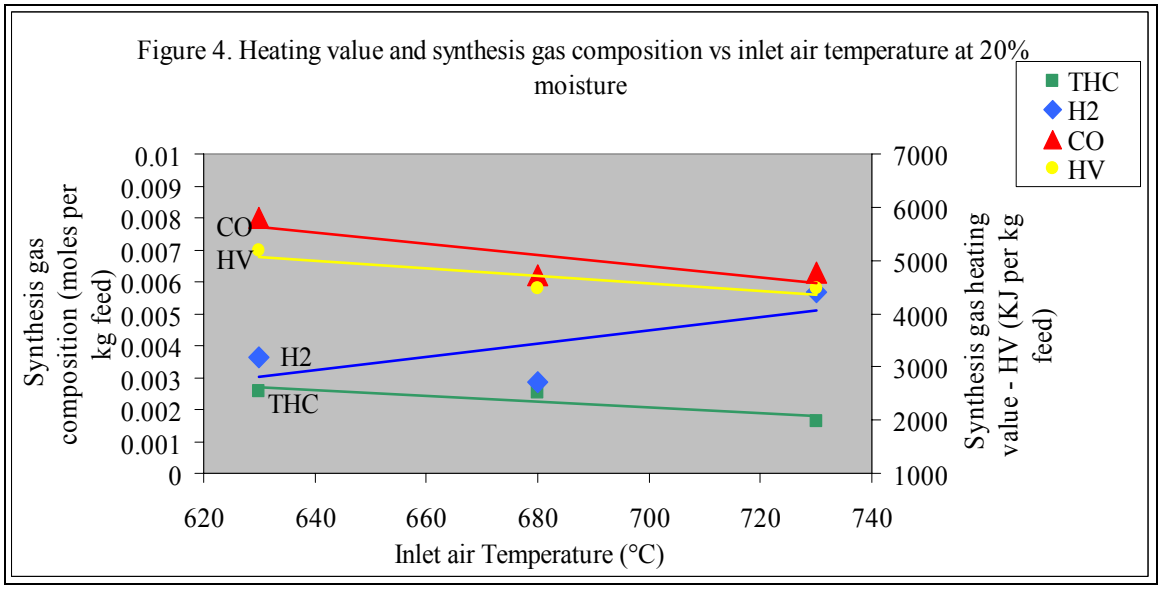


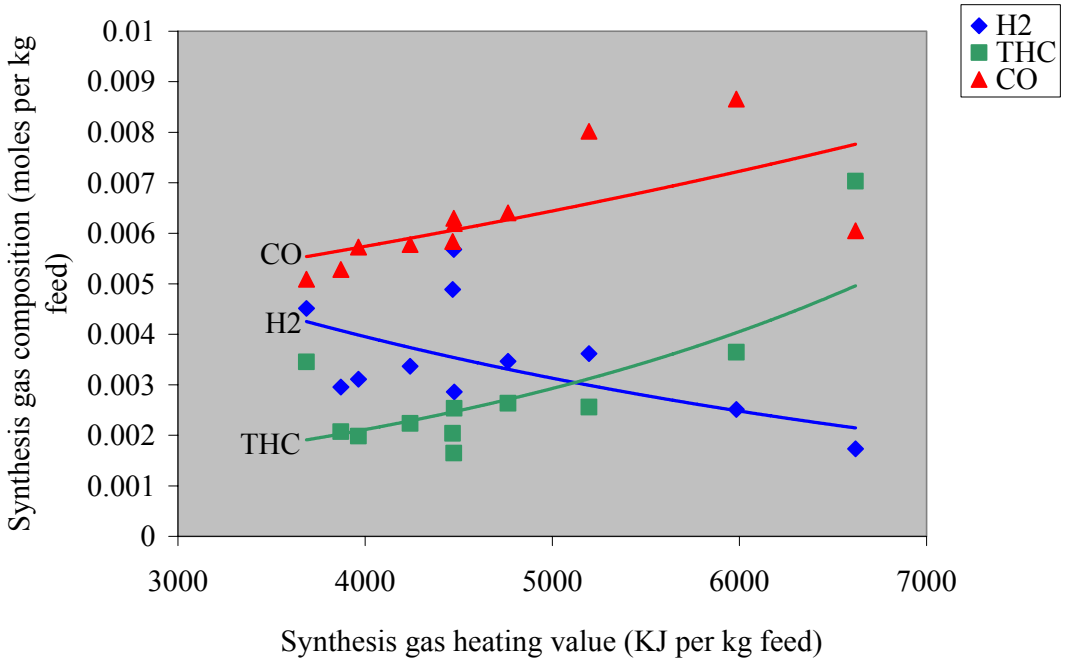
Figure 4 depicts the trends in synthesis gas composition and heating value observed when inlet air temperature is varied and moisture is held constant at 20%. Heating value, THC and CO concentrations decrease while a relatively sharp increase in H_2 yield is observed. This is possibly due to the increased availability of water and heat necessary to shift the equilibrium of the carbon steam reaction to the right as shown in Equation *(4)*. It is possible that some of the heat required to effect this equilibrium shift is derived from combusting CO, explaining the decrease in CO and increase in H_2.



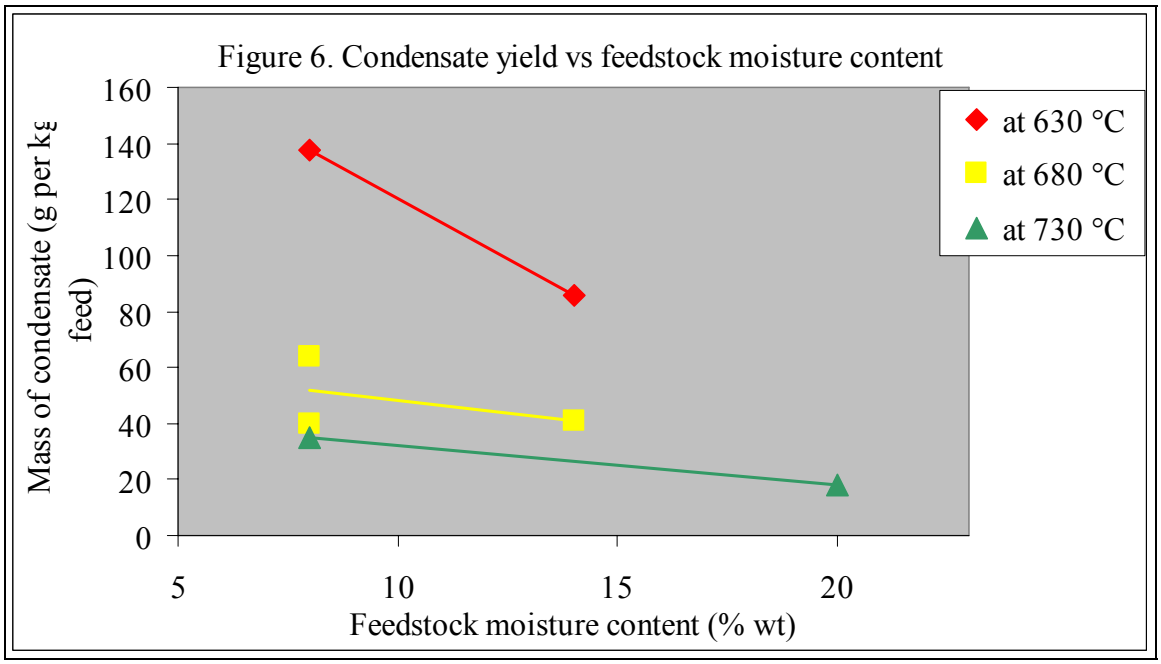
The synthesis gas composition was plotted against the heating value in an attempt to determine what components of the synthesis gas had more influence on its heating value. As seen in Figure 5, THC and CO compositions exhibit a direct proportionality to increased heating value, and from the results of a simple regression performed on the data THC has more influence on the heating value over the 8% and 14% moisture content

range. H_2 concentrations were observed to decrease with increased heating values. Over the 20% moisture range it appears that changes in CO concentration account for more variability in the heating value since H_2 and THC are inversely proportional to each other.

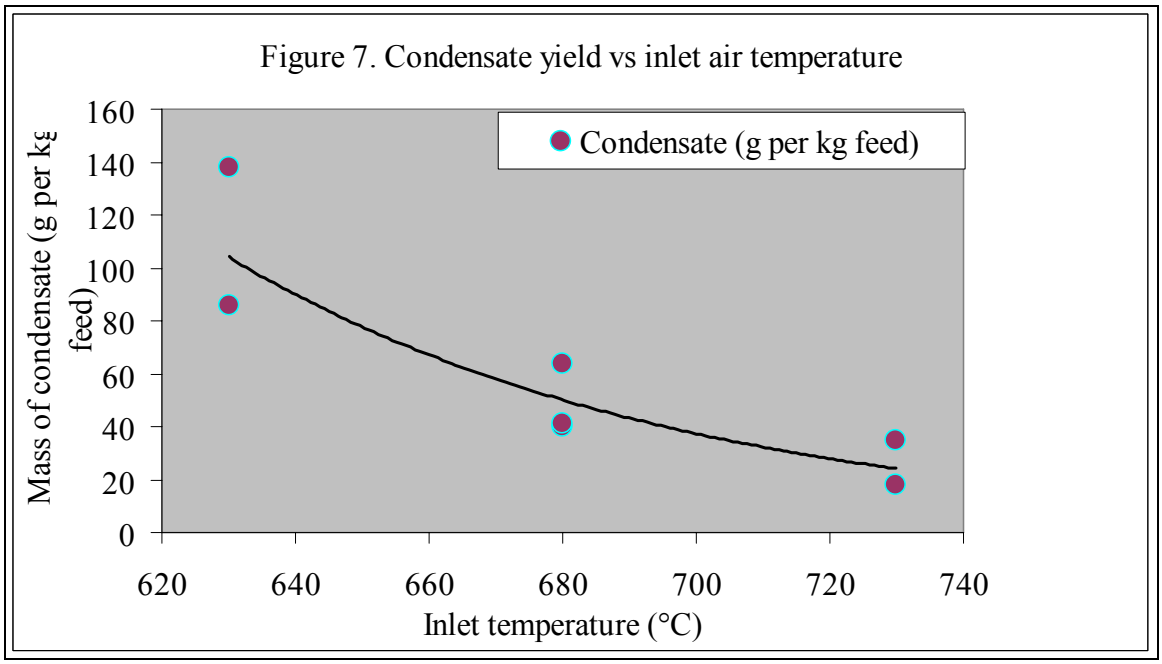
Figure 5. Synthesis gas composition vs heating value



The amounts of condensate (tars and water) collected under different inlet air temperature conditions were plotted against the feedstock moisture content (Figure 6). The amounts of condensate appear to decrease with increased feedstock moisture content. This observation is consistent with previous investigations [8].



When the amounts of condensate were plotted against the inlet air temperature as shown in Figure 7, smaller amounts of condensate seemed to be generated as inlet air temperatures increased. This could be due to the higher inlet air temperatures promoting the thermal cracking of tars inside the reactor, and favoring the carbon steam reaction.



CONCLUSION

Experiments were performed in a bench-scale fixed bed, cross-draft gasifier to evaluate the influence of gasification inlet air temperature and feed moisture content on the synthesis gas yields and composition.

From examining the above results and reviewing related literature, the gasification conditions exhibit a significant influence on the products of the process. The apparent effect of inlet air temperature on tar yield could be instrumental in tar reduction investigations, and was a main consideration in the following assessment of process products. The process energy yield expressed in kJ per kg feedstock is highest at the lowest experimental temperature. It is favorable to use high inlet air temperatures and feedstock with moisture content neighboring the 20% range if tar reduction is a factor in consideration, and to use lower inlet air temperatures and drier feedstock if increasing heating value was a primary objective of the gasification process.

The amount of data that was collected was somewhat limited with few replications and a considerable average relative percent difference of -31%, so additional experimentation would be required to fully assess statistical significance of some experimental parameters. Varying other feedstock properties in addition to its moisture content could provide more insight on the effect of these properties on process products.
The experimental apparatus has been successfully shaken down and could be used to investigate different types of gasification processes on other feedstocks with relative accuracy. A potential idea for future work would be to look at scaling the process up in order to conduct pilot testing of a crossdraft gasifier as an affordable waste management process that agrees with the concept of environmental sustainability.

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