PREDICTION OF PRODUCER GAS COMPOSITION FOR SMALL SCALE COMMERCIAL DOWNDRAFT GASIFIERS

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ABSTRACT: The goal of this study was to produce a model predicting the composition and heating value of producer gas made from a small scale (20-250 kWth), down-draft gasifier. Due the non-ideal conditions in this type of gasifier, classical thermodynamic equilibrium models are inaccurate. A more reliable prediction model for gas produced in a system of this size and type is needed. Eight biomass feedstocks were gasified and analyzed for this study. The pelletized feedstocks chosen were; alfalfa, algae, field grass, hemp, miscanthus, peanut shells, pine, and municipal solid waste. The feedstocks were chosen for their wide ranging availability and low costs. The commercial downdraft gasifier used was an Ankur Scientific WBG-20. This air-fed gasifier is capable of producing synthesis gas at a rate of up to 60 Nm^3/hr (50 kWth). Each feedstock was first characterized by proximate and ultimate analysis, and then the synthesis gas was analyzed by gas chromatography. The large variation of reaction temperatures and equivalence ratios occurring in the economic downdraft gasifier reduced the accuracy of the conventional thermodynamic equilibrium simulation. The synthesis gas produced in these tests was used to create a more applicable model for estimating composition and heating value for this type of system. The model developed from these tests estimates the heating value of the synthesis gas produced from the ultimate and proximate analysis of the feedstock with an average error of 5% over all feedstocks tested. KEYWORDS: Gasification, feedstock, syngas, model

1 INTRODUCTION

1.1 Background and relevance

Gasification is a well proven technology that has been employed in various forms for almost 200 years. It is essentially an oxygen limited thermochemical conversion of carbonaceous material to a useable gaseous fuel. Fossil fuel costs and environmental concerns have driven interests in using gasification of various forms of biomass. The wide range of sources including energy crops, agricultural waste, and municipal solid waste, create easy accessibility to low cost fuel sources for gasification almost anywhere in the world. Small scale (20-250 kWth) downdraft gasifiers are a valuable source of energy for populated rural areas. These units are cheap, easy to use, require minimal maintenance and support and can drastically improve the lives of rural communities that have no access to electricity or gas for cooking. This potential for future growth gives rise to the need for an accurate model for predicting the heating value and composition of the synthesis gas (syngas) produced from many different biomass sources.

1.2 Previous developments and motivation

Several models have been proposed in literature to predict downdraft gasifier syngas composition and heating value from the ultimate and proximate analysis of the fuel source. Zainal et al proposed using a thermodynamic equilibrium model for such predictions, and concluded reasonable agreement with experimental data[1]. Sharma compared a kinetic model to a thermodynamic model[2]. That study concluded that the kinetic model is limited because it uses rate constants based on the difference from the equilibrium value, so for gas composition the equilibrium model is a reasonable alternative to the complexity of the kinetic model. The equilibrium model computes the gas composition, for complete thermochemical conversion, at a specified temperature. In any small scale commercial downdraft gasifier there will not be a single reaction temperature or complete thermochemical conversion. The equilibrium model compared well against experimental data in [1], but for an actual downdraft gasifier the inhomogenous reaction zone causes fluctuating reaction temperatures and conversion efficiencies. These factors lead to inaccuracies in the prediction of composition and heating value of expected syngas. An accurate model of gas composition and heating value is critical for the optimal selection of biomass sources in various parts of the world.

1.3 Approach

A new model was developed from the thermodynamics of the equilibrium model and experimental data gathered from downdraft gasification of various biomass sources. The first step in the process was to analyze each feedstock though ultimate and proximate analysis. Each feedstock was then tested in a commercial downdraft gasifier, and the syngas composition was analyzed at steady state. The estimated gas composition for each feedstock was computed using the equilibrium model averaged over the range of temperatures measured in the reaction zone of the gasifier. The equilibrium model average compositions were compared to the experimental compositions to develop the new model that more accurately predicts composition and heating value

2 EXPERIMENT: MATERIALS AND METHODS

2.1 Biomass

The feedstocks chosen for this study were; alfalfa, algae, field grass, hemp, miscanthus, peanut shells, pine, and municipal solid waste(misc. paper and plastic). The feedstocks were chosen for their wide ranging availability and low costs. All feedstocks were pelletized with a size range of 20 to 50 mm in length and

5 to 12 mm in diameter except the waste pellets which were 30 to 80 mm in length and 20 mm in diameter. The ultimate, proximate, and heating value analyses of these biomass fuel sources were performed by a fuel lab services company (1) and are presented in Table I, Table II, and Table III respectively.

Table I: Ultimate analysis for each fuel (2)

Pelletized FeedStock	Component Mass Percent				
	Carbon	**Hydrogen**	**Nitrogen**	**Oxygen**	**Sulfur**
Alfalfa(Alf)	43.99	5.83	3.3	38.2	0.255
Algae(Alg)	45.62	6.17	3.26	39.43	0.241
Field Grass(Fgr)	47.06	5.94	1.41	39.45	0.129
Hemp(Hmp)	48.46	6.27	5.67	31.27	0.552
Miscanthus(Msc)	48.75	5.94	0.39	43.33	0.069
Peanut Shell(Psh)	50.73	6.16	1.49	37.52	0.088
Pine (Pn)	51.2	6.09	0.16	40.03	0.01
Mun. Waste(Muw)	42.16	5.65	0.07	36.7	0.09

Table II: Proximate analysis for each fuel(3)

Feedstock	Mass Percent Wet Basis				Mass Percent Dry Basis		
	M	**VM**	**FC**	**A**	**VM**	**FC**	**A**
Alf	9.12	67.57	13.42	9.05	74.35	14.77	9.96
Alg	16.2	63.72	14.77	5.34	76.01	17.61	6.37
Fgr	9.06	68.48	15.72	6.73	75.3	17.29	7.4
Hmp	10.7	66.88	15.81	6.6	74.89	17.71	7.4
Msc	10.2	72.03	15.63	2.13	80.21	17.4	2.37
Psh	9.88	67.06	19.62	3.44	74.41	21.77	3.82
Pn	8.68	74.85	16.17	0.3	81.96	17.7	0.33
Muw	7.11	71.88	9.92	11.1	77.38	10.68	11.9

Table III: Heating value analysis for each fuel (4)

Feedstock	Wet Basis (kJ/kg)	Dry Basis (kJ/kg)
Alf	16212.22	17838.09
Alg	15774.93	18817.34
Fgr	17214.73	18928.99
Hmp	18007.89	20168.75
Msc	17061.21	18998.77
Psh	18161.41	20150.14
Pn	18754.54	20538.58
Muw	16700.68	17321.72

2.2 Gasification

The gasifier used for these experiments was an Ankur Scientific WBG-20 rated at 50 kWth. This air fed gasifier is capable of producing syngas at a rate of up to 60 Nm^3/hr. It was designed primarily for woody biomass, but can handle many different feedstocks if they are pelletized and have a wet basis moisture content below 25%. The gasifier has a 114.3 mm (4.5-inch) restricted hearth that creates the high temperature reaction zone, a diagram of which can be seen in Figure 1. The hearth sits directly above an inert charcoal bed and biomass is batch fed into the hearth through the use of a hopper. An induced pressure drop is used to draw in air just above the hearth through two 19 mm (0.75-inch) air intakes. The oxygen in the incoming air combusts with some of the biomass in order to generate the heat that is then used by the pyrolysis and gasification reactions. The resulting syngas exits through the bottom of the bed along with small particles of ash into an outer chamber that surrounds the charcoal bed. The ash that exits the bottom of the charcoal bed falls down into an ash removal box and the syngas is drawn out of the gasifier through the use of a venturi water scrubber at the syngas exit. The venturi also induces the pressure drop that draws the air into the gasifier. After the gas is drawn out of the reactor it enters a series of apparatuses meant to clean the gas, which can be seen in Figure 2.
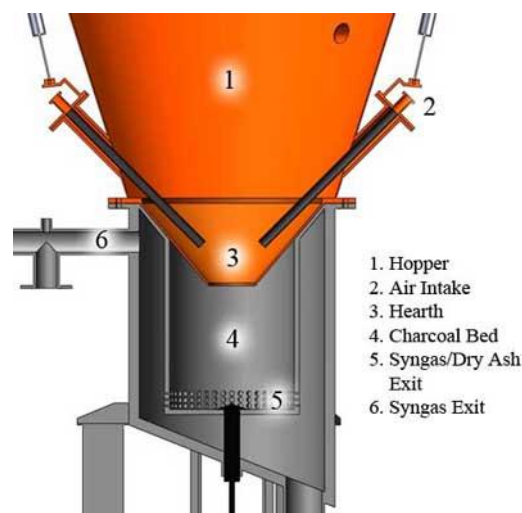

Figure 1: Internal view of gasifier reaction zone

1. Hopper
2. Air Intake
3. Hearth
4. Charcoal Bed
5. Syngas/Dry Ash Exit
6. Syngas Exit

a) Reaction Zone
b) Feed Door
c) Ash Removal Box
d) Cyclone Separator
e) Wastewater Box
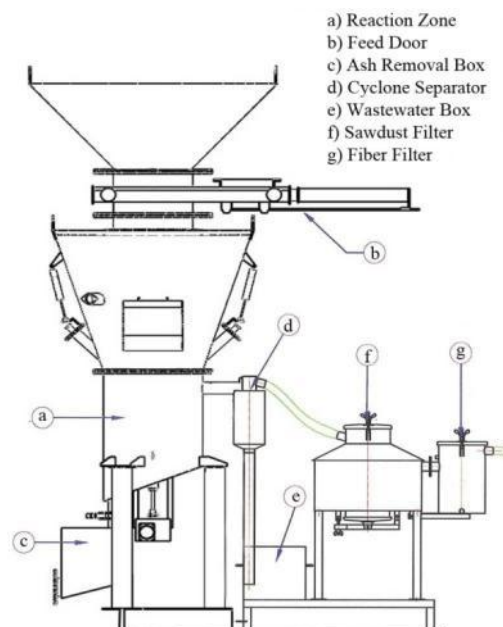f) Sawdust Filter
g) Fiber Filter

Figure 2: Schematic of total gasification system

In the schematic shown in Figure 2, (a) is the outer view of the section shown in Figure 1. The items marked by (b) and (c) are the feed door and the ash removal box, respectively. The venturi scrubber, which is connected to the syngas exit, utilizes a pressurized water spray to drive the syngas and water mixture into the cyclone separator (d). The cyclone separator allows the tars to fall into the wastewater box (e), which drains into an effluent container. The scrubbed gas flows into a passive sawdust filter (f) where it is further dried and cleaned before flowing into a final fiber filter (g). The syngas that exits the fiber filter is now a relatively clean product that can then be burned off or run into a modified natural gas engine. Running the gas into an engine creates additional pressure drop that increases the air being drawn into the gasifier, thus increasing the production and flow of syngas being produced. For this study the negative pressure in the reactor was held constant with the

engine's peak flow or burned off at an equal rate through the use of a blower.

2.3 Measuring instruments

A gas chromatograph was used for syngas composition analysis. The chromatograph used was the Agilent MicroGC300, which is on-line, and can sample roughly once every 2-3 minutes. It samples small amounts of the syngas from the flow line after the fiber filter in Figure 2. Three K-type high temperature thermocouples were placed in the constricting hearth area of the reactor. An Omega PX409 vacuum pressure transducer was connected to the hopper to monitor the negative pressure above the reaction. A venturi type flowmeter, located before the chromatograph on the clean syngas line, was used in-line in conjunction with an Omega PX653 differential pressure sensor to monitor the syngas flowrate.

2.4 Experiment method

For each feedstock 10 kg of charcoal was placed in the charcoal bed. At least 45 kg of the selected feedstock was then placed in the hopper, filling the area above the charcoal bed. The gasifier was sealed and the venturi scrubber pump was turned on to induce a pressure drop. The bed was then lit with a kerosene torch applied to the air inlets after a ten minute warm-up period. The engine or blower was then started to bring the syngas production to its peak. Chromatograph sampling was started shortly after. The sampling was continued until the composition reached a steady state. The reactor pressure drop and syngas flow rate were monitored to ensure equivalent operating conditions for each sample.

3   EXPERIMENT RESULTS

The steady state gas composition for each feedstock was gathered by the gas chromatograph. The main elements can be seen in Table IV below. The heavier hydrocarbons (HHC) are added together in Table IV, and their separated values can be seen in Table V immediately after.

Table IV: Principal component steady state gas compositions

Feed-stock	Component Mole Percent						
	H_2	O	N_2	CH_4	CO	CO_2	HHC
Alf	12.823	0.02	53.004	2.067	12.245	18.589	1.253
Alg	10.768	0.035	59.395	1.564	9.911	17.317	1.011
Fgr	12.454	0.023	51.621	2.86	13.63	17.795	1.617
Hmp	10.362	0.019	58.546	2.098	12.622	14.891	1.463
Msc	9.147	0.039	53.152	2.685	17.509	16.194	1.274
Psh	13.41	0.033	51.017	2.635	15.833	15.735	1.337
Pn	13.53	0.577	50.07	2.759	16.374	15.369	1.323
Muw	11.323	0.029	59.493	1.899	9.615	16.257	1.384

Table V: HHC components in gas compositions

Feedstock	Component Mole Percent			
	C_2H_4	C_2H_6	C_2H_2	C_3H_6
Alf	0.604	0.326	0.02	0.303
Alg	0.573	0.256	0.033	0.149
Fgr	0.952	0.281	0.097	0.287
Hmp	1.001	0.181	0.13	0.151
Msc	0.772	0.295	0.076	0.131
Psh	0.787	0.261	0.044	0.245
Pn	0.855	0.204	0.128	0.136
Muw	0.895	0.082	0.353	0.054

The heating values of the syngas were computed for each of the feedstocks. Both high and low heating values of the syngas were calculated from the gas composition and known parameters for each component at standard temperature and pressure. The results of these calculations can be seen in Table VI.

Table VI: Heating values for experimental gas composition of each feedstock

Feedstock	LHV (kJ/kg)	HHV (kJ/kg)
Alf	3678.163	4000.447
Alg	2916.97	3175.04
Fgr	4208.508	4561.601
Hmp	3566.498	3850.353
Msc	3978.779	4253.81
Psh	4400.464	4759.779
Pn	4486.674	4848.825
Muw	3217.832	3501.673

The thermocouples in the hearth showed a large variation in the reaction zone for every fuel tested, but values ranged between 600 and 900 Celsius for each feedstock tested. Average temperatures for the feedstocks varied within this range. The values continued to vary during steady state operations due to the inhomogenous movement of mass through the reaction zone.

4   EQUILIBRIUM MODEL APPROACH[1]

The equilibrium model is used to compute gas compositions from known compositional data of the fuel. The model is computed on the assumption that all reactions are in thermodynamic equilibrium. The global equation for gasification based on one carbon atom of biomass is defined as follows.

$$CH_{hc}O_{oc} + wH_2O + mO_2 + 3.76mN_2 = x_1H2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + 3.76mN_2 \quad \{Eq. 1\}$$
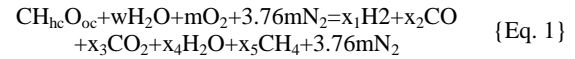
The unknown values in equation 1 are; m, which is the amount of oxygen per kmol biomass, and the x values which are the mole percentages of the resultant gases. The known values from fuel composition are; hc and oc, which are the hydrogen and oxygen ratios in the biomass respectively, and w, the amount of moisture which can be computed from the proximate analysis moisture content on a mass basis as follows.

$$w = \frac{4 * moisture}{3 * (1 - moisture)} \quad \{Eq. 2\}$$

Using the individual reaction equations, equilibrium constants, and an assumed adiabatic heat balance for the global gasification reaction, three equations in terms of three unknowns can be derived.

$$x_1^2 K_1 + x_2 + x_3 - 1 = 0 \quad \{Eq. 3\}$$

$$-K_2(x_1 x_2) + (w - (2 - .5hc))K_2 x_2 + 2K_2 x_2^2 - x_1 x_3 + 2K_2 x_2 x_3 = 0 \quad \{Eq. 4\}$$

$$Ax_1 + Bx_2 + Cx_3 + Dw + E = 0 \quad \{Eq. 5\}$$

In equation 5 the constants A-E are computed as follows.

$$A = dH_{H_2} + dH_{H_2Og} - 1.88dH_{N_2} \quad \{Eq. 6\}$$

$$B = dH_{CO} + 2dH_{H_2Og} - dH_{CH_4} + 5.64dH_{N_2} \quad \{Eq. 7\}$$

$$C = dH_{CO_2} + 2dH_{H_2Og} - dH_{CH_4} + 7.52dH_{N_2} \quad \{Eq. 8\}$$

$$D = dH_{H_2Og} - dH_{H_2Ol} \qquad \{Eq.\ 9\}$$

$$E = dH_{CH_4} - (2-.5hc)dH_{H_2Og} - 3.6472dH_{N_2} - dH_{biomass} \qquad \{Eq.\ 10\}$$

The method to calculate the unknowns in equations 6 to 10 is as follows.

$$dH_{anygas} = H_f^0 + C_p\Delta T \qquad \{Eq.\ 11\}$$

$$dH_{H_2Ol} = H_{fH_2Ol}^0 + H_{vap} \qquad \{Eq.\ 12\}$$

$$dH_{biomass} = H_{fbiomass}^0 \qquad \{Eq.\ 13\}$$

The H_f^0 values for each biomass feedstock are computed from the fuel's heating value and a theoretical complete combustion formula adjusted for ash content. This calculation can be seen in equation 14 below.

$$H_{fbiomass}^0 = DryFuelHV + \frac{\sum H_{fi}n_{fi}}{combProd}{1-ash} \quad [3] \qquad \{Eq.\ 14\}$$

The C_p values needed in equation 11 for each gas are temperature dependent and given by the following formula.

$$C_p = R(C_1 + C_2 T_{ave} + \frac{C_3}{3}(4T_{ave}^2 - T_1 T_2) + \frac{C_4}{T_1 T_2}) \qquad \{Eq.\ 15\}$$

In equation 15, R is the universal gas constant, T_1 is considered to be ambient temperature, and T_2 is the temperature at which equilibrium is being solved for. All temperatures in the equations in this section are in Kelvin. The C_x constants can be looked up in a thermodynamic table for the constituent gas being solved for. The equilibrium constants K_1 and K_2 in equations 3 and 4 respectively are also temperature dependent constants. They can both be computed as follows.

$$\ln(K) = -\frac{\Delta G^0}{RT} \qquad \{Eq.\ 16\}$$

$$K_1 \rightarrow C + 2H_2 = CH_4 \qquad \{Eq.\ 17\}$$

$$K_2 \rightarrow CO + H_2O = CO_2 + H_2 \qquad \{Eq.\ 18\}$$

In equation 16, ΔG^0 is the standard Gibbs function of formation. It is also temperature dependent, and governed by the following relationship.

$$\frac{d(\Delta G^0/RT)}{dT} = -\frac{\Delta H^0}{RT^2} \qquad \{Eq.\ 19\}$$

Equation 19 can now be related to equation 16 for the desired K, equation 17 or 18, and integrated with the Gibbs function value and specific heat constants of the relevant components to calculate the integration constant. This procedure is carried out the same for K_1 and K_2 based on which reaction they represent. Now that all constants at a specific temperature have been computed for equations 3,4, and 5, a numerical solver such as the Newton-Raphson method can be used. The remaining unknown compositions can be computed from the following equations.

$$x_4 = x_1 + 2x_2 + 2x_3 + w - (2-.5hc) \qquad \{Eq.\ 20\}$$

$$x_5 = 1 - x_2 - x_3 \qquad \{Eq.\ 21\}$$

$$m = .5(-x_1 + 3x_2 + 4x_3 - ((2-.5hc) + oc)) \qquad \{Eq.\ 22\}$$

$$x_6 = 3.76m \qquad \{Eq.\ 23\}$$

5 EQUILIBRIUM MODEL RESULTS

The overall gas composition for a specific temperature is computed following the method in the previous section. This is insufficient to model a small scale downdraft gasifier because of the widely varying temperatures measured in the experimental runs. To accommodate for the unsteady 600-900 C temperature range, it was noted that moisture content in the fuel was inversely proportional to the average temperature computed during steady-state syngas composition. The temperature dependent model is calculated over the range of temperatures with a weighted average for each feedstock's temperature average. The heating values for this modeled syngas composition can be seen in Table VII.

Table VII: Heating values of equilibrium model for each feedstock

Feedstock	LHV (kJ/kg)	HHV (kJ/kg)
Alf	3672.899	3991.09
Alg	4462.061	4875.129
Fgr	4203.366	4555.503
Hmp	3972.192	4313.856
Msc	5002.313	5415.614
Psh	4470.011	4838.093
Pn	5299.926	5721.308
Muw	2719.478	2956.188

The percent error of the equilibrium modeled heating values to the experimental heating values can be seen in Figure 3.
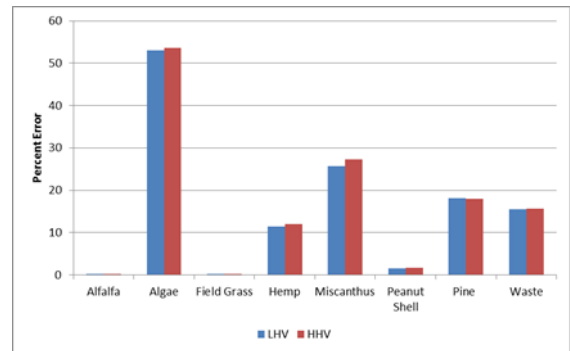

Figure 3: Error of equilibrium model in predicting heating value

The average error for all feedstocks is calculated to be about 15.7% for lower heating value and 16.1% for higher heating value. The syngas composition computed for each feedstock using the equilibrium model can be seen in Table VIII.

Table VIII: Equilibrium model gas compositions

Feedstock	Component Mole Percent				
	H_2	N_2	CH_4	CO	CO_2
Alf	16.225	53.156	1.198	16.183	13.238
Alg	19.890	47.962	1.663	17.312	13.174
Fgr	17.559	50.281	1.307	18.758	12.096
Hmp	16.959	53.395	1.307	17.211	11.129
Msc	19.935	45.124	1.523	21.927	11.491
Psh	18.086	49.664	1.359	20.004	10.887
Pn	20.067	45.117	1.516	23.761	9.540
Muw	12.768	59.169	0.856	12.546	14.661

The average error in composition for each feedstock and average error in each component for all feedstocks combined can be seen in Figures 4 and 5 below.
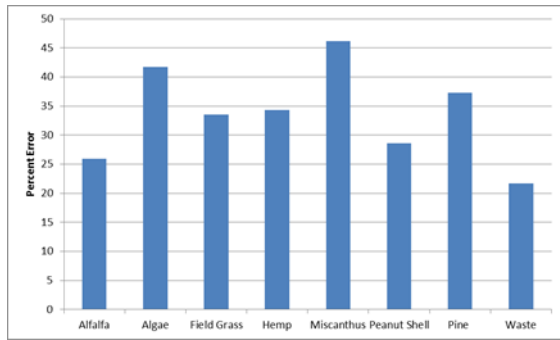
Figure 4: Average percent error in equilibrium model syngas composition for all feedstocks
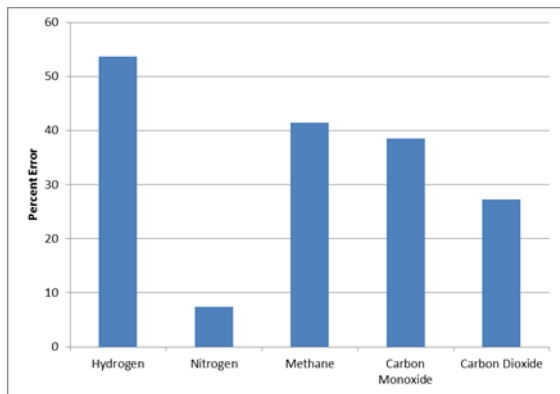
Figure 5: Average percent error of equilibrium model for each component in all feedstocks combined

In total, for all feedstocks and all gas components included in model calculations, the average percent error was found to be about 34%. This is not a very good estimate for composition, and it is actually higher because heavy hydrocarbons are not computed in this model. The model needs to be adjusted to correlate more accurately with the actual compositions resulting from gasification in small scale downdraft gasifiers.

6   MODEL ADJUSTMENT

The first step in correcting the equilibrium model is to identify the major factors in the composition that lead to the errors in the equilibrium model's composition predictions. One method of determining these error sources is by using Pearson's correlation coefficient to determine the relationship between many of the variables used in the model. A simplified formula for computing the coefficient ρ between any two variables x and y can be seen below.

$$\rho_{xy} = \frac{\text{cov}(X,Y)}{\sigma_x \sigma_y} \quad [4] \qquad \{\text{Eq. 24}\}$$

In equation 24 above the denominator is the product of the standard deviations for each variable. The numerator is the covariance between the two variables which is computed as follows.

$$\text{cov}(X,Y) = \sum_{i=1}^{N} \frac{(x_i - \bar{x})(y_i - \bar{y})}{N} \quad [4] \qquad \{\text{Eq. 25}\}$$

Several notable influences on the error of the model can be determined using Pearson's correlation coefficient. Significant correlations between the moisture and ash from the wet basis proximate analysis and the error in hydrogen, nitrogen, and carbon monoxide in the computed syngas composition were found. For oxygen, the new model will still assume equilibrium without adjustment because of the low contents and zero energy value. Regression analysis between each correlated variable was coupled with its Pearsons's coefficient to provide adjustment formulas to calculate gas composition. Therefore, the method to compute these adjusted gas compositions is to run the temperature averaged equilibrium model from the previous section, then use the following equations to adjust the compositions calculated using that model(5).

$$\Delta H_2 = 4.0904 - .2999\text{ash}_p + .3503\text{moisture}_p \qquad \{\text{Eq. 26}\}$$

$$\Delta CO = 3.9742 - .1403\text{ash}_p + .1784\text{moisture}_p \qquad \{\text{Eq. 27}\}$$

$$\Delta N_2 = 1.2526\text{moisture}_p - 8.5795 \qquad \{\text{Eq. 28}\}$$

The previous equations were used to calculate the adjusted compositions for several of the components. The heavy hydrocarbons are formed out of equilibrium so using equilibrium constants to compute their formation is not possible. It can be seen from comparing the experimental data to the equilibrium model that it is predicting too much hydrogen and carbon monoxide in all cases. The adjustments computed for hydrogen and carbon monoxide can be used to adjust the remaining syngas components. To ensure that adjustments to the other elements stay in balance the following compositional balance equation is used.

$$11H_2 + 20CO = 10CO_2 + CH_4 + C_2H_4 + C_2H_6 + C_2H_2 + C_3H_6 \qquad \{\text{Eq. 29}\}$$
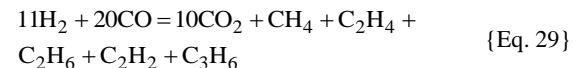
The composition can be solved by plugging in the computed adjustments for hydrogen and carbon monoxide from equations 26 and 27. Equation 29 ensures that the decreases computed in hydrogen and carbon monoxide are distributed as increases in balance with the remaining components. Results for the adjusted compositions can be seen in Table IX.

Table IX: Adjusted model gas compositions

Feed-stock	Component Mole Percent					
	H$_2$	N$_2$	CH$_4$	CO	CO$_2$	HHC
Alf	11.761	56.519	1.554	11.961	16.815	1.388
Alg	11.138	58.599	1.081	10.632	17.530	1.151
Fgr	12.496	53.840	1.708	14.322	16.098	1.536
Hmp	11.078	58.138	1.713	12.232	15.196	1.642
Msc	10.080	51.968	2.517	17.148	16.882	1.415
Psh	11.723	54.186	2.325	14.950	15.635	1.233
Pn	13.457	49.479	2.550	18.385	14.687	1.452
Muw	10.760	60.021	1.659	9.088	17.344	1.128

The average error in composition for each feedstock and average error in each component for all feedstocks combined can be seen in Figures 6 and 7.
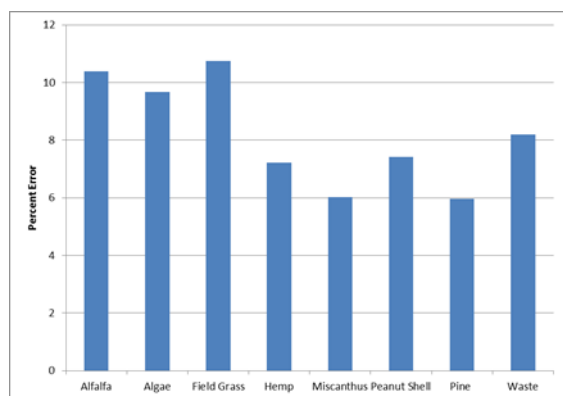
Figure 6: Average percent error in adjusted model syngas composition for all feedstocks
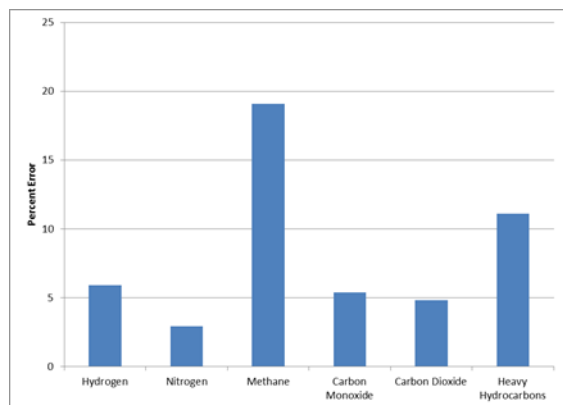

Figure 7: Average percent error of adjusted model for each component in all feedstocks combined

The average percent error for all feedstocks and all gas components included in model calculations was found to be 8.2%. This is a much better prediction than the ordinary equilibrium model. The average error of the old equilibrium model to experiment values was about 34%, therefore this adjustment provides a roughly 26% decrease in error. To further validate the model the heating values need to be computed from the adjusted model syngas compositions. The higher and lower heating values for the new gas compositions were computed as before and can be seen in Table X.

Table X: Heating values of adjusted model for each feedstock

Feedstock	LHV (kJ/kg)	HHV (kJ/kg)
Alf	3436.595	3724.852
Alg	2966.609	3218.835
Fgr	3911.152	4225.116
Hmp	3594.169	3886.747
Msc	4081.54	4373.009
Psh	3939.573	4251.421
Pn	4711.794	5071.354
Muw	2914.171	3177.262

The error of the adjusted model heating values to the experimental heating values can be seen in Figure 8.
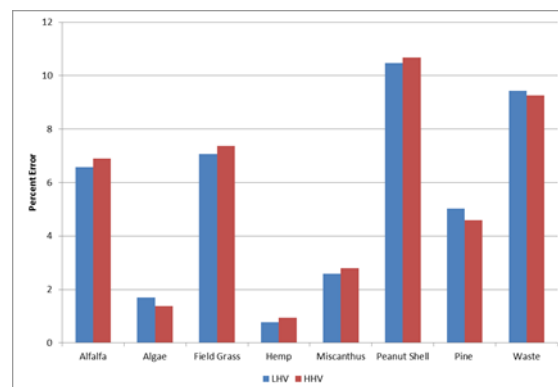

Figure 8: Error of adjusted model in predicting heating value

The average error for all feedstocks is calculated to be about 5.45% for lower heating value and 5.95% for higher heating value. The average error for the old equilibrium model was 15.7% and 16.1% for lower and higher heating values respectively. Therefore, the new model provides about a 10% decrease in error for heating value prediction.

7 MODEL TESTING AND COMPARISON

It is clear that adjusting the equilibrium model to better correlate with experimental data will improve the accuracy of the model for that set of data. To be able to validate the usefulness of the model, it needs to be tested against experimental data from other studies not included in the development data set. The adjusted model must now be compared to experimental data from other small scale downdraft gasifiers available in literature. The standard equilibrium model will also be computed to compare the improvements achieved with the adjusted model. In many of the other tests available in the literature the gas measurement devices did not read the extent of heavy hydrocarbons as read by the Agilent chromatograph used in this experiment, so the heavy hydrocarbons will be left as a sum value for error comparisons. The heating values computed for both models and the experimental heating values from the literature can be seen in Table XI.

Table XI: Model comparison for heating values of selected feedstocks

Feedstock	Experiment (kJ/kg)	Equilibrium Model (kJ/kg)	Adjusted Model (kJ/kg)
Hazelnut[5]	4660	4525.1	4325.16
Olive Kernel[6]	3000	3520.757	3365.21
Sawdust[7]	4393.8	4830.189	4464.128
Rubberwood 1[8]	3630.491	5156.753	4221.55
Rubberwood 2[8]	3585.44	5061.399	4056.38
Rubberwood 3[8]	4122.747	4932.166	3953.645
Rubberwood 4[8]	4339.426	4767.162	4046.87
Charcoal[9]	4510	5195	4862.14

In Figure 9, the experimental heating values of the syngas from these studies were compared to the equilibrium model and the adjusted equilibrium model in terms of percent error. Only the LHV is shown because HHV data was not published by the majority of the studies.
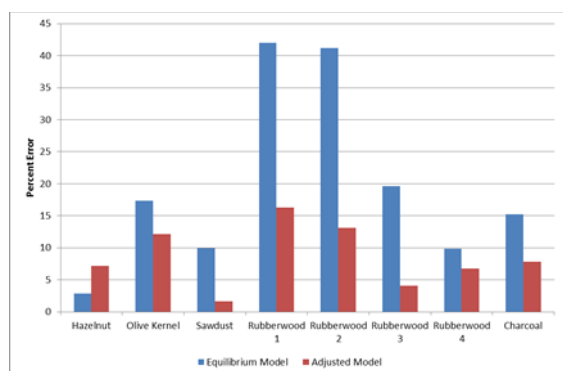

Figure 9: Percent error of heating values computed with equilibrium and adjusted model

The total average error in heating value for all feedstocks with the equilibrium model was found to be 19.7%. The total average error in heating value for all feedstocks with the adjusted model was found to be 8.6%. The adjusted model results in about an 11% decrease in error. In Figures 10 and 11 that follow, the compositions of the syngas computed from the equilibrium model and the adjusted model are compared to their experimental values by percent error. Figure 10 represents the average percent error of both models with all components for each feedstock in the literature. Figure 11 is a plot of the average percent error of both models in each component for all feedstocks combined.
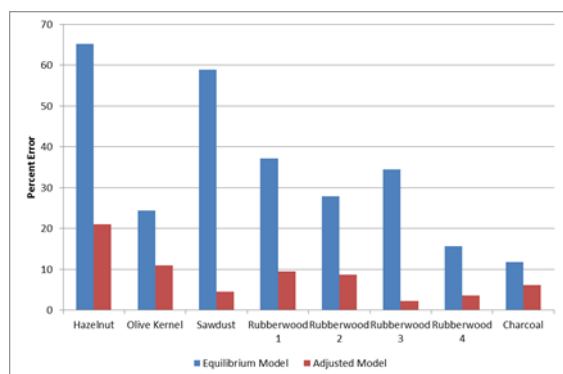

Figure 10: Average percent error in each model's syngas composition for all feedstocks
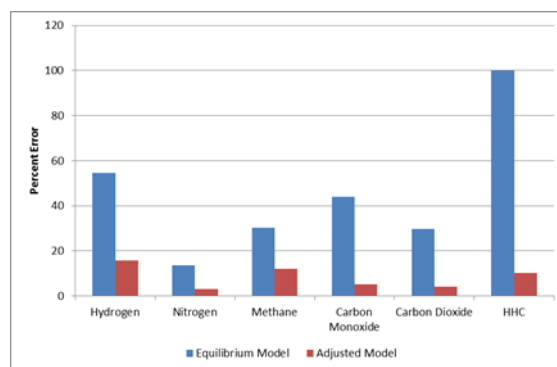

Figure 11: Average percent error by component for both models in all feedstock's combined

The total average error for all feedstocks and components was found to be about 31% for the equilibrium model with heavy hydrocarbons not included. The total average error for all feedstocks and components for the adjusted model was found to be about 8.4% including heavy hydrocarbons.

8   DISCUSSIONS AND CONCLUSION

The gasification of several chosen feedstocks was performed in a 50 kWth downdraft gasifier. The syngas produced was measured with a gas chromatograph. The temperature of the reaction conditions along with ultimate and proximate analyses of the fuels was used to compute the composition using the thermodynamic equilibrium method. The experimental data was used to develop an adjusted model of the equilibrium model. This adjusted model showed significant improvement in estimating the heating values and composition of the syngas. Several studies available in literature were also compared to the equilibrium model and the adjusted model. Significant improvement was shown by the adjusted model over the equilibrium model. The adjusted model was not as accurate for these outside studies as compared to the experimental data used to form the adjustment because gasifier conditions were not exactly the same. For example, the downdraft gasifier used in the hazelnut study was roughly half the thermal output power of the Ankur gasifier used in this study[5]. The gasifier used in the rubberwood study was about 2/3 larger in thermal output than the gasifier used in this study[8]. The sawdust and olive kernel gasifiers were very close to the same size[6][7]. The adjusted model was able to predict the compositions from all outside studies with an 8.4% error. The errors in prediction tended to increase as the difference between the size of the study's gasifier and our experimental gasifier increased. Overall, this adjusted model evaluated the syngas composition for similar sized downdraft gasifiers with a noticeable improvement over a generalized equilibrium model, without the complexities involved in a kinetic model.

9   NOTES

(1) Columbia Analytical Services
(2) Ultimate Analysis Methods: CHNO detection by D5373-Combustion/ TC and IR, S detection by D4239-Combustion/IR
(3) Proximate Analysis Methods: D5142-Automated

thermo-gravimetric system. In the table M represents moisture content, VM represents volatile matter, FC represents fixed carbon, and A represents ash
(4) Heating Values by D5865-Adiabatic calorimetry
(5) In the equations subscript u represents ultimate analysis, subscript p represents proximate analysis

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11 ACKNOWLEDGEMENTS

12 AFFILIATIONS

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