



## **HIGH TEMPERATURE AIR/STEAM GASIFICATION OF STEAM EXPLODED BIOMASS**

Duleeka Sandamali Gunarathne\*, Jan Karol Chmielewski, Weihong Yang

Royal Institute of Technology, Department of Material Science and Engineering,  
Division of Energy and Furnace Technology, Brinellvägen 23, 100-44  
Stockholm, Sweden

Tel: +4687908402, Fax: +468207681

\* Corresponding author, rmdsgu@kth.se

---

### **ABSTRACT**

Pretreatment of biomass under high pressure steam is called steam explosion. Hydrophobic dark coloured pellets (here referred as Black pellets) produced from this pretreatment technology were used in gasification experiments with both pure air and air-steam mixture as gasifying agents at an updraft High Temperature Air/steam Gasification (HTAG) unit. For comparison purpose, similar experiments were carried out with un-pretreated biomass pellets (referred as Gray pellets).

Black pellets show the possibility to co-gasification with peat. Require less volume but, with high height to diameter ratio of the gasifier. High temperature gasification is preferred but decomposes at low temperature resulting around two times higher CO/CO<sub>2</sub> ratio.

With Black pellets, CO and hydro carbon contents of syngas is higher while H<sub>2</sub> content is higher with Gray pellets. Air gasification gave higher Lower Heating Value (LHV) with Black pellets compared to Gray pellets and was around 7.3 MJ/Nm<sup>3</sup>. Gas yields were higher with Gray pellets and they were more efficient in air gasification and efficiency was around 79.5% with higher Equivalence Ratio (ER).

With steam addition to the feed gas of Black pellets result in syngas with LHV of 10.6 MJ/Nm<sup>3</sup> compared to 8.2 MJ/Nm<sup>3</sup> with Gray pellets. Steam addition has reduced the gas yield of both pellet types. Efficiency was higher with Black pellets around 76.9%.

Black pellets gave slightly more tar content in syngas compared to Gray pellets and was composed of mainly secondary tar while Gray pellets gave more tertiary tar. Cases with steam and high ER lowered the tar content. Under the tested conditions, Indene/Naphthalene ratio can be used to predict the tar content even when steam was added.

In general, steam gasification of Black pellets is more feasible if syngas with high energy value is desired. But, Gray pellets with high ER was most efficient and contained lowest tar. If higher H<sub>2</sub> yield is preferred, unpretreated pellets are more attractive.

*Keywords: High temperature gasification; Steam explosion; Tar*

---



## **1 Introduction**

Nowadays, biomass pelletization is widely used technology in order to overcome problems such as low bulk density, non-uniformity of fuel, low energy density, etc. when using conventional biomass in thermal applications. However, pelletization does not overcome difficulty of low ash sintering temperature. Lower hardness or durability of pellets also causes handling difficulties.

There are several pretreatment technologies that have been developed in order to improve the quality of biomass further before pelletization. Pretreatment of biomass enhance its energy content and also improve some mechanical properties such as grindability and hydrophobicity. Most commonly used pretreatment technologies are steam explosion and torrefaction.

Steam explosion involves heating biomass under high pressure saturated steam and sudden release of pressure assuring explosive decompression resulting dark brown colour product. The structural changes such as releasing hemicellulose in to solution and alteration of lignin structures are reported [1- 3].

Many studies can be found on steam explosion pretreatment of biomass particularly focussing on ultimate use for fermentation to ethanol [4-7]. Several studies based on combustion of fermentation residue were also found [8-10]. But, thermal applications of steam exploded biomass is really lacking to date. Some studies on thermochemical behaviour of steam exploded material shows promising features such as early thermal degradation which is important for thermal applications of this process [11-15].

Some researchers claim that even though some pretreatment techniques such as solvent based or ionic liquid based lignocellulose fractionation reduce the crystallinity by disrupting highly ordered hydrogen bonds in crystalline cellulose fibres, dilute acid or steam pretreatment increase the crystallinity due to removal of amorphous fractions such as hemicellulose [16]. Some other researchers [11 and 13] also found that steam explosion result in increase of crystallinity of biomass. According to a recent study [17] increased crystallinity may cause heat diffusion limitations due to highly ordered crystalline region may act as a barrier to heat diffusion. But, these heat transfer limitations may be minimized by high temperature operations.

With these promising features, we forwarded our attempt to a practical thermal application of pellets produced from steam exploded biomass. In this study, High Temperature Air/Steam Gasification (HTAG) system in updraft configuration was used for air and air/steam gasification of steam pretreated biomass pellets compared to untreated biomass pellets in order to analyze qualitative and quantitative gasification performance.

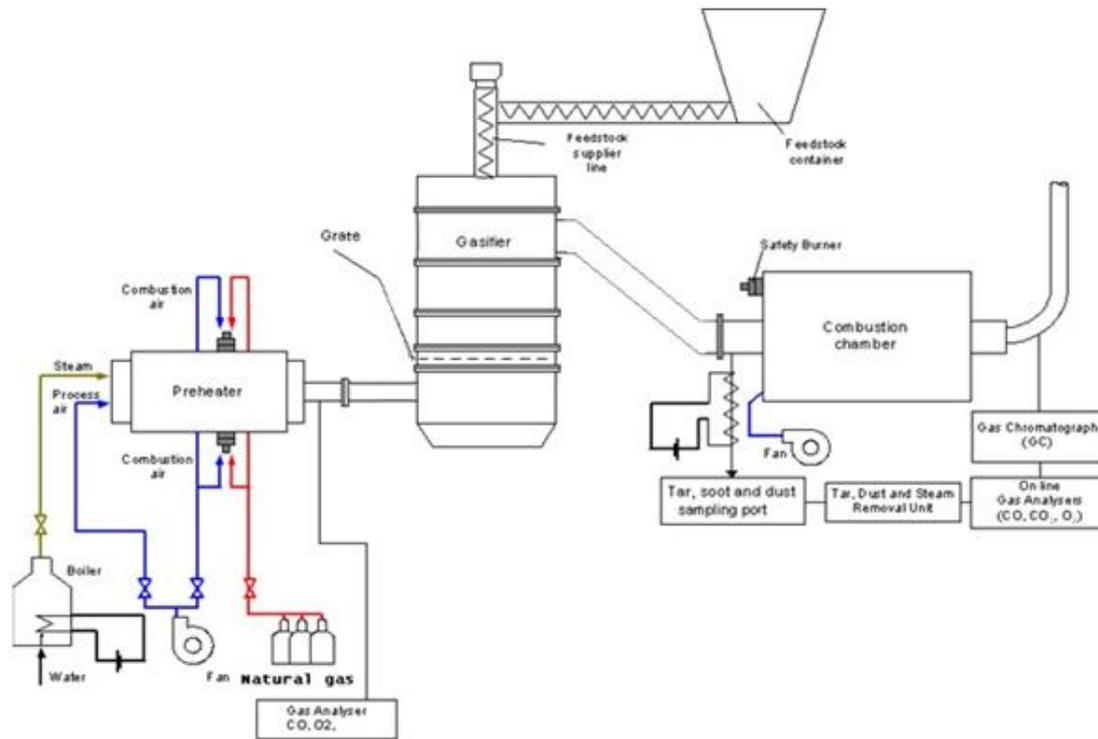
## **2 Experimental Methodology**

### **2.1 Gasifier System**

The experiments were carried out in a High Temperature Air/steam Gasifier (HTAG) unit in updraft configuration. (Figure 1). HTAG is a method in which a preheated air/steam is used as the gasification agent. This preheated air/steam oxidizer supplies



additional amount of energy into the gasification process which as a result enhances the thermal decomposition of the biomass feedstock and increase product gas yield, gas composition, heating value, cold gas efficiency with low tar content [18-22]. The unit is composed of feed gas preheater, fuel feeding system and syngas post combustion unit.



**Figure 1: HTAG in updraft configuration**

Biomass pellets stored in the feed tank is transported to the gasifier via a screw conveyor. Preheated air from the preheater is introduced to the gasifier at the side of bottom section below the perforated grate made out of Kanthal steel which is suitable for high temperature operation. The system has the facility to add steam to the feed stream if steam gasification is to be performed. The flow of hot gases and biomass is countercurrent. The syngas which flows upward, leaves the gasifier at the side of the top section and is burned out at the combustion chamber. The small particles left after reaction can pass through the grate and collected below.

## 2.2 Feedstock Materials

The biomass types used for the investigation were Black pellets and Gray pellets (See Figure 2 a and b).



**Figure 2: a. Black pellets b. Gray pellets**

Black pellets are based on the 75% soft wood and 25% hard wood, pretreated with steam explosion. Gray pellets are normal pellets without pretreatment. Fuel properties are given in Table 1.

**Table 1: Fuel characteristics**

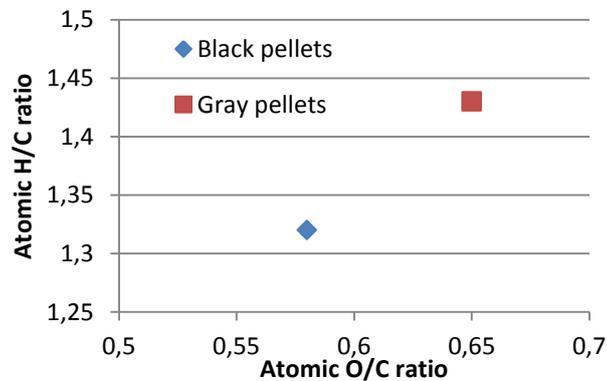
	<b>Black pellets</b>	<b>Gray pellets</b>
<b>Proximate analysis</b>		
Moisture content at 105°C	4,2%	9,8 %
Ash cont. at 550°C	0,9% (dry)	1,9 % (dry)
LHV (as received)	19,3 MJ/kg	16,6 MJ/kg
Volatile matter	76,8% (dry)	81,2 % (dry)
Bulk density	740 kg/m <sup>3</sup>	603 kg/m <sup>3</sup>
<b>Ultimate analysis</b>		
Carbon C	52,6% (dry)	49,4 % (dry)
Hydrogen H	5,8% (dry)	5,9 % (dry)
Nitrogen N	<0,1 % (dry)	0,17 % (dry)
Oxygen O	40,6% (dry)	42,6 % (dry)
<b>Ash fusion temperatures (oxidizing conditions)</b>		
Shrinking temperature, ST	1050 °C	1050 °C
Deformation temperature, DT	1480 °C	1190 °C
Hemisphere temperature, HT	1490 °C	1210 °C
Flow temperature, FT	1500 °C	1230 °C

Steam exploded pellets show high fixed carbon content and low volatile and ash content. According to literature [15 and 23], char yield is associated with lignin content and alkali metal content of biomass. Lignin produces more char while cellulose and hemicellulose produces less. Alkali metal has a catalytic effect on char yield. Then, even with low alkali metal content, higher fixed carbon can be explained by comparative increment of lignin content as a result of loss of hemicellulose in steam exploded pellets. This fact is observed by some other researchers also [12, 14, 15 and 24]. On the other hand, hemicellulose consists of easy to volatile structures with many



branches [25] and therefore, loss of hemicellulose result in low volatiles. While pretreatment, the biomass undergo destruction of lignocelluloses structure and this result in release of mineral matter contained in original biomass to the liquid phase ultimately reducing alkali metal and also the total ash content of pretreated sample [24].

Both atomic ratios are reduced with Black pellets due to steam explosion pretreatment. Then it has shifted close to the peat region in van krevelen diagram as given in Figure 3. This makes possibility to co-gasification of Black pellets with peat. Hemi-cellulose and cellulose contain more O than lignin [13] and reduction of hemicellulose which cause reduction of O and increment of lignin that cause increase of C can be the reason for having low O/C and H/C ratios. Similar results have been obtained by other researchers [13, 24].



**Figure 3: Representation of two pellet types in van krevelen diagram**

Due to the pretreatment, Black pellets have higher LHV. Generally C and H give positive effect on heating value while O, N and ash give negative effects. Reduced O/C ratio and ash increase the heating value even though reduced H/C gives and detrimental effect. In overall, the heating value has increased.

Reduction in biomass particle size by steam explosion has reported [1]. Another study [24] also identified that severe treatment of biomass has resulted in more fines and hence result in higher pellet density. Not only due to high pellet density, high bulk density of Black pellets can be further explained by small diameter of Black pellets used in this experiments which is 6mm compared to 8 mm Gray pellets (However, small particles create more pressure drop). Both the facts high heating value and high bulk density result in increase of energy density which is important factor related to transportation and storage. Energy density of Black pellets is  $14.3 \text{ GJ/m}^3$  and it is  $10 \text{ GJ/m}^3$  for Gray pellets. Further, this result in reactor to be more compact due to need of less volume. But, according to literature, steam explosion result in less reactive biomass due to low alkali metal content and low volatile content. This creates the need of having longer bed for better conversion of biomass. Therefore, the reactor should be designed so that it has a high height/diameter ratio.

Another important mechanical property observed with steam exploded pellets is hydrophobicity which is also important factor related to transportation and storage. This is also a result of removal of hemicellulose which has higher affinity to water due to presence of more hydroxyl groups compared to few such groups found in lignin [13].



When ash fusion temperature is concerned, even though shrinking temperature is same with both pellets types, deformation temperature, hemisphere temperature and flow temperature are higher with Black pellets. This can be related to low alkali metal content expected with steam explosion pretreatment. In order to avoid slagging, the gasifier should be operated below deformation temperature ie. 1190 °C with Gray pellets and the temperature limit is much higher for Black pellets, which is 1480 °C which will be a plus point for high temperature gasification in order to minimize the heat diffusion limitations.

### 2.3 Measurements

Temperatures inside the gasifier were measured with eight number of type S thermocouples located along the reactor height and recorded by a data acquisition system connected to a PC. Pressure readings at four different locations along the gasifier were measured using digital manometers and negative pressure at the top was ensured for safety reasons. Dry syngas compositions were monitored with Gas chromatography (GC) in every three minutes. Tar samples were collected by means of a syringe and analysed in an external laboratory.

Due to the negative pressure at the gasifier top, air infiltration to the system through biomass feeding line cannot be avoided. Therefore, a correction procedure was used for N<sub>2</sub> in the syngas in order to get a realistic composition so that comparison is possible. First, a carbon balance was applied to the input and N<sub>2</sub> free gas stream at the outlet assuming negligible carbon content in ash in order to calculate volumetric flow rate of N<sub>2</sub> free gas stream. Then input N<sub>2</sub> amount with air and fuel was added directly to the N<sub>2</sub> free gas stream in order to get total gas flow.

### 2.4 Experimental Procedure

The feeder was pre-calibrated with biomass pellets used in the experiment. Once the desired air temperature was reached by using preheater, feed rate was set by adjusting frequency of feeder.

For each pellet type, experiments were conducted with and without steam addition. In each run of steam addition, the steam to biomass ratio was kept constant with a value of 1.2. For Gray pellets, experiments were conducted with two different ER values without steam. For each run, 20 minutes time interval was selected for analysis. This time interval was selected based on stable temperatures and gas compositions. Average values of gas compositions and temperatures within this time interval were taken for analysis. The analyzed situations are represented in Table 2.

**Table 2: Experimental conditions**

Run	Biomass type	Biomass kg/h	Air m <sup>3</sup> /h	Steam kg/h	ER
1	Black pellets	70	80	0	0,180
2	Black pellets	50	10	60	0,032
3	Gray pellets	60	75	0	0,223
4	Gray pellets	50	75	0	0,267
5	Gray pellets	50	20	60	0,071



### 3 Results

#### 3.1 Syngas Composition

##### 3.1.1 Comparison of steam exploded pellets with and without steam

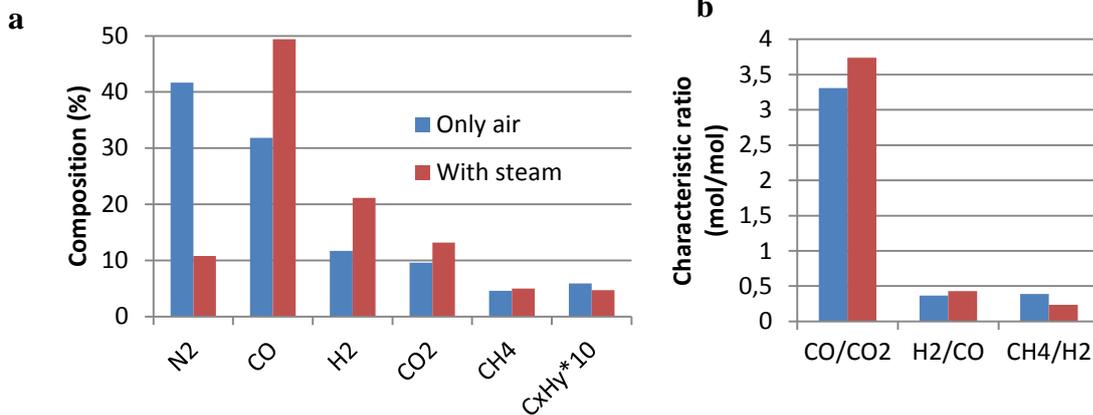


Figure 4: Black pellets a. Gas compositions b. Characteristic ratios

H<sub>2</sub> and CO content was significantly increased by steam addition probably due to steam reforming of C and hydrocarbons. With steam, water gas shift reaction also expected and it should result in high H<sub>2</sub>/CO ratio. But, only slight increment of H<sub>2</sub>/CO ratio was seen with steam addition. Further, high CO/CO<sub>2</sub> ratio was also seen. This can be explained by occurrence of Boudouard reaction at high bed temperature which was around 966 °C resulting more CO. Even though, slight increment of CH<sub>4</sub> content could be seen, C<sub>x</sub>H<sub>y</sub> content has reduced with steam. Higher hydrocarbons reforms to CH<sub>4</sub> and CH<sub>4</sub> reforms to CO and H<sub>2</sub> with steam and the drop of CH<sub>4</sub>/H<sub>2</sub> ratio is also seems to support this explanation. Hydrocarbon cracking also expected at high temperature.

##### 3.1.2 Comparison of normal pellets with and without steam

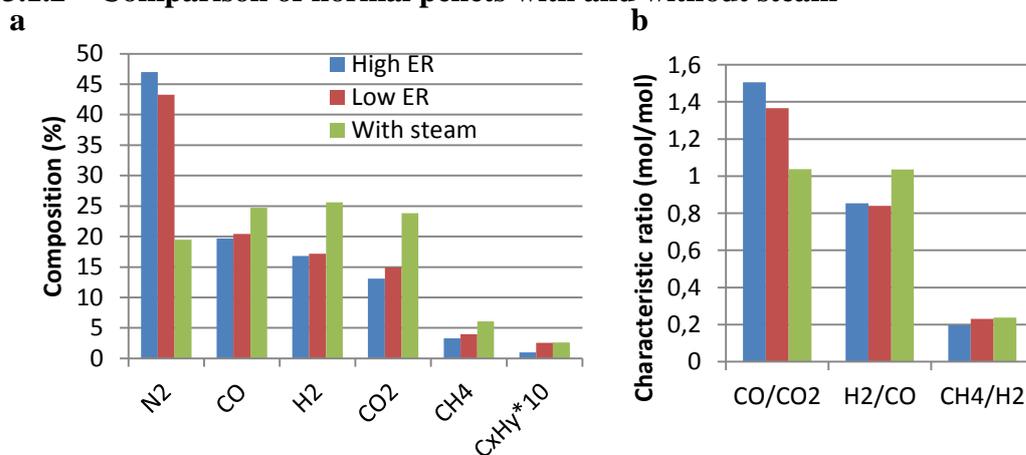


Figure 5: Gray pellets a. Gas compositions b. Characteristic ratios



All the combustible species content have been increased with steam addition. However high  $H_2/CO$  and low  $CO/CO_2$  ratio could be seen and can be expected that water gas shift reaction is dominant in this case. Boudouard reaction has not played much role in this situation may be due to comparatively lower bed temperature which was around 838 °C. Higher  $CH_4$  and  $C_xH_y$  content along with high  $CH_4/H_2$  ratio implies that steam reforming or cracking of hydrocarbons also not much significant.

All the combustible species content has been dropped with increased ER. But both  $CO/CO_2$  and  $H_2/CO$  ratios have increased while  $CH_4/H_2$  ratio has dropped. Increase of  $CO/CO_2$  is due to dominance of Boudouard reaction at high bed temperature (907 °C) as a result of high ER. Low  $CH_4/H_2$  may be due to cracking reactions at high temperature.

### 3.2 LHV, Syngas Yield and Efficiency

Table 3: LHV, syngas yield and efficiency

Run	Biomass type	LHV of biomass MJ/kg	LHV of gas MJ/Nm <sup>3</sup>	Gas yield Nm <sup>3</sup> /kg	Gasification efficiency %
1	Black pellets	19,3	7,3	2,0	75,6
2	Black pellets		10,6	1,4	76,9
3	Gray pellets	16,6	6,0	2,1	75,9
4	Gray pellets		5,5	2,4	79,5
5	Gray pellets		8,2	1,5	74,1

According to Table 3, with both pellet types, steam addition resulted in higher LHV due to increase of combustibles and lower gas yield due to low air flow which in turn reduce dilution with  $N_2$ . With high ER case of Gray pellets lower LHV could be seen due to dilution in  $N_2$  even though higher gas yield was seen. Highest efficiency was also seen with high ER case of Gray pellets. The ER should be optimized with more trials in order to get the maximum output.

### 3.3 Syngas Purity

According to Table 4, with high temperature (due to high ER), almost all the tar components have been reduced. With steam addition also, all the tar components have been reduced even though the temperature is low. Then, in that case, steam reforming has compensated the negative effect on thermal cracking in to some extent.



Table 4: Composition of tar

Tar class [26]	Component	Quantity µg/100ml			
		Black pellets	Black pellets with steam	Gray pellets low ER	Gray pellets high ER
2, 3	<b>Benzene</b>	154,4	125,8	289,2	186,1
2, 3	<b>Toluene</b>	172,4	120,0	120,8	42,9
2	<b>m/p-Xylene</b>	38,4	30,4	12,3	3,1
2	<b>o-Xylene</b>	21,6	17,8	8,0	9,8
2	<b>Indan</b>	7,0	9,6	4,4	4,7
2, 3	<b>Indene</b>	104,6	51,9	127,4	22,3
2, 3	<b>Naphthalene</b>	113,0	64,2	235,4	55,5
2	<b>2-Methylnaphthalene</b>	34,0	19,4	24,4	0,0
2	<b>1-Methylnaphthalene</b>	39,6	39,0	33,8	16,1
2	<b>Biphenyl</b>	8,4	3,9	9,4	0,0
3	<b>Acenaphthylene</b>	58,6	33,4	104,0	19,4
3	<b>Acenaphthene</b>	5,4	3,6	3,3	0,6
3	<b>Fluorene</b>	14,7	5,0	23,0	2,8
3	<b>Phenanthrene</b>	21,3	17,0	27,6	0,0
3	<b>Anthracene</b>	5,2	3,4	8,2	2,2
3	<b>Fluorantene</b>	6,8	4,0	11,1	0,0
3	<b>Pyrene</b>	8,6	0,0	0,0	0,0
2	<b>Phenol</b>	85,4	81,8	48,9	4,1
2	<b>o-Cresol</b>	17,9	20,5	2,0	0,0
2	<b>m-Cresol</b>	36,4	38,6	7,6	0,0
2	<b>p-Cresol</b>	45,8	52,2	1,6	0,0
<b>Other</b>		533,4	399,7	239,1	68,9
<b>Total tar (g/m<sup>3</sup>)</b>		<b>15,4</b>	<b>11,4</b>	<b>13,4</b>	<b>4,4</b>
<b>Total tar (g/kg)</b>		<b>30,8</b>	<b>16,0</b>	<b>28,1</b>	<b>10,6</b>
<b>Gas exit temperature (°C)</b>		<b>658</b>	<b>631</b>	<b>828</b>	<b>837</b>



### **3.4 Comparison of Black pellets and Gray pellets**

Generally, higher CO content with Black pellets and high H<sub>2</sub> content with Gray pellets were seen. This can be explained by difference of H/C ratio of two samples discussed in section 2.2. Ultimately H<sub>2</sub>/CO should be higher with gray pellets and vice versa which is proved by Figures 4 b and 5 b.

Further, lowest bed temperature was seen with Black pellets without steam which was around 781 °C. But, it also yield very high CO/CO<sub>2</sub> ratio which was around 3.3 compared to Gray pellets which resulted in 1.4-1.5 CO/CO<sub>2</sub> ratio even with bed temperature around 887°C and 907°C. The reason may be lower decomposition temperature of Black pellets as a result of pretreatment. With steam explosion, apart from hydrolysis of hemicellulose, the remaining hemicellulose can be depolymerized in to smaller molecular weight components which are more sensitive to low temperature [11]. Further according to literature [12], in addition to depolymerisation, cellulose dehydration also occur at most severe conditions which confirms strong degradation of cellulose leading reduced thermal stability of cellulose. Low lignin decomposition temperature was also observed by some researchers [11 and 13] due to formation of more thermolabile chemical bonds [13]. Therefore, thermal conversion at relatively low temperature can be expected.

Higher C<sub>x</sub>H<sub>y</sub> content obtained with Black pellets can be explained by low gas exit temperature. This may be due to dominance of Boudouard reaction in the bed area (very high CO/CO<sub>2</sub> ratio observed) which is highly endothermic reaction which in turn result in low temperature of gas leaving the bed zone ultimately reducing gas exit temperature also.

When comparing two pellet types, LHV is higher with Black pellets and gas yield is slightly higher with Gray pellets. Higher LHV with black pellets is always expected because it is pretreated biomass with high energy content. Further, main part of the heating value comes from CO and hydrocarbons which are considerably higher than with Gray pellets due to dominance of Boudouard reaction and low gas exit temperature respectively as discussed above. On the other hand heating value of Gray pellets dominate by CO and specially H<sub>2</sub>.

The effect of pretreatment on tar content is difficult to explain at this stage, due to the interference of temperature effect. But, even with significantly low exit temperature with Black pellets, only small increment of tar was seen. Further, in general, tar obtained with Black pellets dominated secondary tar components while that of Gray pellets was mainly tertiary tar. This may be due to high temperature associated with Gray pellets.

### **3.5 Use of characteristic ratios as a measure of total tar content**

There is an interrelation between the total tar and Indene/Naphthalene ratio (I/N), Phenol/Aromatics ratio (P/A) and C<sub>2</sub>H<sub>6</sub>/(C<sub>2</sub>H<sub>4</sub>+C<sub>2</sub>H<sub>2</sub>) ratio which result in possible application of online measurement of tar which is presently done offline [27]. Later, some other researchers [28] also used these ratios for analyzing behavior of tar with waste plastic containing wood pellets in HTAG.

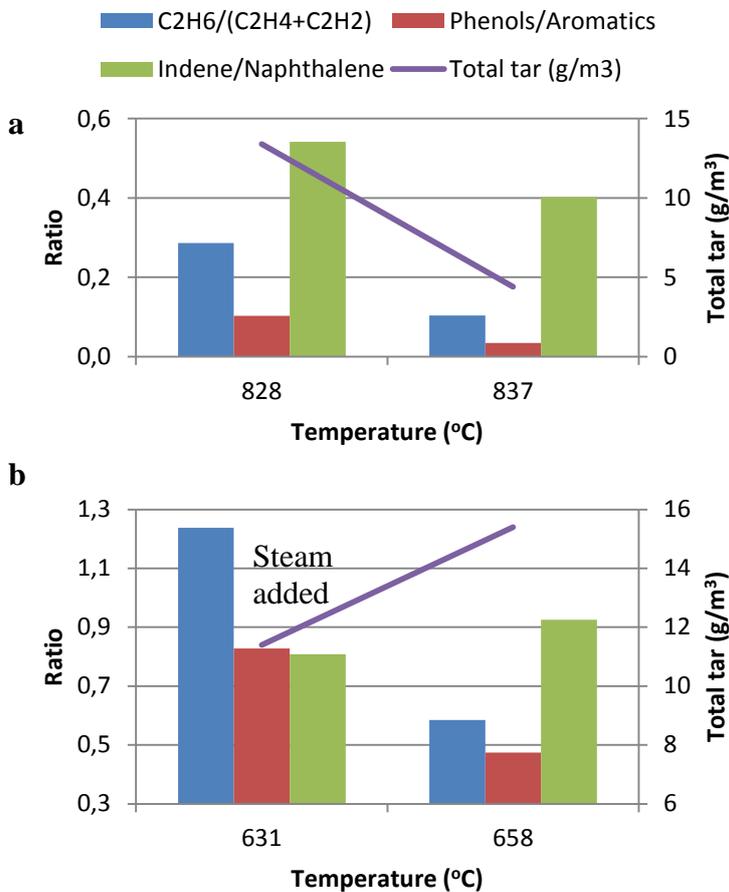


Figure 6: Characteristic ratios of tar a. Gray pellets (low and high ER) b. Black pellets (with and without steam)

All the ratios are higher with low temperature case of Gray pellets (Figure 6 a). With 1% drop of temperature (837°C to 828°C),  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A ratio has almost tripled while I/N ratio shows only slight increment around 35%. Then it is seen that temperature has a higher effect on  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A ratio than I/N ratio. This can be explained by cracking behavior of tar at high temperature. With high temperature,  $C_2H_6$  breaks down to form  $C_2H_4$  and  $C_2H_2$ . Phenols including Cresols break down and form Aromatics (Indene, Naphthalenes, Fluorine, Phenanthrene and Anthracene) [27]. Then, both Indene and Naphthalene increase with temperature due to cracking of Phenol. But comparatively, Indene favours at low temperature while Naphthalene favours at high temperature [27]. Therefore, as a ratio, I/N increase with reduced temperature, but not as much as other two ratios since both Indene and Naphthalene have increasing trends with temperature while others have opposite trends.

In Figure 6 b, with steam addition (4% drop of temperature from 658°C to 631°C),  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A ratio still preserve their dependency of temperature even though to a lower extent (approx. doubled compared to tripled in previous case). But it is clear that, I/N ratio follows the trend of actual tar content by reducing its value by 13% (compared to increase of 35% in previous case). This is because, the effect of steam can't overcome the effect of temperature on  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A



ratio due to their strong dependency on temperature. But, it has overcome the weak dependency of I/N on temperature. With steam addition to Gray pellets, even though the tar content is not measured,  $C_2H_6/(C_2H_4+C_2H_2)$  ratio was found to be 0,7 (almost 2,5 times) at 817 °C (which is 1% drop compared to 828 °C). Then, this also proves that the effect of steam can't overcome the effect of temperature on  $C_2H_6/(C_2H_4+C_2H_2)$  ratio.

Therefore,  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A ratio fail to predict the trend of tar content when steam is present, while I/N ratio still shows valid prediction of the trend of tar content.

#### **4 Conclusions**

The changes of important fuel properties with steam explosion pretreatment were identified. Low atomic ratios result in possibility to co-gasification with peat-like substances and create fuel flexibility. High energy density demands less gasifier volume but due to low reactivity of steam exploded biomass requires high height to diameter ratio of the gasifier and it is just a matter of design. Due to high crystallinity of pretreated biomass, it is important to operate at high temperature in order to minimize heat diffusion limitations and higher ash fusion temperature further facilitates this high temperature operation.

Steam exploded (Black) and normal (Gray) pellets were successfully gasified in HTAG updraft gasifier and performance was evaluated in terms of syngas composition, heating value, gas yield, cold gas efficiency and gas purity. In general, higher CO content with Black pellets and high  $H_2$  content with Gray pellets were seen due to difference in H/C ratio of feed. Around two times higher CO/CO<sub>2</sub> ratio was seen with Black pellets due to low decomposition temperature associated with steam exploded biomass. While both pellet types gave high calorific value gas (5.5 – 10.6 MJ/Nm<sup>3</sup>) steam gasification of Black pellets gave the highest due to high CO and  $C_xH_y$  content. High gas yield was seen with air gasification (2-2.4 Nm<sup>3</sup>/kg) and Gray pellets at high ER was the most efficient (79.5%). Even with significantly low exit temperature with Black pellets, only small increment of tar was seen and dominated secondary tar.

The characteristic ratios of tar were analyzed and their validity of predicting total tar content was discussed when steam is used in gasification. While  $C_2H_6/(C_2H_4+C_2H_2)$  ratio and P/A ratio fail to predict the trend of tar content when steam is present, I/N ratio still shows valid prediction of the trend of tar content at tested conditions.

#### **5 Acknowledgements**

Authors like to acknowledge KIC-innoenergy project which provided the financial support and Zilkha Biomass Energy and Boson Energy S.A. which provided the biomass samples for experimental work.

#### **REFERENCES**

[1] N. Mosier, C. Wyman, B. Dale, R. Elander, Y.Y. Lee, M. Holtzapple et al., Feature of promising technologies for pretreatment of lignocellulosic biomass, *Bioresource Technology*, 96 (2005), 673-686



International Flame Research Foundation  
*The Finnish and Swedish National Committees*  
*Finnish – Swedish Flame Days 2013*

- [2] M. Moniruzzaman, Effect of steam explosion on the physiochemical properties and enzymatic saccharification of rice straw, *Applied Biochemistry Biotechnology*, 59 (1996), 283-97
- [3] J. Li, G. Henriksson, G. Gellerstedt, Lignin depolymerization/repolymerization and its critical role for delignification of aspen wood by steam explosion, *Bioresource Technol.* 98 (2007) 3061-3068.
- [4] L.P. Ramos, The chemistry involved in the steam pretreatment of lignocellulosic materials, *Quim, Nova* 26 (2003) 863–871.
- [5] K. Stenberg, C. Tengborg, M. Galbe, G. Zacchi, Optimisation of steam pretreatment of SO<sub>2</sub>-impregnated mixed softwoods for ethanol production, *Journal of chemical Technology and Biotechnology* 71 (1998) 299–308.
- [6] P. Sassner, Lignocellulosic ethanol production based on steam explosion pretreatment and SSF, Lund University, 2006.
- [7] W.E. Kaar, C.V. Gutierrez, C.M. Kinoshita, Steam explosion of sugarcane bagasse as a pretreatment for conversion to ethanol, *Biomass and Bioenergy* 14 (1998) 277–287.
- [8] M. Öhman, C. Boman, H. Hedman, R. Eklund, Residential combustion performance of pelletized hydrolysis residue from lignocelluloses ethanol production, *Energy Fuels* 20 (2006) 1298–1304.
- [9] G. Eriksson, B. Kjellström, B. Lundqvist, S. Paulrud, Combustion of wood hydrolysis residue in a 150 kW powder burner, *Fuel* 83 (2004), 1635–1641.
- [10] S.L. Blunk, B.M. Jenkins, Combustion properties of lignin residue from lignocellulose fermentation, National Renewable Energy Laboratory, 2000.
- [11] A.K. Biswas, K. Umeki, W. Yang, W. Blasiak, Change of pyrolysis characteristics and structure of woody biomass due to steam explosion pretreatment, *Fuel Processing Technology*, 92 (2011), 1849-1854
- [12] N. Jacquet, N. Quievy, C. Vanderghem, S. Janas, C. Blecker, B. Wathelet, et al., Influence of steam explosion on the thermal stability of cellulose fibres, *Polymer Degradation and Stability*, 96 (2011), 1582-1588
- [13] M.J. Negro, P. Manzanares, J.M. Oliva, I. Ballesteros and M. Ballesteros, Changes in various physical/chemical parameters of Pinus pinaster wood after steam explosion pretreatment, *Biomass and Bioenergy*, 25 (2003), 301-308
- [14] W. Xu, G. Ke, J. Wu, X. Wang, Modification of wool fiber using steam explosion, *European Polymer Journal*, 24-9 (2006), 2168-2173
- [15] Z. Sebestyén, E. Jakab, Z. May, B. Sipos, K. Réczey, Thermal behavior of native, washed and steam exploded lignocellulosic biomass samples, *Journal of Analytical and Applied Pyrolysis* (2013), <http://dx.doi.org/10.1016/j.jaap.2013.02.011>
- [16] N. Sathitsuksanoh, Z. Zhu, S. Wi, Y.-H. P. Zhang, Cellulose Solvent-Based Biomass Pretreatment Breaks Highly Ordered Hydrogen Bonds in Cellulose Fibers of Switchgrass, *Biotechnology and Bioengineering*, 108-3(2011), 521-529



International Flame Research Foundation  
*The Finnish and Swedish National Committees*  
*Finnish – Swedish Flame Days 2013*

- [17] M. Poletto, A. J. Zattera, R.M.C. Santana, Thermal decomposition of wood: Kinetics and degradation mechanisms, *Bioresource Technology*, 126 (2012), 7-12
- [18] W. Blasiak, D. Szewczyk, C. Lucas, Reforming of biomass wastes into fuel gas with high temperature air and steam, *Pyrolysis and Gasification of Biomass and Waste*, 30 September–1 October 2002, Strasbourg, France, 2002.
- [19] S. Kalisz, C. Lucas, A. Jansson, W. Blasiak, D. Szewczyk, Continuous high temperature air/steam gasification (HTAG) of biomass, 6th Int. Conf. on Science in Thermal and Chemical Biomass Conversion STCBC'04, 30 Aug.– 2 Sept. 2004, Victoria, Vancouver Island, Canada, 2004.
- [20] C. Lucas, W. Blasiak, D. Szewczyk, J. Stasiak, High temperature air and steam gasification of wood pellets, *Finnish–Swedish Flame Days 2002*, September 24–25, 2002, Vaasa, Finland, 2002.
- [21] C. Lucas, D. Szewczyk, W. Blasiak, R. Abeyweera, Gasification of biomass wastes in updraft fixed bed gasifier with high temperature air and steam, *Proceedings of the Conference: Regional Conference on Energy Technology towards a Clean Environment*. 12–14 February 2003—Phuket, Thailand, 2003.
- [22] C. Lucas, D. Szewczyk, W. Blasiak, S. Mochida, High-temperature air and steam gasification of densified biofuels, *Biomass and Bioenergy* 27 (2004) 563–575.
- [23] Z. Sebestyén, Z. May, K. Réczey, E. Jakab, The effect of alkaline pretreatment on the thermal decomposition of hemp, *J. Therm. Anal. Calorim.* 105 (2011) 1061-1069
- [24] A. K. Biswas, W. Yang, W. Blasiak, Steam pretreatment of *Salix* to upgrade biomass fuel for wood pellet production, *Fuel Processing Technology*, 92 (2011), 1711-1717
- [25] Yang, H., Yan, R., Chen, H., Lee, D.H., Zheng, C. 2007. Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86(12-13), 1781-1788.
- [26] T.A. Milne, R.J. Evans and N. Abatzoglou *Biomass Gasifier “Tars”*: Their Nature, Formation and Conversion, National Renewable Energy Laboratory, 1998
- [27] C. Brage, Q. Yu, K. Sjöström, Characteristics of evolution of tar from wood pyrolysis in a fixed bed reactor, *Fuel*, 75 (1996), 213–219.
- [28] A. Ponzio, S. Kalisz, W. Blasiak, Effect of operating conditions on tar and gas composition in high temperature air/steam gasification (HTAG) of plastic containing waste, *Fuel Processing Technology* 87(2006), 223-233