Pilot plant experiences with fluidised bed gasification of orujillo and MBM

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Abstract
Gasification tests trials were conducted in a 150 kW_{th} air-blown bubbling fluidised-bed reactor operated at atmospheric pressure. The objective was to study the effect of operating conditions and bed material on gas and ashes produced. This article presents the experience acquired by gasifying two fuels, orujillo and MBM. Orujillo is an agricultural residue from the olive oil industry produced in large quantities in several EU countries, and meat and bone meal (MBM) is a waste difficult to dispose of. The tests were carried out using several bed materials such as silica sand, ofite, and limestone. The gasification of orujillo using sand as bed material was not technically successful because of sintering problems. However, the use of ofite made it possible to successfully avoid sintering and agglomeration to a great extent. The impact of limestone addition was studied. Carbon conversions up to 90% and 98% were achieved for orujillo and MBM, respectively. This paper describes the lessons learned for gasifying the two biomasses and discusses the quality of the ashes generated and their impact on the economics of their future utilisation.

1. Introduction

Atmospheric air gasification of biomass and waste in a bubbling fluidised-bed reactor is an attractive, simple process to convert a solid material to a gaseous fuel [1]. This process leads to a fuel gas suitable for co-firing in existing boilers and, if a proper gas cleaning section is installed, for feeding efficient gas engines and gas turbines for generating electricity. Besides the energetic value and the quality of the producer gas, one of the key factors limiting gasification is related to fly ash quality, especially the carbon content of the ash. This information is of major importance because it has an impact on the process efficiency. An increase in carbon conversion results in higher efficiency and has a direct positive influence on power production efficiency. In addition, the increase of carbon conversion makes it possible to recycle or make use of ashes as raw material in other processes. An essential part of the ash quality improvement and ash volume reduction is therefore the improvement of carbon conversion since it will facilitate the development of sustainable economical methods for ash management.

This work aims to assess the impact of operating conditions (governed by modifying the fuel rate and air-to-biomass ratio) and bed material on the ash produced. It presents the experience acquired by gasifying two fuels: orujillo and MBM. Orujillo is a residue of the olive oil extraction industry available in large quantities in various EU countries, especially Spain, Greece and Italy. This fuel has a high heating value but contains a large amount of alkali metals (primarily potassium), which can cause serious deposit formation and agglomeration in high-temperature processes like fluidised-bed gasification or combustion. Several papers have been published on the gasification of leached orujillo [2], [3], [4]. Leaching obviates especially measures to deal with ash slagging, deposition and bed agglomeration. There are also several papers on the use of this biomass in pilot plants, [5], [6], [7]. References [4], [8] and [5] describe pilot plant tests in a 300 kW_{th} atmospheric CFB using leached orujillo. We found only two studies on the gasification of orujillo in BFBs ([9], [10]). The work described in ref. [9] discusses the impact of two additives (dolomite and olivine) on the producer gas quality (mostly on tar, dust and ammonia). Ref. [10] assesses the technical viability of long-term trials using untreated orujillo (i.e., direct from mill) with high ash content (around 20%). Other studies give useful information about the gasification of orujillo. For instance, refs. [11], [12] and [13] deal with char reactivity studies.

We found no studies on FB gasification of MBM in the specialised literature. Only a few co-gasification experiences have been reported from the IGCC plant in Puertollano [14], where a maximum MBM content of 5% in the feed blends was tested. On the other hand, there is relatively widespread experience with MBM combustion [15], [16].

2. Experimental

2.1. Fuels and bed material

Table 1 presents a typical analysis of the orujillo and MBM used in the tests described in this study. Bed materials used include silica sand, ofite and limestone. Ofite is a subvolcanic rock with mineralogical formula $(Ca·Mg·Fe·Ti·Al)_2·(Si·Al)_2O_6$. The ofite used in this work had an average particle size of 380 µm and a particle density of 2620 kg/m^3. The limestone used in the MBM gasification tests had an average particle size of 750 µm and a particle density of 2580 kg/m^3. Approximately 12 kg of inert bed material were used during each test. In the tests using blends of ofite and limestone as additive, the ratio of ofite to limestone was 65/35% wt. This established an approximate ofite-to-lime ratio of 80/20 after the calcination of the limestone. Table 2 presents the ultimate and proximate analysis of the inert bed materials and their particle-size distribution. The gasification tests using sand as bed material were not technically successful because of defluidisation problems caused by rapid sintering. Hence sand characterisation is not reported here.

2.2. Test facility

The experiments were carried out in an experimental rig described in detail in a previously published article [10]. Therefore, only a brief description is given here. The bubbling fluidised-bed reactor was designed to process up to 30 kg/h of solid biomass. Fig. 1 and Table 3 present a schematic diagram and some relevant operating and design data on the pilot plant, respectively.

The fuel is injected at the bottom of the gasifier where there is a slightly positive pressure. The feed system consists of two hoppers with a knife valve between them. There are also two screws, the feeder screw placed immediately after the metering hopper and the high-speed water-cooled injection screw. The air for combustion or gasification can be preheated in a 7 kW electrical heater and enters the reactor at the plenum located just under the gas distributor.

The BFB gasifier consists of a refractory stainless steel reactor fitted with a perforated distributor plate. It has a total height of 4.2 m and two sections, the 150 mm ID bed zone and the 250 mm ID freeboard. The reactor design is flexible, which makes it possible to remove the ashes and supply heat in several ways. The ashes can be removed by means of an overflow situated in the upper zone. This system allows the ashes to be bled off at various bed heights. The ash can also be purged from the bottom part of the gasifier by manipulating a ball valve situated under the distributor.

The heat is supplied with a 27 kW_{th} refractory lined oven. The oven is used mainly in two ways (see below). Temperatures are measured along the bed and freeboard by means of eight thermocouple probes. Three pressure taps are located along the side of the reactor to monitor the fluidisation conditions of the bed.

The gas leaving the freeboard section passes through two cyclones in series to collect entrained particles and through a wet scrubbing system to remove the condensable tars. Char, ash and inert bed material particles are collected in bins placed under the cyclones. The gas sampling point is located downstream from the scrubber. A slipstream of the fuel gas is taken out by an Inconel probe with a filter to remove particles. The sampling line is electrically heated to avoid condensation of organic compounds within the probe. The composition of the produced gas is measured continuously (CO, CO_2, CH_4, H_2 and O_2). Finally, the producer gas flowrate is measured by a rotameter.

The produced gas is finally introduced into a 85 kW_{th} post-combustion chamber. This is a refractory lined horizontal cylinder, allowing working at temperatures up to 900°C.

2.3. Test design, procedure and sampling

The reactor has a flexible design which enables setting various modes of operation. The tests with orujillo were carried out with the oven off. This form of operation simulated the usual setup found in most gasification pilot plants, insulated with blankets. With this operational setup, the heat losses are high owing to the small scale of the plant. The tests with MBM were performed by adjusting the oven in to provide the heat necessary to compensate for the wall heat losses. Therefore, the tests carried out with MBM can be considered adiabatic. This operational procedure has revealed itself to be ideal to simulate full-scale systems where the area-to-volume ratio is much smaller (and hence relative heat losses based on the thermal biomass input).

In direct or autothermal gasification, given the type of biomass and the bed material, there are two main operating variables that can be independently varied within a limited range: the biomass throughput and the air flowrate. These two variables determine the equivalence ratio (ER), defined as the operating air-to-fuel mass ratio divided by the air-to-fuel mass ratio for stoichiometric combustion. The ER is the most important parameter in this type of gasifiers because it establishes the bed temperature and hence the gasifier performance (gas composition, heating value, carbon conversion, tar content, energetic efficiency and gas yield). An additional degree of freedom is introduced into the system if the heat supply is established independently.

At the beginning of each run, the bed material in the bed is heated up with the preheated air. After about an hour of heating, the bed temperature exceeds 400°C, and a small amount of biomass is fed in. In this oxidising atmosphere, the biomass is combusted and the reactor rapidly heated up to the desired process temperature. The computer-based data acquisition system is activated to monitor and record the temperature, the pressure drop and the feed rate values. The transition from combustion to gasification is made by increasing the biomass feed and thus decreasing the ratio between air and biomass flowrate.

In every test an initial transitory period of around 4-7 hours is followed by a steady-state period of 5-10 hours, which ends with the shutdown of the gasifier. The initial transient period is shorter in tests with MBM because the heating rate is higher, thanks to the heating support provided by the oven. After each test the two cyclone bins, the extraction ash bin and the overflow bin are sampled. The four locations are sampled twice and analysed for each run. Finally, one temperature probe is placed after the cyclones and another just before the blast enters the scrubber. This sampling protocol enabled us to correlate the ash volume and quality to the operating conditions.

3. Results

3.1. Orujillo gasification tests

No valid data using silica sand as bed material were obtained. The sintering and agglomeration processes were problematic, even at low temperatures (750-800ºC), but the difficulties were overcome by using ofite as bed material. This bed material prevented ash from melting and hence established stable operational conditions. The second column of Table 4 presents a summary of the most relevant parameters obtained from gasifying orujillo.

In the tests presented here the effect of ER was analysed using two air flowrates (18 and 20 Nm^3/h) and several orujillo feed rates ranging from 15 to 30 kg/h. These conditions established an air/orujillo mass ratio within the range of 0.8-1.5 (Nm^3 air/kg orujillo d.a.f) and an ER ranging from 0.17 to 0.31.

Table 5 and Table 6 show the characterisation of the ashes sampled. In particular, Table 5 shows the elemental and ultimate analysis of the ashes from the cyclones, ash bin and overflow for a typical orujillo test. For comparison, the first two columns of Table 5 include the analysis of the orujillo. Table 6 displays the carbon content of the ashes taken at various locations. Figure 2 illustrates how the carbon content of ashes from cyclone 1 decreases as temperature increases (or, equivalently, when ER decreases).

The carbon conversion, defined as the degree to which the carbon in the fuel is converted into gaseous products, is presented in Fig. 3. As already discussed, carbon conversion is a key parameter in this work because, apart from the positive impact on efficiency, it also enables the utilisation of the gasification ash produced. This is mainly because the high carbon content of gasification fly ash limits its field of application. In the case of biomass gasification, the typical high chlorine and alkali content of ashes (and heavy metals if wastes are gasified) make its potential utilisation even more difficult. This is very important from the economic point of view in future large-scale applications.

Most practical ER values for biomass gasification range between 0.20 and 0.40. Lower values of ER produce a high-tar-content gas and are therefore allowed only when the produced gas is going to be used as fuel gas in a furnace or in a boiler without previously cooling it. On the other hand, high values of ER give higher operating temperatures and lower amounts of tar in the gas but at the cost of reducing the heating value of the gas produced. Specifically, the ER range studied was 0.17–0.31 and the carbon conversion varied between 73.4% and 86.1%. Fig. 4 shows how the carbon conversion can be properly optimised by demonstrating that there is an optimum of gasification efficiency within the range shown in Figures 3 and 4. By way of summary, the use of ofite allows us to optimise gasification by operating at higher temperature. However, more than 90% conversion is not possible because of the agglomeration problems caused by sintering. Therefore, we have selected a range of ER that makes it possible to obtain relatively acceptable carbon conversion with maximum efficiency.

3.2. MBM gasification tests

Initially, gasification trials with as-received MBM were performed. The typical sizes of as-received MBM ranged between 0.5 and 1.0 mm. Thermal decomposition of MBM in feed bins created a sticky solid deposit on the walls. This phenomenon was due to heat propagation from the gasifier to the feed system and it was necessary to take measures to prevent this, such as filling the feed bin with small batches of MBM, controlling injection of N_2 (1-3 Nm^3/h) to keep the feed screw cool, redesigning the screws to adapt to MBM and screening the MBM to select sizes from 1 to 3 mm. New gasification trials were tried but these measures were not entirely satisfactory. Low feed flowrates of MBM were detected and after two or three hours of operation the plant had to be shut down because of several problems in the feed system. To overcome these problems, the last (also the most expensive) measure taken was pelletisation of the MBM. The pellets had a constant diameter of 4 mm and a variable length ranging between 5 and 20 mm. Finally, the screw was recalibrated for various temperatures for the new feed . After these modifications the pilot plant was ready and satisfactory operation was achieved.

A complete set of successful MBM tests was carried out using ofite, limestone and a mixture of the two as bed material. As with orujillo, two independent variables were used. Three levels of air-to-fuel ratios were set by modifying the air and the MBM flowrates. The gasification tests with MBM showed quite good fluidised behaviour. A summary of the typical results obtained is given in the first column of Table 4. The experimental results indicate that MBM is not a good “gasifiable” feedstock since the final gas composition has low CO and H_2 concentrations.

A general comparison between the gasification performance with MBM and orujillo is given in Table 4. As shown in the table, MBM gasification ashes have lower carbon content (typically 4% for MBM vs. 7-18% for orujillo). In spite of this, the gas obtained from MBM gasification is rather poor (low LHV and gasification efficiency). The reason is probably the severe dilution of the producer gas obtained from MBM gasification. This is due to the lower oxygen content of MBM compared to orujillo, which makes the air-to-fuel ratio higher for MBM gasification.

The tests carried out with lime as bed material (or blends of this with ofite) showed a reduction up to 50% in tar content. However, no major differences were found in gas composition. The effect of using limestone as additive is shown in Table 7.

3.3. Comparison of MBM and orujillo ashes

An extensive characterisation was made of the ashes generated in the foregoing tests, which facilitated an assessment of ways to make use of the ash and hence to design ash treatment methods when needed. A rigorous report of the findings is, nevertheless, beyond the scope of this paper, and we have included only a brief summary, as follows. In general, high concentrations of P and Ca (typical of bones) were found in MBM ashes. In orujillo ashes, on the other hand, high values of K were measured. The solubility of these components, in contrast, was very low. The solubility of P in MBM ashes showed especially low values — under 1% in DIN leaching tests — whereas the results of TCLP leaching tests turned out to be much higher, roughly 60%. In addition, high Cr content was measured in orujillo ashes, but it is thought that the main reason is the decomposition of steel in the reactor due to the severe abrasion in the fluidised-bed process. The chlorine content of orujillo ashes was 0.5-1.5% wt, which is probably the main handicap of this ash. In both ashes the PAH (polyaromatic hydrocarbons) were found to be very high (typically 100 mg/kg). In summary, the high carbon content of both ashes (especially orujillo) is a general handicap difficult to overcome in terms of the economics of future ash utilisation. MBM ash from other thermochemical processes is often considered attractive for fertiliser manufacture. However, the high PAH content found in this work make difficult this application. In addition, the low solubility of P and Ca make the attractiveness of this route doubtful, at least in common soils. In acid soils, however, the solubility of some key agriculture components could improve to a great extent. This is supported by the results from TCLP tests. Therefore, the use of both ashes in agriculture as soil amendments could be a reasonable route if previous treatments such as combustion and washing are applied. Obviously, the economy of these utilisation options needs further evaluation.

4. Conclusions

A biomass (orujillo) and a waste (MBM), were successfully gasified in a pilot-scale fluidised-bed reactor. Long-term gasification tests with orujillo were very challenging due to the agglomeration problems related to its high potassium content. Under a reasonable thermal level and with the selection of a new inert material, ofite, long-term tests were finally successful. For orujillo testing, an optimum ER around 0.25 was established to obtain relatively acceptable carbon conversion (90%) with maximum efficiency. The other fuel gasified was MBM, a residue difficult to dispose of. This waste was included in the study to compare gasification to other thermochemical processes. Up to 97% carbon conversion was achieved for this waste in our study, although the gas quality was rather poor. A brief discussion about the potential utilisation options for the ash produced by the two fuels has been included. In general, the high carbon and PAH content of both ashes and the chlorine content (only for orujillo) make the economics problematic for future utilisation of these ashes. Using them as a soil amendment after some kind of pre-treatment seems to be the most reasonable option for both.

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Table 1. Chemical characterisation of the fuels

	Orujillo		MBM	
	% (w.b.)	% (d.b)	% (w.b.)	% (d.b)
LHV (MJ/kg)	14.09	15.80	19.75	20.57
HHV (MJ/kg)	15.02	16.84	21.27	22.05
C	-	41.01	-	45.04
H	-	4.16	-	6.4
N	-	1.13	-	7.47
S	-	-	-	0.64
O	-	30.64	-	21.58
Moisture	10.82	-	6.91	-
Ashes	20.41	22.88	17.57	18.87
Volatile matter	53.34	59.81	67.05	72.03
Fixed carbon	15.44	17.31	8.47	9.1

Table 2. Chemical and physical characterisation of ofite and limestone.

Main Analysis (wt %)					
	Ofite	**Limestone**		**Ofite**	**Limestone**
Si as SiO_2	53.93	0.30	Na as Na_2O	3.49	-
Al as Al_2O_3	13.61	0.10	K as K_2O	0.48	-
Fe as Fe_2O_3	9.15	-	Sulphates as SO_3	-	0.10
Ca as CaO	11.15	55.40	Moisture at 105ºC	0.47	0.80
Mg as MgO	7.90	0.20	Weight loss at 750ºC	0.64	43.50

Size Distribution (wt %)										
Size (µm)		2500	1900	1410	1000	500	250	125	100	62
wt %	**Ofite**	100	98	74.3	45.6	17.9	8.54	5.9	5.47	3.8
	Limestone	-	-	100	99.9	1.14	0.13	0.10	0.07	0.01

Table 3. Technical and operating data of pilot plant facility

Inside bed diameter	0.15 m
Bed height	1.7 m
Inside freeboard diameter	0.25 m
Freeboard height	2.5 m
Fluidisation velocity	0.8 – 1.4 m/s
Bed material	Ofite, limestone
Fuel	Orujillo, MBM
Fuel feed rate	6 – 35 kg/h
Gasification agent	Air
Operating temperature	700 – 850ºC
Operating pressure	Atmospheric
Fluidisation regime	Bubbling
Maximum thermal capacity	150 kW_{th}

Table 4. Comparison of main MBM and orujillo gasification parameters

	MBM	ORUJILLO
Bed material	Ofite, CaO, Ofite+20%CaO	Ofite
Air ratio (Nm3 air/kg fuel d.a.f.)	1.2 – 2.8	0.8 – 1.5
Equivalent ratio	0.20 – 0.42	0.17 – 0.31
Gasification temperature (ºC)	710 – 860	700 – 820
Freeboard temperature (ºC)	500 – 600	530 – 650
Gas yield (Nm3 gas dry/kg fuel d.a.f.)	2.1 – 3.7	1.9 – 2.5
LHV (MJ/Nm3)	1.0 – 3.0	4.5 – 5.5
Gasification efficiency (cold)	0.25 – 0.40	0.50 – 0.70
Carbon conversion	0.80 – 0.97	0.7 – 0.85
Gas composition (%v/v, dry):		
H2	1.0 – 8.0	8.0 – 12.0
CO	3.0 – 12.0	9.0 – 14.0
CH4	2.0 – 5.0	2.5 – 3.5
CO2	10.0 – 16.0	16.0 – 20.0

Table 5. Typical ash analysis (%) of orujillo ashes for the different sample locations

	Fuel (orujillo)		Cyclone 1		Cyclone 2		Overflow		Bottom ash	
	% (w.b.)	% (d.b)	% (w.b.)	% (d.b)	% (w.b.)	% (d.b)	% (w.b.)	% (d.b)	% (w.b.)	% (d.b)
C	-	41.01	-	8.61	-	11.81	-	9.45	-	0.44
H	-	4.16	-	<0.05	-	0.14	-	0.48	-	<0.05
N	-	1.13	-	0.29	-	0.5	-	0.22	-	0.08
O	-	30.64	-	5.08	-	6.96	-	6.23	-	0.27
Moisture	10.82	-	0.98	-	2.81	-	1.13	-	0.15	-
Ash	20.41	22.88	85.17	86.02	78.32	80.59	82.68	83.62	99.06	99.21
Volatile matter	53.34	59.81	7.79	7.86	11.05	11.37	10.99	11.12	0.96	0.97
Fixed carbon	15.44	17.31	6.06	6.12	7.81	8.04	5.2	5.26	0	0

Table 6. Total carbon content (%) of orujillo ashes for the different sample locations

Test	T bed (ºC)	ER	%C Overflow	%C Cyclone 1	%C Cyclone 2
1	700	0.17	37.54	20.18	22.08
2	740	0.20	20.77	12.00	15.24
3	750	0.22	37.44	15.78	18.08
4	760	0.23	29.85	14.51	19.51
5	785	0.24	19.85	14.03	15.86
6	780	0.29	8.24	11.58	9.66
7	820	0.31	5.33	9.09	12.04

Table 7. Effect of additive on gas produced and analysis of volume and quality of ash generated by MBM gasification (100% ofite and ofite/CaO=80/20)

	without CaO	with 20% CaO
Tar content (g/Nm3, dry)	17 – 21	8 – 13
Particle content (mg/Nm3, dry)	200 – 900	2000 – 4000
Carbon cyclone 1 (%w)	4	8
Carbon cyclone 2 (%w)	12	9
W/F (kg inert/kg fuel·h-1)	1.25	1.3
C1/F (kg ash/ kg fuel)	0.07	0.13
C2/F (kg ash/ kg fuel)	$1.52 \cdot 10^{-3}$	$1.16 \cdot 10^{-3}$

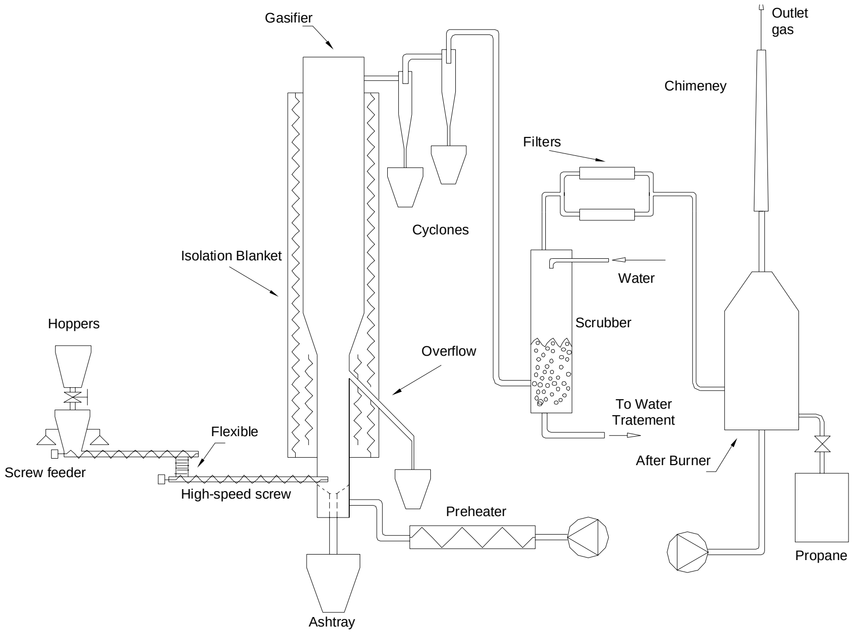

Figure 1. BFB 150 kW_{th} pilot plant facility

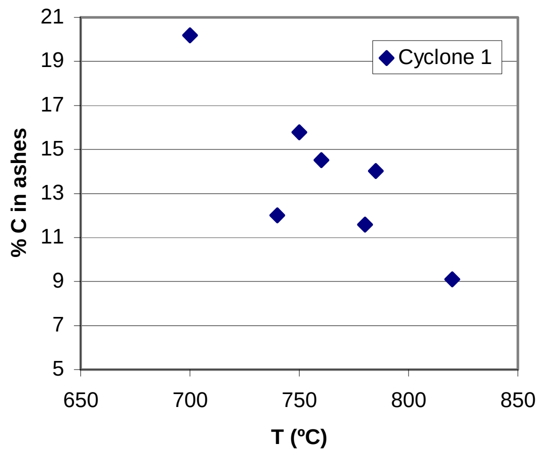

Figure 2. Carbon content of ashes in cyclone 1 as a function of T

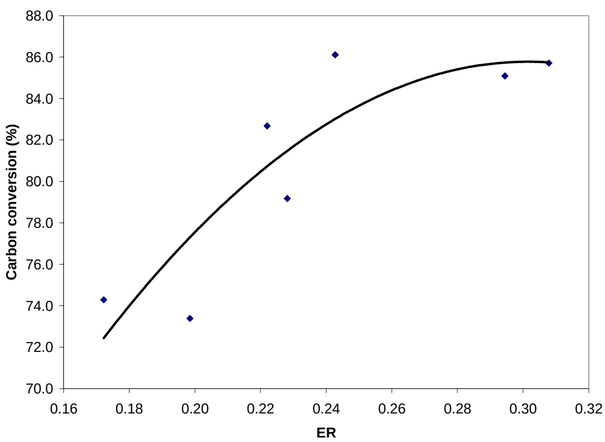

Figure 3. Carbon conversion vs. ER

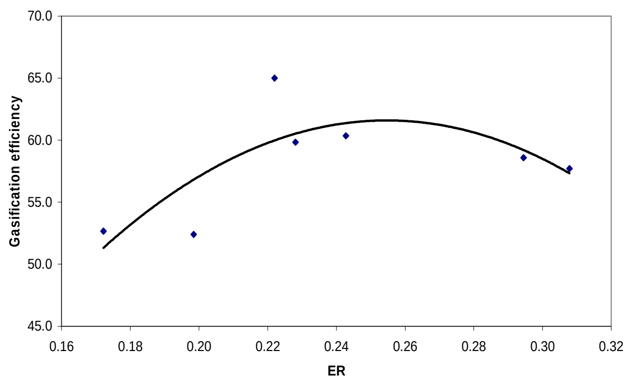

Figure 4. Gasification Efficiency vs. ER