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# COMPARISON OF COAL/SOLID RECOVERED FUEL (SRF) WITH COAL/REFUSE DERIVED FUEL (RDF) IN A FLUIDISED BED REACTOR

**S.T. Wagland[a], P. Kilgallon[a], R. Coveney[a], A. Garg[b], R. Smith[a], P.J. Longhurst[a], S.J.T. Pollard[a] and N. Simms[a]***

[a]School of Applied Sciences, Sustainable Systems Department, Cranfield University, Cranfield, Bedfordshire, UK, MK43 0AL

[b]Centre for Environmental Science and Engineering (CESE), Indian Institute of Technology Bombay, Powai, Mumbai, INDIA, 400076

**Abstract**

An experimental study was undertaken to compare the differences between municipal solid waste (MSW) derived solid recovered fuel (SRF) (complying with CEN standards) and refuse derived fuel (RDF). Both fuels were co-combusted with coal in a 50 kW fluidised bed combustor and the metal emissions were compared. Synthetic SRF was prepared in the laboratory by grinding major constituents of MSW such as paper, plastic, textile and wood. RDF was obtained from a local mechanical treatment plant. Heavy metal emissions in flue gas and ash samples from the (coal + 10% SRF) fuel mixture were found to be within the acceptable range and were generally lower than that obtained for coal + 10% RDF fuel mixture. The relative distribution of heavy metals in ash components and the flue gas stream shows the presence of a large fraction (up to 98%) of most of the metals in the ash (except Hg and As). Thermo-gravimetric (TG) analysis of SRF constituents was performed to understand the behaviour of fuel mixtures in the absence and presence of air. The results obtained from the experimental study will enhance the confidence of fuel users towards using MSW-derived SRF as an alternative fuel.

***Key Words***: Fluidized bed combustion; coal; municipal solid waste; solid recovered fuel; refuse derived fuel; metal analysis; thermo-gravimetric analysis

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* Corresponding author. Tel.: +44 1234 750111 extn 2954; Fax: +44 1234 754755,

E-mail address: n.j.simms@cranfield.ac.uk (N. Simms)

## 1. Introduction

Combustion of biomass rich waste derived fuels is currently being promoted worldwide, as the use of such fuels in energy intensive industries can mitigate greenhouse gas (GHG) emissions and can be economical for energy users. The biomass fraction of such fuels is considered 'carbon neutral' and thus these may also bring incentives in the form of renewable energy for end users. The EU Landfill Directive (Council of the European Union, 1999) offers further incentive by prescribing targets to member states for diverting biodegradable municipal solid waste (MSW) from landfill. Failure to achieve these targets may incur a heavy financial penalty on the local authorities (LAs) who fail to meet their own targets set by national government. In the context of the UK, the situation is particularly challenging due to the heavy reliance on landfilling in the past. The most recent data suggest that England still landfilled 54.4% of the total MSW in 2007-08 (Defra, 2008), which is 15.5 million tonnes (Defra, 2008).

In recent years, several combustion studies have been performed using unsorted or pre-treated MSW (Chang et al., 1998; Ferrer et al., 2005; Garg et al., 2007b; Guo et al., 2001; Kobyashi et al., 2005; Kouvo and Backman, 2003; Piao et al., 2000; Piao et al., 1998). However, there are still concerns surrounding the heterogeneity of waste material, calorific value (CV) and heavy metal emissions. To overcome this ambiguous situation regarding fuel quality, the European Commission has given mandate to CEN Technical Committee CEN/TC 343 "Solid Recovered Fuels" to prepare a document classifying solid recovered fuels (SRF) (European Committee for Standardisation, 2006). Recently, SRF co-combustion studies have been performed in a pulverised fuel-fired combustion reactor to observe the fate of mercury and chlorine (Hilber et al., 2007b). Two different qualities of SRF complying with CEN standards were being used as co-fuel. One of these was derived from the high calorific fractions of MSW and the resulting SRF was mixed with commercial waste (25%) to prepare the other SRF. Addition of commercial waste reduces the quantity of

chlorine in the resulting product. It was found that chlorine concentrations in the flue gas stream rises with increase in SRF share. However, use of SRF did not change total mercury content significantly. Gaseous elemental mercury was found to be reduced behind the filter, whereas the $HgCl_2$ concentration increased behind the filter. In another study, Hilber *et al.* (Hilber et al., 2007a) also developed a method to characterise the de-volatilisation process of SRF meeting CEN requirements.

In order to prepare a fuel complying with CEN standards, residual or mixed MSW can be treated using mechanical biological treatment (MBT) or extensive mechanical treatment (MT) process. MSW derived fuel is known as solid recovered fuel (SRF) or refuse derived fuel (RDF) depending upon the composition and characteristics of fuel. SRF is considered more homogeneous and less contaminated fuel, and is market-driven due to tighter quality specifications, whereas RDF has an input-driven specification (Juniper Consultancy Services Ltd, 2005). The present study was undertaken to compare the heavy metal emissions resulting from the co-combustion of synthetic SRF and real RDF (derived from MSW) with coal.

MBT is a method for treating residual or mixed MSW and in some parts of Europe it is relatively widespread, e.g. Germany, Italy and Austria (Steiner, 2005). In MBT processes, a series of biological and mechanical treatment unit operations are employed to separate out recyclables, compost, biogas and fuel. MSW derived SRF or RDF has paper, plastic, textile and wood as their main constituents. The Ecodeco process (Ecodeco, 2010) is an example of a commercially available MBT process producing SRF, which is currently operating in the UK in East London, England and Dumfries and Galloway, Scotland. This process employs a bio-drying method for partial stabilisation of untreated MSW (Friends of the Earth, 2008). The bio-drying process reduces the moisture in the waste, thus making mechanical separation more efficient. SRF has the potential use as co-fuel in cement kilns, power plants and dedicated incineration facilities (Garg et al., 2009; Garg

et al., 2007a). However, it is necessary to address the emissions from the co-combustion of this material prior to adoption in the UK, as limited information is available in the open literature.

The aim of this study was to produce synthetic SRF in the laboratory by grinding paper, plastic, wood and textile and perform co-combustion studies with coal in a fluidized bed combustor. The heavy metal emissions obtained from SRF co-combustion studies were compared with those from coal and coal + RDF mixture combustion studies. The MSW derived SRF and RDF proportion in the final fuel mixture was kept at 10% (w/w) as, in practice, the supply of SRF or RDF could not easily exceed 10% of total fuel for coal-fired power stations. The distribution of trace elements in the ash components and flue gas stream was also calculated. The thermal behaviour of the paper, plastic and coal was investigated in the presence and absence of oxygen using thermo-gravimetric analysis (TGA).

## 2. Experimental

### *2.1. Fluidized bed combustor*

The combustion of the fuel or fuel blends was carried out in a 50 kW capacity pilot scale fluidised bed combustor test facility located in the Centre for Energy and Resource Technology (CERT) at Cranfield University, UK (Figure 1).

The fuel was fed continuously into the combustor through a hopper via a drop tube above the surface of fluidized silica sand bed. The combustion was controlled by adjustments to the fuel feed rate and the preheated air flow rate. The flue gas passed into a second (refractory lined) chamber then through a water-cooled heat exchanger assembly. The resulting gas stream was then entered into the cyclone separator, where fly ash was separated from flue gas. After the cyclone, flue gas was sent to an extraction fan before release to atmosphere via a stack. The combustor was operated

at below atmospheric pressure to prevent the release of gases into the combustion hall. The combustor was equipped with bottom and fly ash removal devices and thermocouples were installed to measure the fluidised bed temperature at the top of the combustion zone and pre-heater. Fly ash samples were collected from the fly ash silo located under the cyclone assembly. The CO concentration was kept as low as possible (near to zero) to achieve optimum combustion.

The fluidised bed combustor was used for relatively short periods with solid fuels allowing a sufficient steady state period; therefore no extraction of bed material was necessary during its operation. The bed was emptied only when cool after an operational run and replaced with fresh sand before the next experimental run.

### *2.2. Sampling, measurement and analytical methods*

Gas sampler ports were provided in the combustor for sampling. One port was used for online CO and $CO_2$ monitoring of the flue gases, while the other one was used for trace metal sampling. The air flow rate was measured by means of rotameters and this was kept at *ca.* 1400 l/min. The flue gas samples for metal analysis were collected by three bubbling traps immersed in a cold bath. The first two traps contained 10% nitric acid to dissolve the metals into solution and the third one was a guard of water to protect the pump from the acid. The metals measured in the flue gas samples include Cr, Zn, Cu, Ni, Pb, Fe, Ca, Mg, Na, K, Al, Mn, Cd and Co. Measurements of metal concentrations were made using an Atomic Absorption Spectrophotometer (AAS) (Hitachi Z8100 Polarized Zeeman Spectrophotometer).

Bottom ash and fly ash samples were sent to a commercial testing agency (TES Bretby, Staffordshire, UK) for the determination of heavy metals (including Hg).

TGA was carried out using a thermogravimetric analyser manufactured by CI Instruments Ltd. (ROBAL with a 5 gram head). Experimental runs were performed at a heating rate of 10 °C/

min with a target temperature of 800 °C. Two types of experimental runs were undertaken; $N_2$ was used for pyrolysis volatilization and air used for the combustion runs. Gas flow rate in both was kept at 20 ml/min. A sample size of 200 mg was used for the experimental runs.

### *2.3. Fuel samples*

The coal used for the combustion experiments was a bituminous coal from Daw Mill mine, UK. For experimental purposes, the coal was sieved to provide a particle size between 5 and 13 mm. Synthetic SRF was prepared by shredding and grinding paper, saw dust, polypropylene, polyethylene, PVC, and textiles. The composition of synthetic SRF sample was similar to that obtained from the Ecodeco process (Cozens, 2004) as this is a commercially operational facility . The synthetic fuel comprised 58% paper, 22% plastic, 15% textile and 5% wood by weight (w/w). Polypropylene (8% w/w), polyethylene (12% w/w) and PVC (2% w/w) were used as representative of plastics, whereas conifer saw dust was used for wood. Polypropylene and PVC were supplied by Aldrich, UK. Polyethylene was in the form of unused carrier bags obtained from a local supermarket. Junk mail and household sheets were used to represent paper and textile, respectively. In addition, 8% (w/w) water was added to the dry mixture.

MSW derived RDF was obtained from a local mechanical treatment plant situated in Leicester, UK. The RDF comprised 82% paper and card, 13% plastic, 5% others (wood, textiles and miscellaneous combustibles). RDF was also shredded and homogenised in a blender prior to pelletization.

SRF and RDF were used in the form of pellets having a diameter of 18 mm and a length of 30 mm in the combustion runs. This was a constraint of the combustion rig.

Samples of coal, synthetic SRF components, SRF and RDF were sent to TES Bretby, Staffordshire, UK for proximate, ultimate and ash analyses. Clean silica sand of grade 16/30 (size 0.50 mm- 1.00 mm) (supplied by Garside sands, Leighton Buzzard, Bedfordshire, UK) was used as

bed material during the combustion trials and was also sent to the same laboratory for the metal and oxide determination. The metals, including Silicon, were determined by solubilising the ash samples by acid dissolution and analysis of the solution by inductively coupled plasma (ICP) spectroscopy. The measured content of metals is then reported in the form of their highest oxide. Results obtained from the analyses are presented in Tables 1 and 2.

## 3. Results and discussion

### *3.1. Synthetic SRF characterisation*

The results from proximate and ultimate analyses of the fuels revealed that the net CV of the synthetic SRF was found to be 21.4 MJ/kg (as received basis) in comparison to 13.15 MJ/kg (as received) for RDF. The net CV of SRF was comparable to that of coal (26.75 MJ/kg, as received basis). The moisture and ash contents for RDF were found to be much higher in comparison to the other two fuels. The chemical analyses of the SRF constituents suggested that paper contributed mainly in the ash content of SRF. However, the volatile matter is much higher in SRF (79%) with RDF and coal only containing 46% and 33% volatile matter, respectively. Other major components such as, Cl and Hg in SRF were also found to be much lower quantity than RDF and coal. Higher concentrations of Hg, Zn, Cd, Pb, Cr metals in RDF shows the presence of materials containing hazardous components like batteries, cosmetics and paint (Sharma et al., 1997). Paper and plastics are also sources of Pb, Cu, Zn and Cd. Synthetic SRF contains smaller concentrations of these metals due to the absence of hazardous materials. RDF has the much higher quantities of Na and K in comparison to synthetic SRF and coal. This indicates the presence of salt in the RDF originating from food waste (Ward and Litterick, 2004). According to the CEN classification, the class code of

synthetic SRF used in the present study will be designated as (European Committee for Standardisation, 2006):

Class code Net CV 2; Cl 1; Hg 1.

SRF of this specification is suitable for cement kilns, power plants and fluidized bed combustion plants (van Tubergen et al., 2005). However, power plant operators may be more interested in the biomass content (Juniper Consultancy Services Ltd, 2005) as this can increase revenues in the form of Renewable Obligation Certificates (ROCs) (Ofgem, 2009). A material will qualify as biomass if 90% of energy could be derived from the biogenic fraction (Department of Trade and Industry (DTI), 2006). It is anticipated that MSW derived fuel can be made rich in biomass fraction by introducing partially stabilised biodegradable organic material in SRF, as the biogenic content of the SRF used in this study is likely to be significantly lower than 90% due to the plastic content (15%).

### *3.2. Fluidized bed combustor results*

#### *3.2.1. Combustion performance*

In this study, coal, coal + 10%w/w synthetic SRF and coal + 10%w/w RDF fuels were tested. The feed rate of the mixtures was varied from 6-9 kg/h to maintain the temperature of the combustion unit. The fuel mixture having lower CV and higher moisture content required a higher feed rate. During combustion experiments, the fluidized bed temperature varied between 750 and 950 °C. Temperature profiles with time for three fuel/ fuel mixtures revealed that temperature would rarely reach 900 °C for coal and RDF mixture during the whole run (2.5 h), whereas for the coal and

SRF mixture, the combustor attained a 950 °C temperature. This can be attributed to the higher moisture content of RDF (~30%) in comparison to synthetic SRF (~3%). Another reason could have been the presence of more volatile matter in SRF (~79%) that leads to a sharp increase in temperature. The fuel having lower moisture content and high volatile matter exhibited a faster increase in temperature, consistent with previous literature (Ferrer et al., 2005). A summary of the process conditions during the combustion trials is provided in Table 3.

Bottom ash samples obtained after coal and coal + 10% SRF fuels combustion were tested for carbon content. Samples were heated in a furnace at a temperature of 550 °C for 2 h. No loss in weight of coal bottom ash sample was observed, whereas a slight reduction (around 1%) was obtained in the latter case. These results indicate zero or low levels of carbon containing compounds in the ash.

***3.2.2. Metal concentrations in flue gas samples***

Figure 2 shows the concentrations of different metals in flue gases as a result of the combustion of different fuels. Metal emissions from coal combustion were found to be much lower in comparison to the other fuel mixtures except for Cr, Zn and Ni. However, little difference was observed in metal emissions for the (coal +10% RDF) and (coal + 10% SRF) mixtures.

The presence of Cu and Zn in the flue gas is indicative of the chloride species of the metals, as reported earlier by Kouvo and Backman (Kouvo and Backman, 2003). Pb concentrations were similar (~ 120 $\mu g/m^3$) in the flue gas samples obtained from coal and coal + 10% SRF. However, the flue gas sample from coal + 10% RDF combustion exhibited high Pb release (more than twice that obtained with other fuels). This may be due to the higher Pb concentration (~ 70 mg/kg) in RDF. According to a study reported by the Environment Agency in 2001 (Environment Agency, 2001), other metal emissions (such as Cr, Cu, Ni, Pb, Co, Mn etc.) must be below 1000 $\mu g/m^3$ for co-combustion in cement kilns. In the present study, the sum of these metals was 660 $\mu g/m^3$ for coal

and coal + 10% SRF fuels and 830 μg/m$^3$ for coal + 10% RDF. Nevertheless, Cd was higher in the flue gas sample obtained from coal + 10% SRF sample than samples from the other two fuels, though this was well below the prescribed limits [max. (Cd + Tl) < 100 μg/m$^3$] (Environment Agency, 2001), as is evident from Figure 2. Tl was found to be in non-detectable quantities in the fuel samples. In comparison to unsorted MSW combustion (Chang et al., 1998), the coal + SRF mixture showed much lower amounts of Pb and Cd.

### *3.2.3. Metal analysis in ash samples*

Metal concentrations were measured in bottom ash and fly ash samples obtained after the combustion of coal, coal + 10% SRF and coal + 10% RDF fuels. Results are shown in Figures 3 and 4. The release of different trace elements depends upon the volatility of metals and the fuel feed rate. The more volatile metals will be present in the fly ash samples, and a higher fuel feed rate will result in more fuel being passed through the system, therefore introducing higher quantities of the metals.

Among the tested elements, As, Cd, Hg and Pb are considered of principal concern. These metals are the most volatile between 800 and 900 °C temperatures (Miller et al., 2002). From Figure 4, it is indicated that the major fraction of these metals was found in fly ash. Cd and Pb releases were lower in bottom and fly ash samples obtained from (coal + 10% SRF) fuel combustion than the other two fuel/fuel blends. From Figure 3, it is observed that in general the use of RDF as co-fuel increases heavy metals accumulation in bottom ash except Zn, Mn and Hg. A higher metal release with the coal and RDF mixture was expected due the metals content being the highest in this fuel. However, no significant difference in the metal concentrations was observed in fly ash samples obtained as a result of the combustion studies (Figure 4).

### *3.2.4. Relative distribution of metal contents in ash and flue gas stream*

The distribution of different metals among bottom ash, fly ash and flue gas was also seen for three combustion scenarios (Figures 5a, b and c). It is evident from the figures that a major part of the trace elements is retained in the ash. Only the significant quantities of Hg and As are released with flue gas into the atmosphere. Combustion studies with sewage sludge have revealed that typically between 75-98% of Cd, Cr, Cu, Pb and Zn are retained in the ash (Cenni et al., 1998; George et al., 2010; Lopes et al., 2003; Werther and Ogada, 1999). It has also been found that most of the mercury is released to the atmosphere via flue gas due to high volatility (Germani, 1988; Lee et al., 2006; Otero-Rey et al., 2003; Reddy et al., 2005; Sandelin and Backman, 2001; Werther and Ogada, 1999). During combustion, generally mercury is found in three forms, namely, particle-bound, gaseous elemental mercury and in oxidized form (Lee et al., 2006). At high temperature in the combustion zone, Hg vaporises into the elemental form. With a temperature reduction, it is oxidized by flue gas components forming $HgCl_2$ and HgO. A small fraction of Hg can also be condensed on ash particles due to temperature reduction. Otero-Rey *et al.* have reported that Cd, Mn and Pb are readily incorporated in the bottom ash, whereas the larger fractions of As, Cr, Cu and Zn are found in fly ash (Otero-Rey et al., 2003). Our results are consistent with Cu, Zn, As, Mn and Cr in the samples obtained from coal only and (coal + 10% SRF) combustion studies. Cd was found in the fly ash rather than in bottom ash in all three combustion runs; this result is similar to that obtained for coal combustion by Reddy *et al*. Significant quantities of arsenic were found in flue gas stream (ca. 50%, 30% and 30% for coal, (coal + 10% SRF) and (coal + 10% RDF) combustion, respectively). Variation in the behaviour of metals can be attributed to the different fuel properties. The mass of a particular element can also affect the mobility of the metal (Sushil and Batra, 2006). For example, the lighter element such as Cu and Zn can be carried with fly ash. It has also been found that trace metals composition can be varied even from a single power plant. In addition to

these aspects, the particle size of feedstock may have an impact on metal fractionation in different streams. The presence of heavy metals in the ash samples is also influenced by the composition of waste and its handling (Chang et al., 1998).

### *3.3. Thermogravimetric experiments*

Thermogravimetric experiments were carried out for the two major components of SRF (paper and various plastics) in an air and nitrogen atmosphere to investigate the thermal behaviour of these components. The results from this analysis are shown in Figures 6a and 6b.

#### *3.3.1. In the presence of air*

Figure 6a illustrates the thermal behaviour of paper and plastic fractions (polyethylene, polypropylene and PVC) in the presence of air. In all materials, initial weight loss with an increase in temperature takes place due to moisture loss and volatilization. This stage is followed by gradual or no further weight reduction before volatilisation. Polyethylene and polypropylene profiles exhibited the sharp decrease in weight in the temperature range of 400-500 °C. However, almost no ash was found for polypropylene. An ash content of *ca.* 10% was obtained for polyethylene. For paper, a weight loss of 10% was observed up to 300 °C heating due to the loss of moisture. This was followed by two zones of sharp weight reduction (First zone: 300-375 °C and second zone: 375-500 °C). Beyond 500 °C, there was a continuous gradual reduction in weight to *ca.* 30% of the original, which may go further with an increase in temperature due to the presence of inorganic fillers. Results for paper are consistent with those found by other researchers (Guo et al., 2001; Lu et al., 1996; Lu et al., 1999). However, the ash content was found to be much higher in comparison with previous studies. This may be a function of different types of paper. For PVC, weight loss due to moisture was negligible (as for other plastic components). Three zones for weight loss were

observed; (a) 300-350 °C, (b) 400-525 °C, and (c) 525-800 °C. It was found that the weight losses in each temperature zone decreased with increasing temperature. A major fraction of weight reduction (*ca.* 65%) was obtained during the first heating zone followed by ca. 15% and 8% weight reduction in the second and third zones, respectively. The first weight loss for PVC may be due to the loss of HCl as reported by Lu *et al.* (Lu et al., 1996). The second and third weight loss might be due to the decomposition of the materials and combustion of carbon residue (Lu et al., 1996; Lu et al., 1999).

### *3.3.2. In the presence of nitrogen*

The thermal behaviour of paper, polyethylene, polypropylene and PVC was also observed in an inert atmosphere ($N_2$). TGA curves for different components are shown in Figure 6b. Similar curves were obtained for polypropylene and polyethylene. A single degradation zone was observed for each of these plastics. No char yield was observed for polypropylene, whereas, *ca.* 8% char was formed for polyethylene. The TG curve for paper shows the loss of moisture in the first degradation zone followed by faster weight loss over a temperature range of 300-350 °C in the second thermal degradation zone. Reduction in weight up to 350 °C was 50%. Beyond 350 °C, the gradual decrease in weight loss might be attributed to the thermal degradation of calcium carbonate, which is used as filler in the paper manufacturing process (Cozzani et al., 1995). The TG pattern for PVC reveals a weight reduction of *ca.* 60% in the first thermal degradation zone (in a temperature range of ~ 300-350 °C). This might be due to the elimination of HCl and a small amount of benzene (Ma et al., 2002). In the second thermal degradation zone, *ca.* 20% weight loss was observed, this might be attributed to the pyrolysis of the polyethylene sequences that formed during the first stage (Ma et al., 2002).

## 4. Conclusions

The synthetic SRF (58% paper, 22% plastic, 15% textile and 5% wood) contained less chlorine and mercury than Daw Mill coal and RDF. However, as for RDF, the composition of real SRF is dependent on MSW composition and the type and performance of specific unit operations employed for preparing fuel from waste. The SRF prepared in the present study was suitable for cement works and power sectors, as indicated by its characteristics. The biomass content of the SRF was *ca.* 70%. The pure coal and coal + 10% SRF mixture showed a comparable combustion performance for heavy metals release from flue gas and ash (bottom and fly ash) samples. The coal and 10% RDF mixture produced slightly higher emissions.

The relative distribution study confirms the findings of previous studies that most of the Hg releases into the atmosphere with flue gas and other heavy metals remain in ash. Volatility and mass also affect the mobility of trace elements in fly ash and bottom ash samples. A major portion of Cu, Zn, Cd, Pb, Cr and As were found in fly ash, whereas a large fraction of Mn remained in the bottom ash.

TG analysis was carried out to study the combustion behaviour of the main components of waste derived fuel. This provides the information on temperature ranges for various reactions taking place during the combustion or pyrolysis of the fuel.

The results obtained from this study highlight the potential use of waste derived fuels, and support the findings of an options appraisal of SRF by Garg *et al* (2009). A high calorific value, low chlorine and mercury content, lower metal emissions and the comparatively inexpensive availability of fuel could be attractive to cement kiln operators, power plants and industrial boiler facilities.

Future studies should be targeted at measuring gaseous emissions. The share of SRF in the fuel mixture should be increased (up to 20%) and the resulting emissions should be determined. The kinetics of the TG analysis can be studied by performing differential thermal analysis.

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1 **Table 1 – Composition of simulated SRF Components**

| Fuel | Textile | Paper | Polyethylene | Sawdust | PVC | Polypropylene |
|---|---|---|---|---|---|---|
| **Proximate and ultimate analyses (as received)** | | | | | | |
| Moisture (%) | 1.5 | 3.3 | 0.1 | 8.2 | 0.1 | 0.1 |
| Ash (%) | 1.0 | 15.9 | 8.7 | 2.6 | 0.2 | 0.2 |
| Volatile Matter (%) | 89.1 | 72.2 | 91.3 | 70.6 | 95.8 | 99.8 |
| HHV/ Gross CV | 20.3 | 16.7 | 40.8 | 19.5 | 21.8 | 46.3 |
| LHV/ Net CV (MJ/kg) | 19.2 | 15.8 | 38.0 | 18.2 | 20.7 | 43.2 |
| C (%) | 52.5 | 33.2 | 76.2 | 46.5 | 38.6 | 86.6 |
| H (%) | 4.9 | 4.0 | 12.9 | 5.3 | 4.9 | 14.7 |
| N (%) | 0.60 | 0.04 | 0.06 | 0.42 | 0.17 | 0.18 |
| S (%) | 0.15 | 0.08 | 0.10 | 0.05 | 0.08 | 0.21 |
| Cl (%) | 0.01 | 0.02 | 0.01 | 0.01 | 5.97 | 0.01 |
| **Metal analysis (mg/kg$_{fuel}$, dry basis)** | | | | | | |
| Pb | 1.2 | 0.4 | | 6.5 | | |
| Cu | 2.2 | 10.7 | | 3.4 | | |
| Zn | 7.1 | 18.6 | | 40.4 | | |
| As | <0.1 | <0.1 | | 0.2 | | |
| Cd | 0.02 | 0.04 | | 0.21 | | |
| Mn | 1.6 | 49.3 | | 640 | | |
| Cr | 6.5 | 4.9 | | 3.7 | | |
| Na | 245 | 472 | | 193 | | |
| K | 91 | 1056 | | 1489 | | |
| Tl | <0.1 | <0.1 | | <0.1 | | |
| Hg | 0.05 | 0.05 | | 0.04 | | |
| **Elemental oxide analysis (%, in ash)** | | | | | | |
| $SiO_2$ | 13.4 | 9.8 | | 40.4 | | |
| $Al_2O_3$ | 4.6 | 5.8 | | 7.5 | | |
| $Fe_2O_3$ | 1.2 | 0.4 | | 6.1 | | |
| $TiO_2$ | 7.5 | 0.1 | | 0.4 | | |
| CaO | 27.5 | 74 | | 19.8 | | |
| MgO | 2.2 | 2.1 | | 3.2 | | |
| $Na_2O$ | 3.3 | 0.4 | | 1 | | |
| $K_2O$ | 1.1 | 0.8 | | 6.9 | | |
| $P_2O_5$ | 22.5 | 0.1 | | 2.3 | | |

2

3

**Table 2 – Composition of fuel samples and silica sand**

| Fuel | Coal | SRF | RDF | Silica sand |
|---|---|---|---|---|
| **Proximate and ultimate analyses (as received)** | | | | |
| Moisture (%) | 6.2 | 3.0 | 30.4 | - |
| Ash (%) | 11.4 | 11.1 | 16.2 | - |
| Volatile Matter (%) | 33 | 79.6 | 46.1 | - |
| HHV/ Gross Calorific Value (MJ/kg) | 27.6 | 13.0 | 14.8 | - |
| LHV/ Net Calorific Value (MJ/kg) | 26.5 | 11.8 | 13.2 | - |
| C (%) | 66.3 | 40.5 | 28.1 | - |
| H (%) | 4.2 | 5.3 | 3.4 | - |
| N (%) | 1.2 | 0.03 | 0.98 | - |
| S (%) | 1.7 | 0.07 | 0.32 | - |
| Cl (%) | 0.28 | 0.02 | 0.25 | - |
| **Metal analysis (mg/kg$_{fuel}$, dry basis)** | | | | |
| Pb | 13.8 | 1.0 | 71.2 | - |
| Cu | 13.6 | 6.4 | 66.3 | - |
| Zn | 5.6 | 10.8 | 1970 | - |
| As | 12 | 0.01 | 2.1 | - |
| Cd | 0.07 | 0.05 | 0.30 | - |
| Mn | 207 | 39.6 | 164 | - |
| Cr | 14 | 4.5 | 25.2 | - |
| Na | 868 | 247 | 5362 | - |
| K | 1845 | 92 | 3454 | - |
| Tl | 0.3 | <0.1 | <0.1 | - |
| Hg | 0.3 | 0.07 | 0.19 | - |
| **Elemental oxide analysis (%, in ash)** | | | | |
| $SiO_2$ | 49 | 7.5 | 48.1 | 95.4 |
| $Al_2O_3$ | 22.8 | 4.3 | 9.5 | 0.1 |
| $Fe_2O_3$ | 11.5 | 4.5 | 2.7 | 1.0 |
| $TiO_2$ | 1 | 8.1 | 1.8 | <0.1 |
| CaO | 4 | 60.4 | 18.5 | <0.1 |
| MgO | 2.2 | 1.2 | 2 | <0.1 |
| $Na_2O$ | 1 | 0.3 | 3.3 | <0.1 |
| $K_2O$ | 1.9 | 0.1 | 1.9 | <0.1 |
| $P_2O_5$ | 0.3 | 0.8 | 1.5 | <0.1 |

**Table 3 – Summary of process conditions during combustion trials**

| Process parameters | Fuel | | |
|---|---|---|---|
| | **Coal only** | **Coal + 10% SRF** | **Coal + 10% RDF** |
| Fuel feed rate (kg/h) | 6.0 | 7.0 | 9.0 |
| Duration of the run (h) | 2.5 | 4.0 | 2.5 |
| Fluidised bed Temperature (°C) | 800 - 900 | 800 - 950 | 750 - 900 |
| Secondary chamber temperature (°C) | 550 - 600 | 600 - 700 | 500 - 600 |

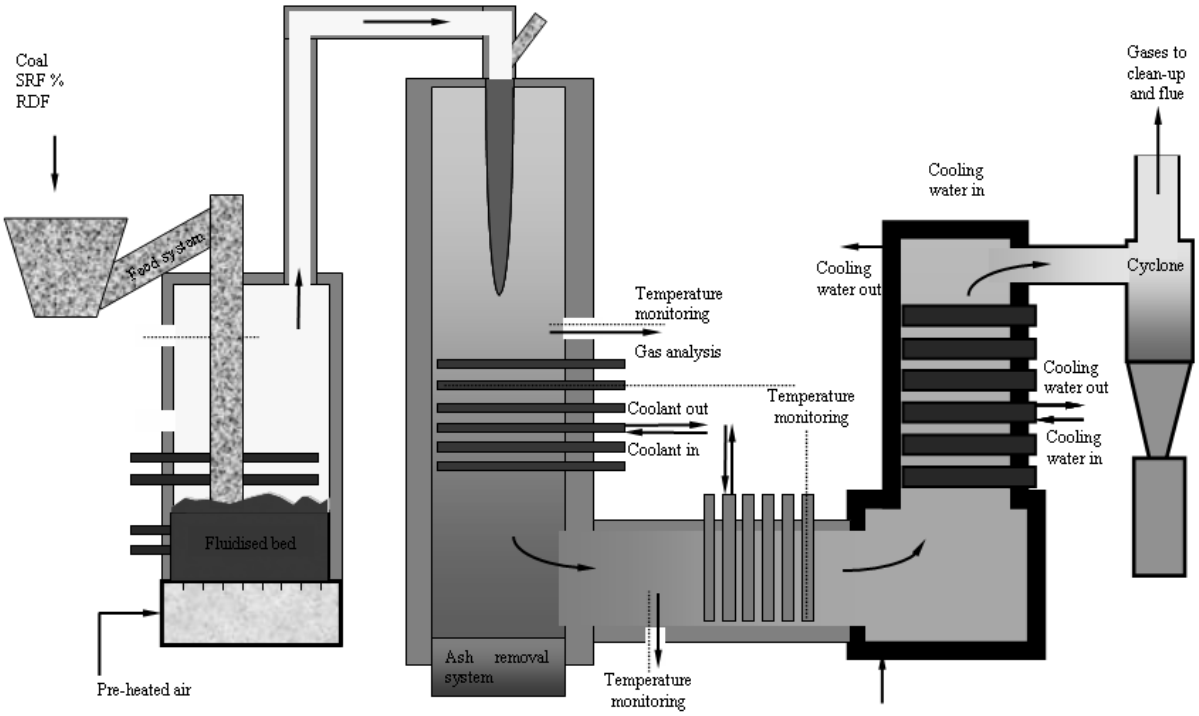



**Figure 1. Schematic diagram of fluidized bed combustor**

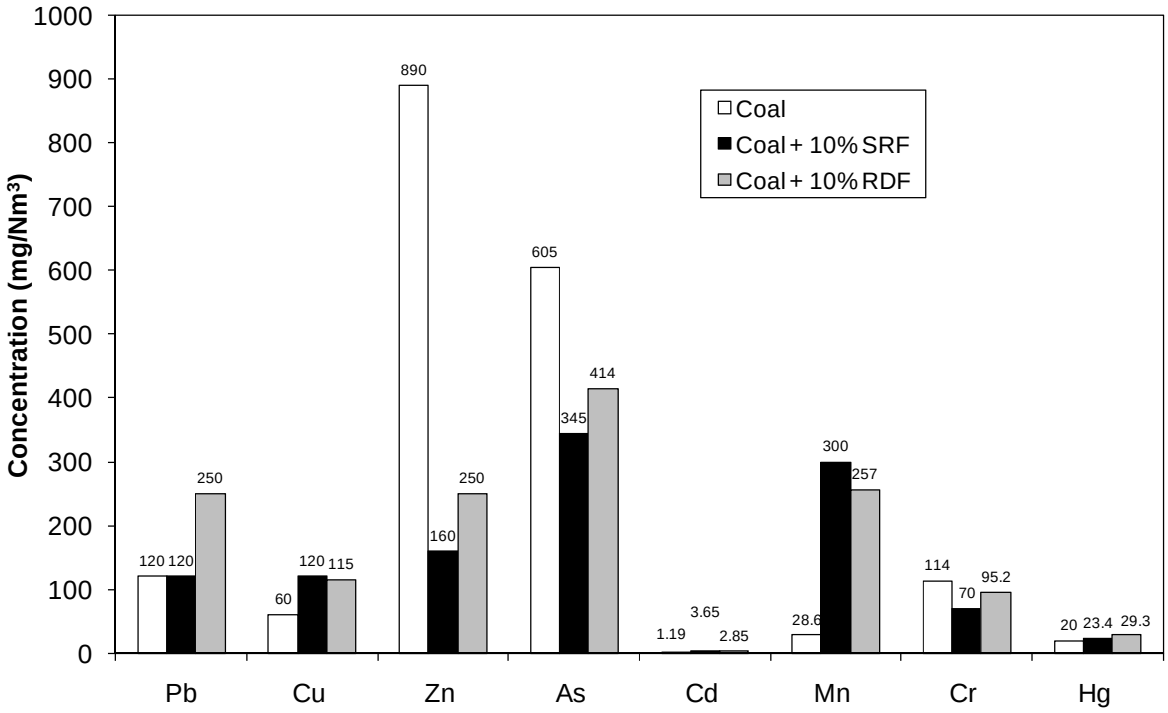



Figure 2. Metals concentration in flue gas samples obtained during the combustion of coal, (coal + 10% SRF) and (coal + 10% RDF) fuels

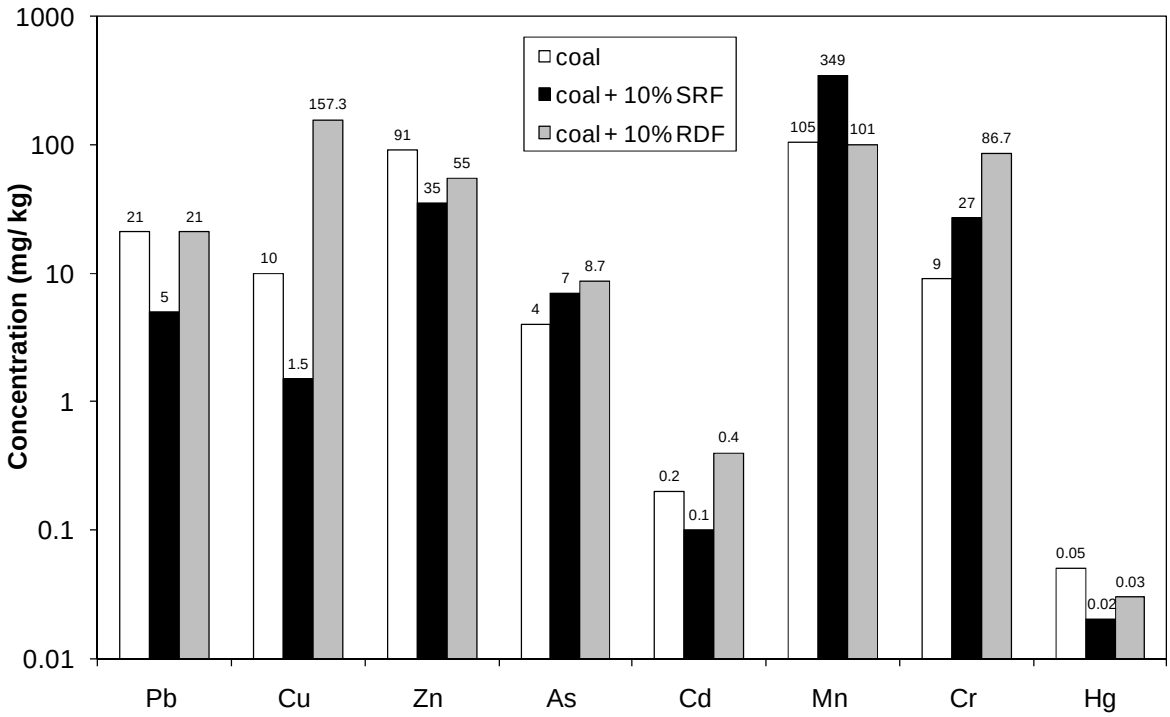



**Figure 3. Metal concentrations in the bottom ash samples obtained after combustion of fuels**

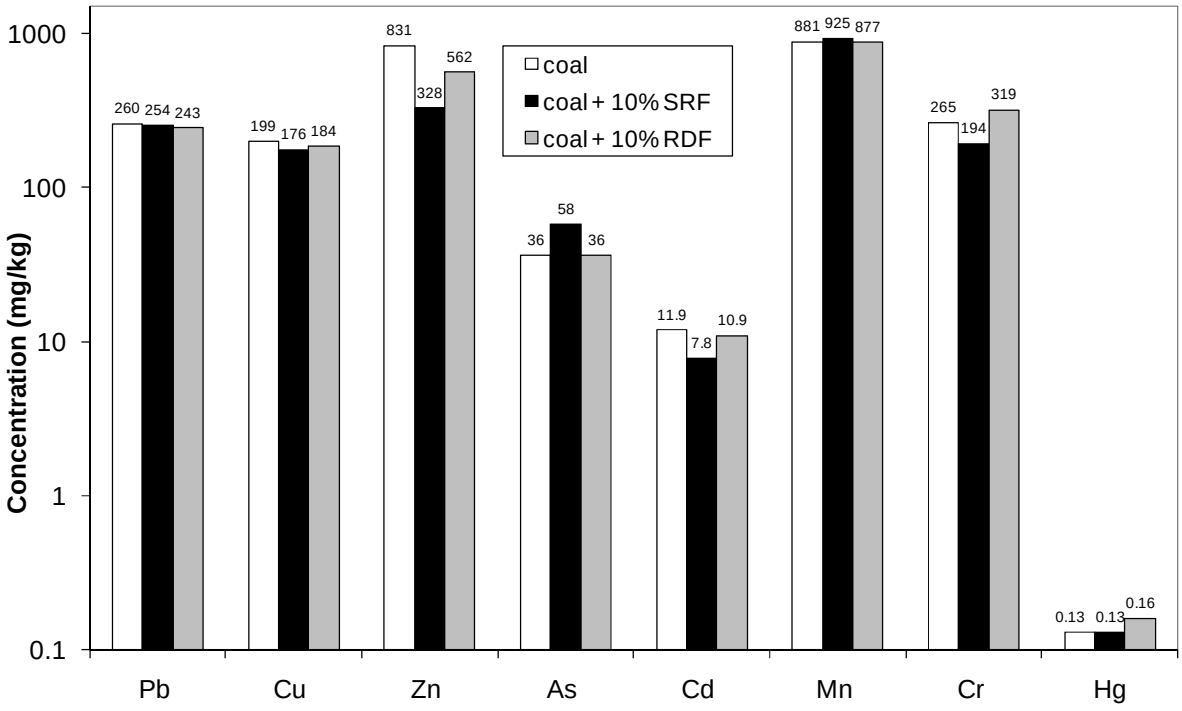
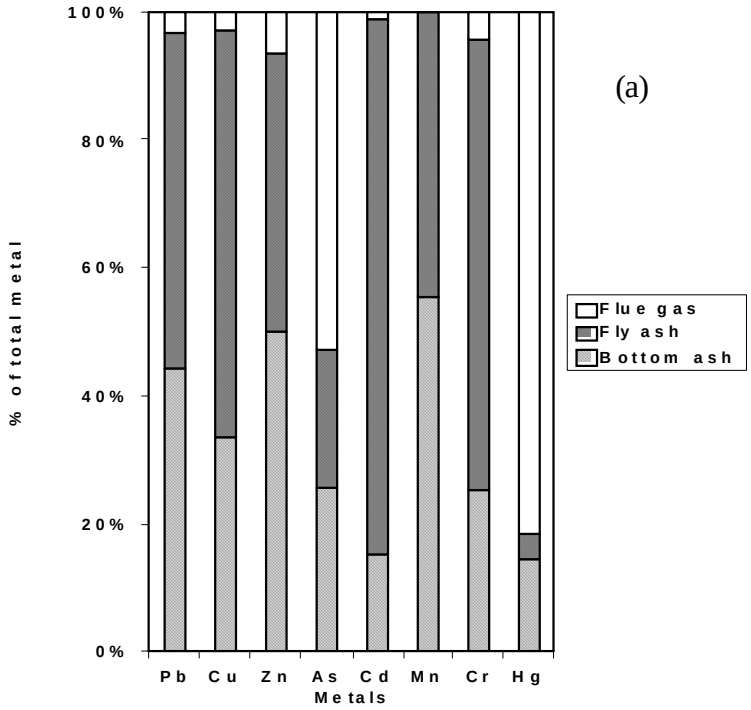
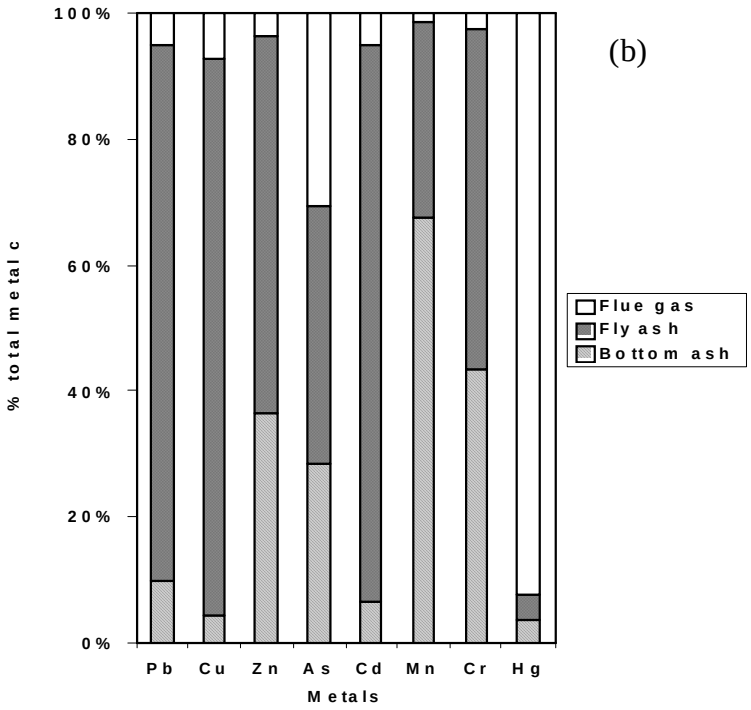



**Figure 4. Metal concentrations in the fly ash samples obtained after combustion of fuels**


100%
80%
60%
40%
20%
0%
% of total metal
Pb
Cu
Zn
As
Cd
Mn
Cr
Hg
Metals
Flue gas
Fly ash
Bottom ash

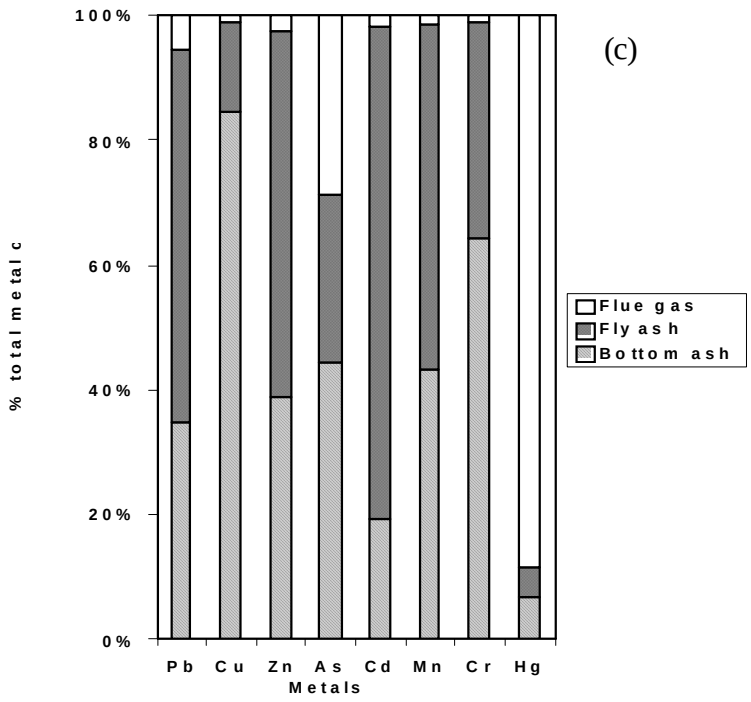
(a)

1


100%
80%
60%
40%
20%
0%
% total metal c
Pb
Cu
Zn
As
Cd
Mn
Cr
Hg
Metals
Flue gas
Fly ash
Bottom ash

(b)

2




1

2 **Figure 5. Metal distribution in ash and flue gas as a result of (a) coal combustion, (b) coal + 10%**

3 **SRF, and (c) coal + 10% RDF**

4

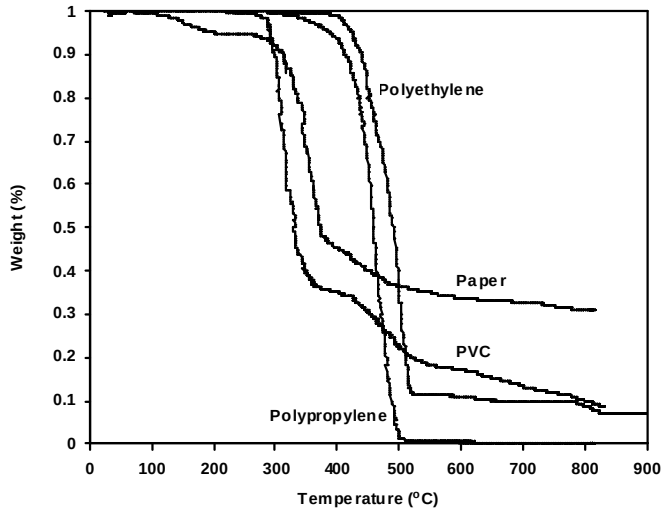



**Figure 6a. Comparison of TGA curves for paper and plastics (Heating rate = 10 °C/min, Air flow rate = 20 ml/min)**

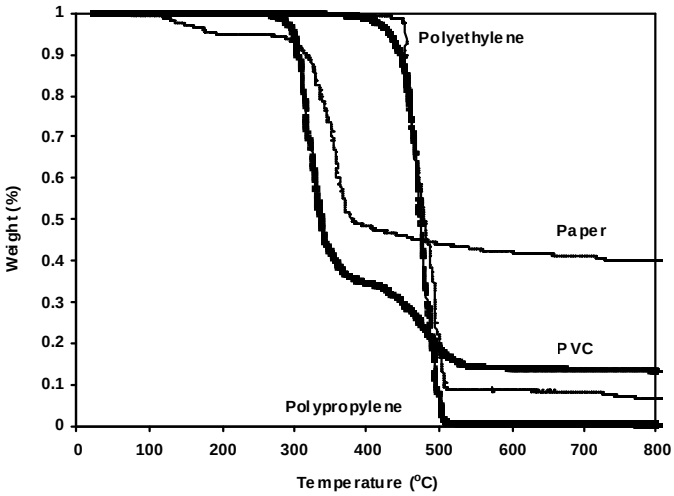



**Figure 6b. Comparison of TGA curves for paper and plastics (Heating rate = 10 °C/min, $N_2$ flow rate = 20 ml/min)**



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# Comparison of coal/solid recovered fuel (SRF) with coal /refuse derived fuel (RDF) in a fluidised bed reactor.

**Wagland, Stuart T.; Kilgallon, Paul J.; Coveney, R.; Garg, Anurag; Smith, Richard ...**

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