



## Research article

## The co-combustion performance and reaction kinetics of refuse derived fuels with South African high ash coal



Kerina Isaac, Samson O. Bada\*

DSI-NRF SARChI Clean Coal Technology Research Group, Faculty of Engineering and the Built Environment, University of the Witwatersrand, South Africa

## ARTICLE INFO

## Keywords:

Energy  
Environmental science  
Chemical engineering  
Co-combustion  
Discard coal  
RDF  
Thermogravimetric analysis  
Waste utilisation  
Biomass  
Chemical reaction engineering  
Energy sustainability  
Fuel technology  
Materials characterization  
Waste

## ABSTRACT

This research focuses on the co-firing of low-quality coal with refuse derived fuel (RDF) as a means to reduce the volume of waste dumped in landfill sites. The co-combustion behaviour and kinetics of various RDF/coal blends at different weight ratios, along with their physicochemical characteristics were investigated. The physicochemical analysis revealed that the run-of-mine and discard coal have relatively low calorific values of 21.7 MJ/kg and 16.7 MJ/kg, respectively. The RDF samples, plastic blend (31.2 MJ/kg) and paper blend (22.4 MJ/kg), were found to have higher energy contents. The thermogravimetric analysis was performed in an atmosphere of air, over a temperature range of 25–850 °C, and the results showed that the RDF samples had lower ignition, devolatilisation, and burnout temperatures compared to the coals. The ignition temperatures for the blended fuel occurs in the lower temperature region when RDF is added to the blend, likewise the peak temperatures and burnout temperature shifted to a lower temperature zone. The activation energies ( $E_a$ ) were determined using the Coats-Redfern method. The  $E_a$  for the run-of-mine (ROM) coal of 104.4 kJ/mol, was found to reduce to 31.4 kJ/mol for the 75% PB + 25% ROM coal blend and 35 kJ/mol for the 75% PL + 25% ROM coal blend, respectively. The discard coal which had an  $E_a$  of 109.9 kJ/mol was reduced to 30.9 kJ/mol for the 75% PB + 25% discard blend, and 33.5 kJ/mol for the 75% PL + 25% discard coal blend. It was determined that the most favourable blend for co-combustion was 70% discard coal + 30% PL RDF due to the similarity of the combustion profile to that of 100% coal and the simultaneous reduction in apparent activation energy.

## 1. Introduction

In 2016 over 2.01 billion tonnes of waste was produced worldwide, this is expected to increase to 3.4 billion tonnes by 2050 [1]. South Africa produces about 54.2 million tons of waste per year, of which only 38.6 % is recycled and 61.4 % is dumped in landfills [2]. Some paper types are difficult to recycle due to the chemicals they contain, this includes waterproof paper, wax or polyethylene (PE) coated paper, and paper with adhesive layers; these papers can be co-combusted and used for energy production instead of being discarded [3]. Therefore, it is highly important that research into the utilization of waste, with a view of separating out the combustible fractions for power generation should be conducted.

According to Eskom, the major power utility in South Africa, the amount of electricity generated from coal-fired power plants in the country increased to 91% in 2018, of the total 221 936 GWh of electricity produced [4]. The Koeberg nuclear power plant generated 6.4%, and the remaining 2.6% of all South Africa's electricity was produced from hydro

power and other renewable energy sources [4]. With the abundance of the coal resource and the long-life span of coal-fired power plants, the use of coal in developing countries has increased, and globally, it is still projected to contribute about 26% to the world's electricity in 2040 [5]. It is widely known that numerous challenges associated with utilising coal, including its in-situ ash content, low quality, and future coalfields being located further away from points of use [6]. In addition, the production of acid mine drainage and the  $\text{CO}_2$ ,  $\text{SO}_x$  and  $\text{NO}_x$  emissions associated with coal combustion are of great concerns for the future utilization of coal [6]. This has led to more stringent emission measures being imposed on coal power plants to cut down  $\text{SO}_2$  pollution, and to promote new techniques for co-firing coal with low-sulfur fuels to meet the new  $\text{SO}_2$  standards [4].

Refuse derived fuel (RDF) is made up of combustible materials derived from municipal solid waste (MSW), commercial, or industrial waste [7]. It is a more homogenous fuel with a higher calorific value and energy density compared to the municipal solid waste. The co-firing of coal with RDF could be an option which can be implemented in the

\* Corresponding author.

E-mail address: [Samson.Bada@wits.ac.za](mailto:Samson.Bada@wits.ac.za) (S.O. Bada).

existing infrastructure of coal power plants to supplement the declining coal supply and reduce the costs of energy production, as waste is abundant and renewable [8].

Surveys have indicated that the emission of greenhouse gases (GHG) could be reduced through co-firing RDF with coal, at the same time reducing the gases and leachate from landfill sites, as considerably as the volume of waste dumped [7, 9, 10]. A study conducted by Zabetta et al. (2008) [11] had shown that corrosive deposits formed in boilers when waste is combusted solely can be reduced through co-combustion. Akdag et al. (2016) [12] also noted that the presence of high alkali and alkali earth metals, along with chlorine content in RDF are some of the drawbacks faced in combusting RDF solely. The co-firing of coal with RDF was noted by Zabetta et al. (2008) [11] as part of the solution for reducing the impacts of RDF combustion on the environment. The characteristics of RDF have also been found to have an influence on the concentration of gases emitted during combustion.

An investigation was reported by Muthuramen et al. (2010) [13], which investigated the co-combustion performance of hydrothermally treated municipal solid waste and Indonesian coal with high ash Indian coal. The author observed that as the percentage of MSW in the blends increases, the ignition temperature and the volatile matter initiation temperature decreased [13]. An investigation conducted by Malaćák et al. (2018) [3], showed that the low sulphur and nitrogen content in the waste papers co-fired with coal does lower the concentration of the emitted gases. Yanik et al. (2018) [14] found a decrease in SO<sub>2</sub> emissions when co-firing lignite with torrefied biomass, however, no benefit was observed for the emissions of NO<sub>x</sub>. The combustion and co-combustion behaviour of different types of wastes and their blends with lignite coal was studied by Iordanidis et al. (2018) [15] in a thermogravimetric analyser (TGA). The author found that the higher volatile matter content of the wastes lowers the ignition temperature of the combustion of the blends with waste compared to that from the 100 % lignite coal [15]. The reaction of the co-combusted coal and waste was more intense, and the thermal profile shows the co-combusted fuel with a higher peak temperature and a lower burnout temperature compared to lignite alone [15].

This study seeks to utilize South African fine coal as co-fired fuel with RDF, based on the above-mentioned attributes of RDF and the strategy adopted by the South Africa's waste management, which is to minimize the amount of waste dumped, by utilizing it, rather than disposing of it [16]. The RDF utilized was sourced from a plant established in line with this waste strategy, where waste is sorted into combustible and non-combustible products, with the combustibles further segregated into RDF [17]. There are more than a billion tons of discard coal in the country and this resource requires utilisation [18, 19]. There is little to no literature available on the co-combustion of South African coal discard with RDF, especially with a high ash coal above 40%, known to be highly rich in inertinite and considered an inert component. This study also investigates two different types of RDF, with paper waste being the major component of one, and plastic waste the major component of the other, in order to determine the effect on the combustion profiles and the reaction kinetics.

In this investigation, the physicochemical properties of the coals and RDF samples were analysed. The estimated potential energy content in the RDF produced in SA for power generation, through combustion was calculated by using the lower heating value (LHV) of the RDF fractions involved in this study. The combustion and co-combustion characteristics of RDF with coal at different percentage ratios were reported and the activation energy from the co-combustion of each blend was determined using the model-fitting Coats-Redfern method. In a study done on the kinetic parameters of various biomass fuels it was found that the model-free methods tested were not suitable for the determination of the activation energy in biomass due to the assumption for these two methods that  $E_a/RT$  be greater or equal to 20 and smaller or equal to 60 [20]. In the study conducted by Alvarez et al. (2016) [20] this condition was not met during the combustion of lignin making these methods unsuitable for

biomass when lignin combustion takes place. On the other hand, the Coats-Redfern method was applied to determine the kinetic parameters of all the biomass fuels with success [20].

## 2. Material and methods

### 2.1. Materials

The RDF used in this study was sourced from Interwaste, an environmental solutions company which specializes in integrated waste management, in Johannesburg, South Africa. The samples were sorted from waste, which includes cardboard, paper, wood, textiles and plastics, and shredded in a primary and secondary shredder to reduce the particle size of the composite [17]. The composites are densified and stored in bales depending on their intended use [17]. The majority of the waste was made up of paper, powdered soup packing, spice packaging and soap packaging. In addition, it contained ice cream packaging, wax paper, lotion containers, margarine containers, nitrile gloves, boxes, polypropylene film, and rags.

Two different types of RDF were investigated; sample PB contained a blend of 53 % brown paper and cardboard, 32% yellow coated paper, 10% plastic and 5% textiles, while sample PL contained 85% plastic, 10% paper and 5% textiles. These samples were chosen in order to determine the effect on the energy characteristics when utilising an RDF containing mostly paper waste in comparison to an RDF containing mostly plastic waste. The run-of-mine (ROM) and discard coals utilized were sourced from the Witbank coalfield, and labelled as sample C1 and sample C2, respectively. Both the RDF and the coal samples were crushed in a Retsch 200 cutting mill and then pulverized to -250 μm. A representative sample from each coal was prepared for all the analyses, including the combustion test, according to ASTM D2013M. Different blends of coal and RDF were prepared for the co-combustion test. PL was blended with sample C1 (ROM) at 15%, 30%, 50% and 75% by weight percentage. The same procedure was repeated for PL with C2 (discard coal). This procedure was followed for the blended paper RDF sample (PB) with the coal samples.

### 2.2. Analytical techniques

The proximate analysis was conducted with approximately 1 g of each sample, in accordance with the standard ASTM D-5142, in a Leco TGA 701 analyzer. The moisture determination was conducted in an atmosphere of nitrogen by heating the sample to 107 °C at a ramp rate of 6 °C/min, this step was completed when the weight was constant. The crucibles were then covered and the temperature was increased from 107 °C to 950 °C at a ramp rate of 43 °C/min to determine the volatile matter content. The crucible covers were removed for the ash determination and the temperature was increased from 600 °C to 750 °C at a rate of 3 °C/min in an atmosphere of oxygen. The step was completed when the final weight was constant. The fixed carbon content was then found by difference.

The ultimate analysis for all samples was conducted in accordance with ASTM D 5373-02 using the Elementar vario EL cube analyser. About 5 mg of each sample was weighed into capsules and loaded into the equipment's carousel. The sample was then automatically transferred to the combustion vessel where the samples were flushed with helium (He). The combustion of the samples was carried out at 1150 °C. The percentage concentrations of C, H, N and S were determined with the analyser and the percentage concentration of O was determined by difference according to Eq. (1).

$$O(\%) = 100 - (C + H + N + S + \text{Moisture} + \text{Ash}) \quad \text{Eq. (1)}$$

Approximately 1 g of each sample was used to conduct the calorific value test in the Leco AC500 bomb calorimeter, in an atmosphere of oxygen, according to standard ASTM D5865-04. The system uses an

electronic thermometer with an accuracy of 0.0001 °C to measure the temperature every six seconds, with the results obtained within 4.5–7.5 min.

### 2.3. Combustion and co-combustion of RDF with coal

The combustion and co-combustion tests were conducted in the Leco TGA 701 in an oxidative atmosphere using air and approximately 150 mg of each sample of raw RDF, coal and their blends. The samples were heated from 25 °C to 850 °C at a constant heating rate of 10 °C/min. The temperature was then held at 850 °C for 20 min to complete the combustion. The heating rate was selected based on the experimental procedure of other authors, while the final temperature was selected as the point at which no further weight loss was observed [13, 21]. A reference crucible with no sample was utilised to eliminate any instrumental errors and the combustion experiments were repeated to ensure reproducibility.

The derivative thermogravimetric curve (DTG) and the thermogravimetric curves (TG) were plotted from the data obtained, and this was used to evaluate the combustion performance including the ignition temperature ( $T_i$ ), the initiation temperature of the volatile matter ( $IT_{VM}$ ), initiation temperature of fixed carbon ( $IT_{FC}$ ), peak temperature (PT) and burnout temperature ( $T_b$ ). The intersection method and the conversion method were used to determine the ignition and burnout temperatures of the samples, respectively.

The interactions between the ROM coal and the plastic were determined by comparing the weighted average of the DTG plot, calculated from Eq. (2), to the actual DTG from the experimental plot. The  $W_{total}$  is represented as the total weight loss rate,  $x$  is the mass fraction of the fuel in the blend, and  $W$  is the individual weight loss rate of each fuel.

$$W_{total} = x_{ROM}W_{ROM} + x_{PL}W_{PL} \quad \text{Eq. (2)}$$

### 2.4. Reaction kinetics

The kinetic method used in this investigation to determine the kinetic parameters controlling the combustion and co-combustion of RDF and the high ash coal utilized was based on the Arrhenius equation (Eq. 5). This equation is noted to govern the two-stage reaction kinetics of thermal decomposition of biomass in an oxidative environment. From this equation, the Coats–Redfern model was derived. This model is used in determining the kinetics and mechanism of thermal decomposition of different biomass, RDF, and their co-combustion with coal under an oxidative environment was derived [22, 23]. The following equations were used in deriving the reaction kinetics for all the samples tested [24].

$$d\alpha / dt = k(T)f(\alpha) \quad \text{Eq. (3)}$$

The term  $d\alpha/dt$  is the rate of conversion,  $k(T)$  is the rate constant,  $f(\alpha)$  is a function representing the reaction model, and  $\alpha$  represents the conversion which can also be expressed as shown in Eq. (4).

$$\alpha = m_0 - m_t / m_0 - m_f \quad \text{Eq. (4)}$$

where  $m_0$  is the initial mass of the sample,  $m_t$  is the mass of the sample at time  $t$  and  $m_f$  is the final mass of the sample. The rate constant,  $k$ , can be expressed by the Arrhenius equation as shown in Eq. (5).

$$k = Ae^{-E_a/RT} \quad \text{Eq. (5)}$$

where  $A$  is the pre-exponential factor ( $\text{min}^{-1}$ ),  $E_a$  is the apparent activation energy ( $\text{kJ/mol}$ ),  $R$  is the gas constant ( $\text{J/(K.mol)}$ ), and  $T$  is the temperature ( $\text{K}$ ). Combining Eqs. (3) and (4) results in the general rate equation (Eq. 6) [24].

$$d\alpha / dt = Ae^{-E_a/RT}f(\alpha) \quad \text{Eq. (6)}$$

The heating rate, used in the thermogravimetric analysis can be

expressed as  $\beta = dT/dt$ . Using this equation with Eq. (6) and rearranging results in Eq. (7).

$$d\alpha / f(\alpha) = (A / \beta)e^{-E_a/RT}dT \quad \text{Eq. (7)}$$

From this equation, the integral in Eq. (8) is obtained, which is referred to as  $g(\alpha)$ .

$$g(\alpha) = \int_0^\alpha d\alpha / f(\alpha) = \frac{A}{\beta} \int_{T_0}^T e^{-E_a/RT}dT = (AE_a / \beta R)p(E_a / RT) \quad \text{Eq. (8)}$$

The term  $p(E_a / RT)$  has no solution and is solved using approximations or numerical methods [20]. In order to approximate the solution to the integral expressed in Eq. (8), the Coats–Redfern method uses the asymptotic series expansion to obtain Eq. (9).

$$\ln[g(\alpha) / T^2] = \ln[AR / \beta E_a(1 - (2RT / E_a))] - E_a / RT \quad \text{Eq. (9)}$$

Assuming that the term is  $2RT/E_a$  much smaller than one, it can be ignored which results in Eq. (10) which is used to plot  $\ln(g(\alpha) / T^2)$  versus  $1/T$  [22]. The apparent activation energy was then determined from the slope of the trend line through the data. The solid-state reaction model with a linear regression constant ( $R^2$ ) closest to 1 was deemed to be the model controlling the reaction rate.

$$\ln(g(\alpha) / T^2) = \ln(AR / \beta E_a) - E_a / RT \quad \text{Eq. (10)}$$

### 2.5. Estimating the energy potential of the RDF

The lower heating value (LHV) of the plastic and the paper blend RDFs utilized in this study were determined using Eq. (9). The  $LHV_i$  is noted as the lower heating value of component  $i$ ,  $HHV_i$  is the higher heating value of component  $i$ ,  $W_e$  is the heat of evaporation of water (2.441 MJ/kg),  $H_i$  and  $M_i$  are the hydrogen and moisture contents of component  $i$ , respectively [25]. The total LHV from the two RDF resources were estimated from Eq. (12), where  $m_{total}$  is the total mass of waste produced per year. For this evaluation, the  $\sigma$  known as the efficiency of RDF production, was assumed to be 80% for the eight provinces in South Africa combined, and  $P_i$  is the proportion of the waste component  $i$ .

$$LHV_i = HHV_i - W_e(9H_i + M_i) \quad \text{Eq. (11)}$$

$$LHV_{total} = m_{total}\sigma \sum P_i LHV_i \quad \text{Eq. (12)}$$

## 3. Results and discussion

### 3.1. Physicochemical properties of the RDF and coal samples

Table 1 provides the results of the conventional physicochemical analyses conducted on the four samples under investigation. The RDF samples contained a very large volatile matter, which was in the range of 81.15–81.67%. The discard coal possesses the lowest volatile matter contents of 20.17 %, and all samples had low inherent moisture contents, ranging from 1.23 to 3.19 %. The plastic sample (PL), had a higher ash content of 11.11 %, compared to the RDF PB, while the discard coal has the highest ash content (41.95%) of all the samples utilized. It can be seen from Table 1 that the coals used in this research are of lower quality, especially the discard coal (C2), which was found to have a very high ash content (41.95%) compared to the coal used in the South African coal fired plants. The ash content of a typical coal used in the South African coal power plants is within the range of 25–35.9%, this was reported in a recent study conducted by Rautenbach et al. (2018) [26]. The ROM coal (C1) used in this study, with an ash content of 29.42% is similar to the quality used in the present South African coal power plants, but this coal may need to be washed in order to upgrade its volatile matter content to above 30%. With a volatile matter content of 22.88%, this coal is

**Table 1.** Physicochemical properties of the four samples.

Parameters	Plastic RDF (PL)	Paper blend (PB)	C1 (ROM)	C2 (DISCARD)
Proximate analysis (wt%, db)				
Fixed Carbon	6.07	9.30	46.51	36.58
Volatile Matter	82.68	83.82	23.40	20.59
Ash content	11.25	6.88	30.09	42.83
Moisture (wt%: Ar)	1.23	3.19	2.24	2.06
Ultimate analysis (wt%, db)				
Hydrogen	9.38	8.63	3.26	2.73
Nitrogen	0.35	0.30	1.46	1.17
Total Carbon	58.09	59.04	59.64	49.62
Sulphur	UT	UT	0.87	1.37
Oxygen	20.93	25.15	4.68	2.28
CV: (MJ/kg)	31.23	22.4	21.72	16.73

Ar: As received; db: dry basis; CV: Calorific value; O: Oxygen by difference  $[100-(M + \text{Ash} + H + C + N)]$ ; UT: untraceable.

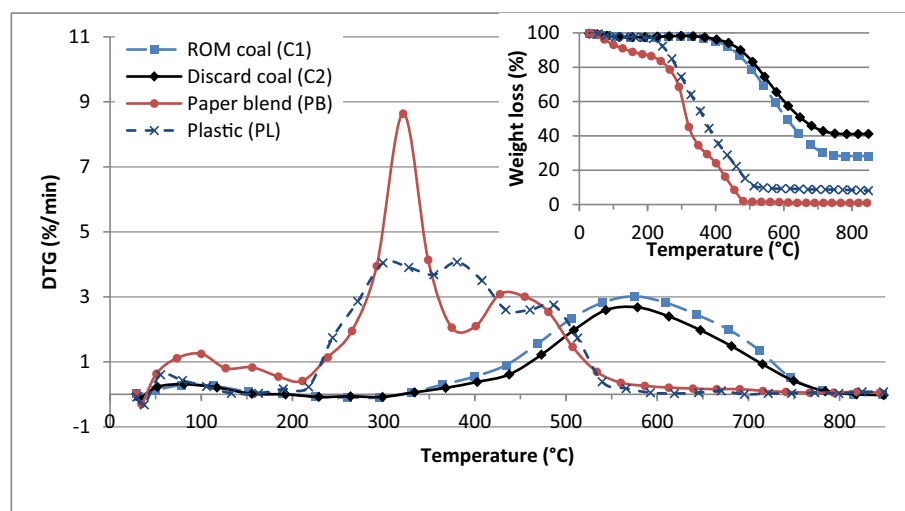
expected to have a higher ignition temperature and less stable flame stability compared to the two RDFs.

The hydrogen content of the RDF is much higher in comparison to the coal samples, which is consistent with the higher volatile matter content of these samples. The nitrogen content is much lower in the RDF samples (0.29% for PB and 0.35% for PL) when compared to the coal samples (1.43% for C1 and 1.15% for C2). It was also observed that the percentage sulphur content in the two RDF samples was untraceable, therefore, co-firing of these RDF samples with the ROM and discard coal is expected to reduce the SO<sub>2</sub> emission from the coals. The two coals can be categorized as a high ash coal according to the ash yield classification of SANS 11760:2007. Sample PL, which had the highest volatile matter content and hydrogen content, was noted to have the highest calorific value of 31.23 MJ/kg, compared to discard coal with the lowest calorific value of 16.73 MJ/kg. In terms of calorific value, under the South African coal standard classification, the ROM coal barely made the Grade D2, while the discard is below the Grade D3 of < 21.5 MJ/kg. In order to determine the energy potential of the RDF resource in South Africa the lower heating value of the resource was determined from Eq. (12). The LHV of the individual paper waste and plastic waste components determined through Eq. (11) were found to be 20.3 MJ/kg and 29.2 MJ/kg, respectively. The total mass of waste produced in the country was taken from the Department of Environmental Affairs, State of Waste Report (2018), as 54.2 million tonnes and the proportion of plastic and paper

waste was reported to be 3.3% and 4.7%, respectively. This resulted in a total LHV for the RDF resource in South Africa to be estimated as 83 629 702 GJ/year.

### 3.2. Combustion performance of the RDF and coal

The thermographs for the combustion of the raw RDF samples, PL (plastic blend) and PB (paper blend), as well as the coal samples C1 (ROM coal) and C2 (discard coal) can be seen in Figure 1. The DTG of sample C1 shows a combustion profile for ROM coal with three different reaction stages. The first stage showed an initial peak at 78 °C which indicated the release of the inherent moisture from the sample. As the temperature increases, both coals (C1 & C2), displayed a slight dip below the X-axis, which occurs due to solid-state oxidation of the organic matter in both samples [27]. With a continuing increase in temperature, the initiation of the volatile matter (IT<sub>VM</sub>) was seen as the curve crosses the X-axis (320 °C–434 °C) for the ROM coal (Figure 1). This denoted the second stage of combustion; the release and combustion of the volatile matter. The third stage represents the initiation of the fixed carbon (IT<sub>FC</sub>), where the gradient of the curve increases, leading to the combustion of the fixed carbon. The ignition temperature of the sample (C1), occurs at 440 °C, and it reaches its peak temperature at 575 °C, with a burn out temperature (T<sub>b</sub>) of 740 °C, similar to that observed for sample C2.



**Figure 1.** The combustion profiles of the RDF samples PL and PB, and the coal samples C1 and C2.



The coal samples utilized in this study were found to be less reactive than the RDF samples. The ignition temperatures and  $IT_{VM}$  for both RDFs are seen (Figure 1) occurring at a lower temperature compared to that of coal, and this is due to the larger volatile matter content of the RDF. The paper blend (PB) was seen to have two distinct peaks, which is expected as a result of the hemicellulose, cellulose and lignin functional groups in paper [28]. The first peak could be attributed to the degradation of hemicellulose and cellulose which occurs in the temperature range 250–350 °C [29]. Whilst the second peak observed at a temperature of 430 °C, could be attributed to the decomposition of lignin, which has been found to degrade over a wide range of temperatures, up to 900 °C [29].

Multiple peaks were observed in the plastic blend RDF, with the combustion of the light volatile components occurring within 218 °C–355 °C, followed by the combustion of the heavier volatile components which took place from 355 °C to 460 °C. These multiple peaks indicate the heterogeneous nature of the fuel as the different components exhibit different reactivities [30]. The first peak from the DTG plot is in the range of the decomposition of hemicellulose and cellulose of the paper component in the sample. The second peak seen in this profile might be as result of the decomposition of polypropylene present in the sample, while the third peak of the DTG plot could be due to the decomposition of polyethylene. This is in line with the findings of Porshnov et al. (2018) [28] who found that polypropylene (PP) decomposes in the temperature range of 267–498 °C, while polyethylene decomposes in the temperature range of 397–519 °C. The fourth stage was the combustion of the char and residues which occurred from 460 °C to 670 °C and exhibited one smaller peak at 486 °C at a weight loss rate of 2.75 %/min. The ignition temperature ( $T_i$ ) determined for the PL sample was 250 °C, which is similar to that reported for plastic from MSW (249 °C) by Iordanidis et al. (2018) [15]. From Figure 1, the PB sample possesses the highest reactivity (8.64 %/min), followed by the PL, ROM coal and the discard coal. This could be due to the lower ash content in the PB resulting in the easy diffusion of oxygen to the surface of the char, rather than hindering the diffusion and limiting the sample's reactivity [31].

### 3.3. Co-combustion performance of ROM and discard coal with RDF

The co-combustion performance of C1 (ROM coal) and both RDF samples, PB (paper blend) and PL (plastic blend), can be seen in Figures 2 and 3, respectively. The ignition temperatures of the ROM coal and the discard coal decreases as the ratio of the RDF increases in the blend. This was in agreement with the findings of Iordanidis et al. (2018) [15] where increasing MSW content in lignite/MSW co-firing had led to decreased ignition temperature. The lowest ignition temperature achieved in Figure 2 was found to be 246 °C, and this was attained for the blend of

75% PL + 25% ROM coal. The same trend of decreasing ignition temperature was observed in the blends of discard coal with RDF PL (Figure 2). The initiation of volatile matter temperatures also reduced to a lower temperature region for both C1 and C2 blends with the addition of RDF. A similar observation was made by Wang et al. (2012) [21] during the co-pyrolysis of coal and biomass. From this study, it is evident that for both types of RDF; PL and PB (Figures 2, 3, 4, and 5) the minimum temperature for  $IT_{VM}$  is achieved when 30% of RDF is present in the blend.

The peak temperature for both C1 and C2 occurred at a much higher temperature zone compared to the raw RDF samples and their blends. It was observed in Figures 2, 3, 4, and 5, that as the percentage of coal in the blend increases, the reactivity was seen to decrease due to the reduction in the volatile matter content. The initiation temperature of fixed carbon also moved to a higher temperature region with the addition of coal. The RDF samples have lower burn out temperatures ( $T_b$ ) compared to both coal C1, C2 and their blends. At 75% of PB in the blend with C1, a  $T_b$  of 673 °C was achieved (Figure 4), compared to the  $T_b$  of 619 °C achieved for the blend containing 75% PL. The same reduction in burnout temperature when co-firing the blends of waste or biomass with coal was observed by other authors [15, 23, 32]. All the figures depicted under the co-combustion of RDF with the two South African coals used in this study, have shown that the RDF samples are more reactive than the coal samples, they also ignite and burnout at a lower temperature.

### 3.4. Interactions between ROM coal and plastic RDF

The interactions between the ROM coal and the plastic RDF used in this study were calculated using Eq. (2). The reaction between ROM coal and the plastic RDF can be described as either a synergistic or a linear additive reaction. An interaction in which the experimental total weight loss rate (%/min) is equal to the calculated weighted average is assumed to be an additive or non-synergistic reaction. It is evident from the difference in the combustion profiles obtained in this study that there are some interactions between the RDF and the discard coal utilized. From Figure 6, there seems to be deviations between the experimental and calculated DTG curves for all blend ratios investigated at higher temperature.

As seen in Figure 6, the theoretical and experimental curves show little to no deviation up to the temperature of 199 °C, as this is below the ignition temperature and the initiation temperature of the fixed carbon or decomposition stage. The deviation between the curves was observed as the initiation of the volatile ( $IT_{VM}$ ) began at a slightly higher temperature zone for the experimental profiles in comparison to the theoretical curves. It is evident that as the RDF content in the blend increases, the deviation of the experimental curve from the theoretical curve also

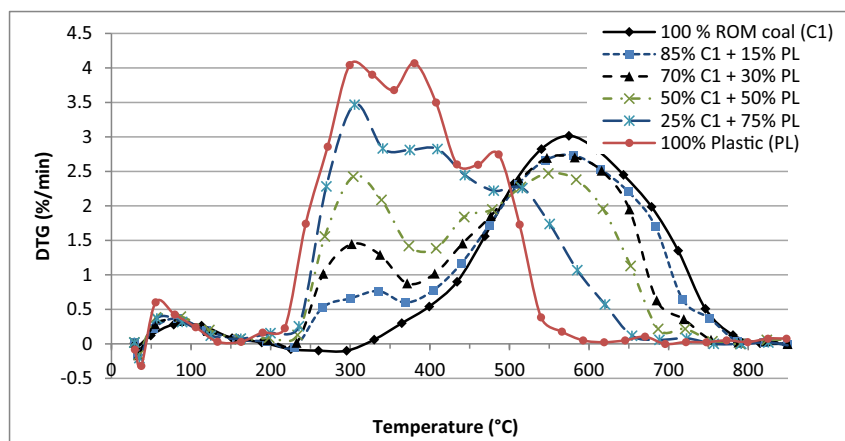


Figure 2. The co-combustion profiles of the RDF sample PL and ROM coal C1.

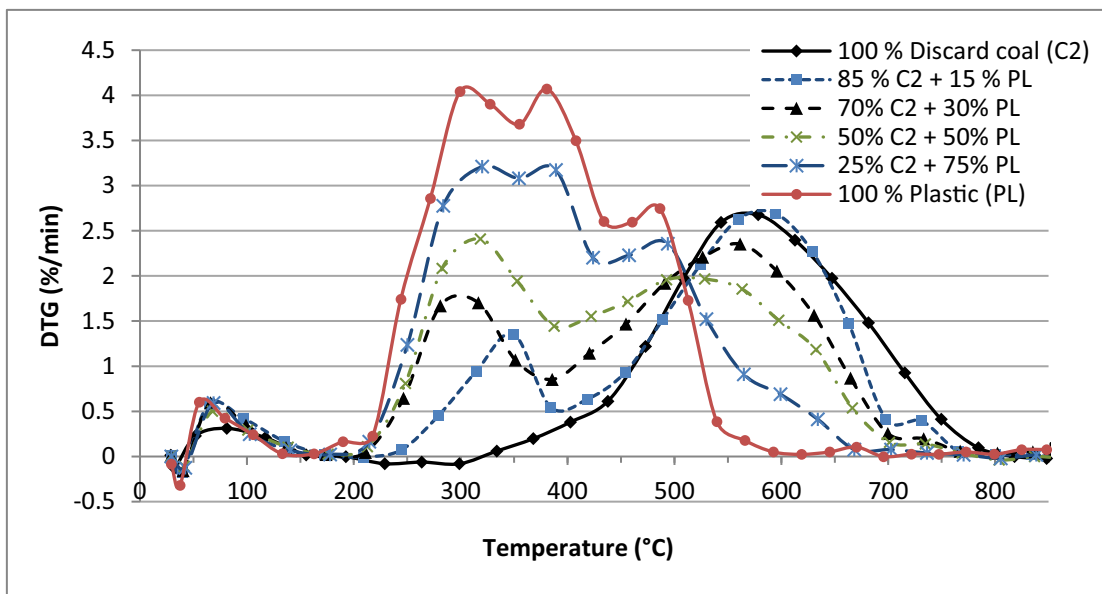


Figure 3. The co-combustion profiles of the RDF sample PL and the discard coal C2.

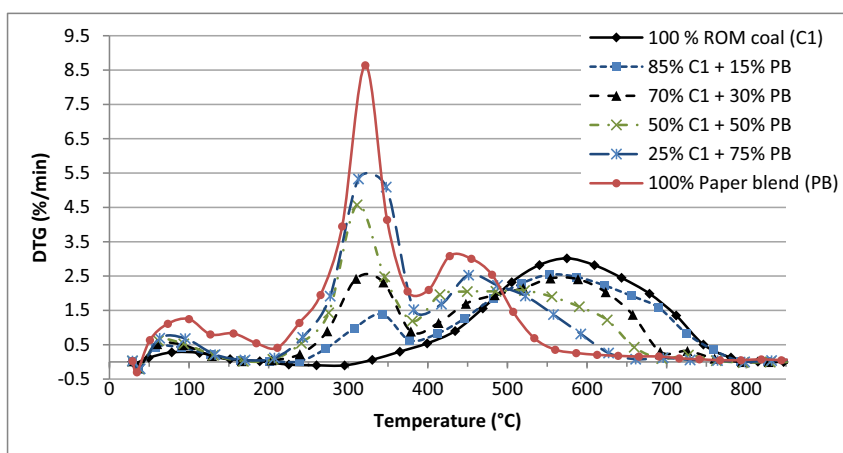


Figure 4. The co-combustion profiles of the RDF sample PB and the ROM coal C1.

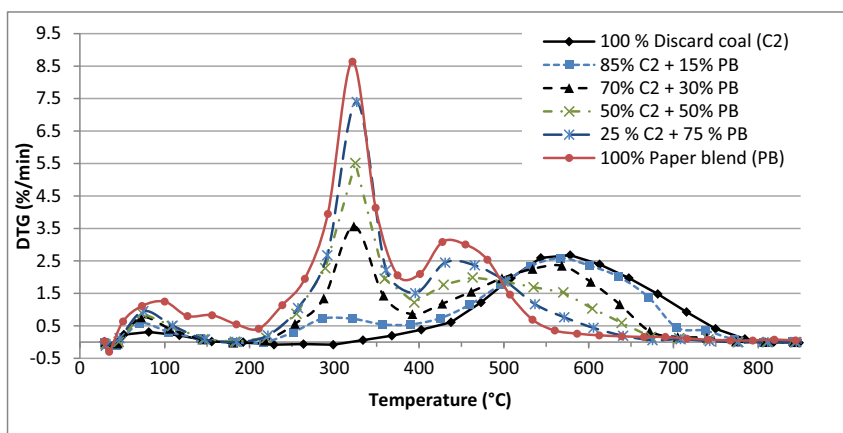


Figure 5. The co-combustion profiles of the RDF sample PB and the discard coal C2.

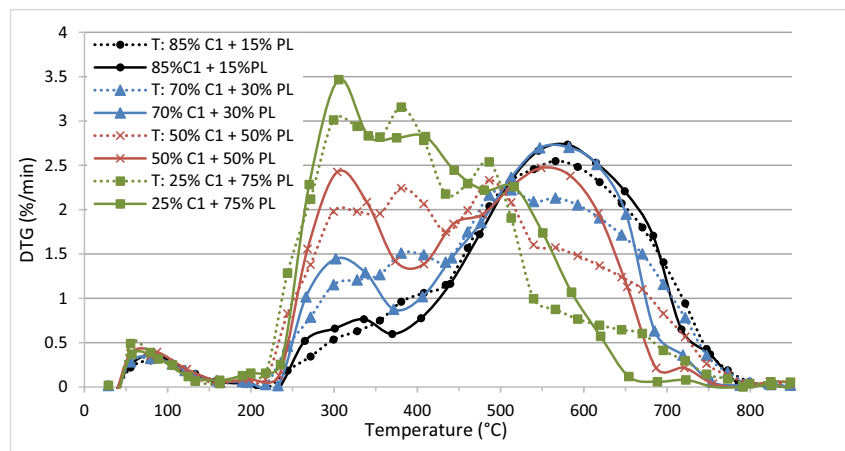


Figure 6. The theoretical and experimental DTG plots of ROM coal and RDF PL.

increases, as seen with an increasing biomass proportion and temperature (Figure 6). This deviation in the theoretical and experimental DTG, shows there is a synergistic reaction between the RDF and ROM coal C1, and this effect is in agreement with the findings of other authors [30, 33].

### 3.5. Reaction kinetics of ROM and discard coal with RDF

The reaction kinetics for different fuels during combustion and co-combustion are determined using a suitable model-free or model-fitted method [20, 22, 34]. The Coats-Redfern model-fitting method was used to determine the apparent activation energies for each raw sample and co-combustion sample. The samples were combusted at a heating rate of 10 °C/min and the conversion of each sample was determined from Eq. (3). In this study the reactions are divided into three or four stages, with the first stage being the loss of moisture. The release and combustion of light volatiles (stage 2) occurs at temperatures between 203 - 396 °C, while during stage 3, the release and combustion of higher molecules volatiles occurred at a higher temperature. The combustion of

higher molecules in the plastic RDF blend took place within the temperature range of 355–434 °C, while stage 3 occurred from 320 - 438 °C for the coal samples (Table 2). Stage 4 occurs as a result of the char combustion, during which diffusion is the rate controlling step as the high temperature allows the chemical reaction to proceed faster than the diffusion of oxygen into the particle [35]. The Jander's diffusion model

$$(D3), g(\alpha) = \left[ 1 - (1 - x)^{\frac{1}{3}} \right]^2$$

combustion very well. This equation for three-dimensional diffusion was developed for spherical solid particles, it describes a reaction where the rate-controlling step is the diffusion of the reactant through the product layer. That is, the product layer which was developed replaces the reactant consumed in a one to one ratio. Gil et al. (2010) [22] also found that the Jander's diffusion model described the combustion kinetics of coal co-fired with biomass very well.

The release and combustion of the volatile matter for the coal samples used in this study showed an apparent activation energy in the range of

Table 2. The reaction kinetics of the co-combustion of RDF and coal.

Sample ID	Stage 1 (°C)	Stage 2 (°C)	Ea (kJ/mol)	R <sup>2</sup>	Stage 3 (°C)	Ea (kJ/mol)	R <sup>2</sup>	Stage 4 (°C)	Ea (kJ/mol)	R <sup>2</sup>
100% C1	25–320				320–434	83.7	0.99	434–740	104.4	0.99
100% C2	25–324				324–438	68.7	0.98	438–741	109.9	0.99
85% C1 + 15% PL	25–235	235–370	47.8	0.99	370–439	42.9	0.99	439–734	78.7	1
70% C1 + 30% PL	25–233	233–372	64.8	0.96	372–441	34.9	0.99	441–710	68.3	0.99
50% C1 + 50% PL	25–234	234–374	72	0.96	374–479	33.8	0.99	479–706	56	0.99
25% C1 + 75% PL	25–236	236–341	83.8	0.97	341–480	41.1	1	480–619	35	0.96
85% C1 + 15% PB	25–238	238–377	53.2	0.98	377–411	28.1	1	411–740	68	1
70% C1 + 30% PB	25–203	203–379	57.3	0.97	379–413	22.2	1	413–710	53.8	0.99
50% C1 + 50% PB	25–205	205–380	67.6	0.95				380–679	42	1
25% C1 + 75% PB	25–207	207–382	73.7	0.96				382–673	31.4	0.97
85% C2 + 15% PL	25–245	245–384	52.4	0.98	384–454	27.2	0.98	454–722	77.8	0.99
70% C2 + 30% PL	25–211	211–386	55.8	0.96	386–455	33.9	0.99	455–728	54.2	0.99
50% C2 + 50% PL	25–213	213–387	70.1	0.97	387–456	32.6	1	456–681	48.1	1
25% C2 + 75% PL	25–215	215–355	88.5	0.99	355–424	44.6	0.98	458–630	33.5	0.99
85% C2 + 15% PB	25–220	220–390	40.2	0.98	390–426	33.3	1	426–730	78.7	1
70% C2 + 30% PB	25–218	218–392	65.3	0.95				392–690	54.1	0.99
50% C2 + 50% PB	25–220	220–394	73.2	0.95				394–667	35.5	0.99
25% C2 + 75% PB	25–222	222–396	78.9	0.95				396–624	30.9	0.99
100% PL	25–218	218–355	96.3	0.98	355–434	49.6	0.99	460–547	37.3	0.91
100% PB	25–211	211–375	71.1	0.95				375–651	31.1	0.95

C1 - ROM coal, C2 - Discard coal, PL- Plastic RDF, PB - Paper blend RDF, E<sub>a</sub> - apparent activation energy, R<sup>2</sup> - linear regression.

68.7–83.7 kJ/mol (Table 2). These values are within the range (53 and 290 kJ/mol) reported by Smith et al. (1981) [35], for the apparent activation energies for various ranks of coals for the release and combustion of the volatiles. The activation energy for the combustion of the fixed carbon in this low-quality ROM and discard coal were found to be 104.4 kJ/mol and 109.9 kJ/mol, respectively. These values are also found to be similar to that obtained from the high-ash coal used by Muthuraman et al. (2010) [13], of  $E_a$  of 119.3 kJ/mol. The activation energy for the release and combustion of the volatile matter in the raw PL and PB samples were divided into two stages. As seen in Table 2, the combustion of volatiles for PL had an  $E_a$  of 96.3 kJ/mol under stage 2, with stage 3 having an  $E_a$  of 49.6 kJ/mol for initiating the combustion of fixed carbon and 37.3 kJ/mol for the combustion of the remaining char in stage 4. For the PB sample, the  $E_a$  obtained was 71.1 kJ/mol for the release and combustion of volatiles, which was lower than that from the PL sample, i.e. less energy is needed for the combustion of paper compared to the plastic sample.

The increase in the percentage ratio of RDF in the coal/PL and coal/PB blends was seen to increase the  $E_a$  during the volatile release and combustion stage. The  $E_a$  for the blend of 85% ROM + 15% PL was increased from 47.8 kJ/mol to 83.8 kJ/mol for the blend of 25% ROM + 75% PL for the volatile combustion. The same trend was observed with discard coal, where the  $E_a$  of the blends increases from 52.4 kJ/mol to 88.5 kJ/mol as the plastic ratio in the blends increases from 15% to 75%, respectively. This was in agreement with the study conducted by Wang et al. (2016) [36] on the co-combustion of coal and biomass. The author found that the  $E_a$  of the volatile combustion was higher than that of the char combustion as a result of the lower temperature environment of the volatile combustion which resulted in a higher energy requirement for the reaction [36]. The result obtained in this study is also in agreement with the findings of other authors for the volatile release and combustion stages [20, 37]. In stage 4, as seen in Table 2, as the ratio of the PL increases in the discard/PL blends, the  $E_a$  was reduced from 77.8 kJ/mol to 33.5 kJ/mol. The same observation was made by other authors on the decreasing  $E_a$  during co-combustion as the percentage biomass increases in the blends for char combustion in stage 4 [13,21].

#### 4. Conclusion

This study sought to establish the difference in the physicochemical properties and burning characteristics of RDF, discard coal and their blends in various proportions. On the basis of combustibility and reaction kinetics, the two different RDF types and the coal utilized in this study displays different combustion performance. The combustion profiles of the RDF samples show that they ignite at relatively low temperatures and are highly reactive, which implies that it could serve as a fuel in a fluidized bed combustor. The DTG profiles of the RDF samples displayed two or more peaks, while the discard and the ROM coal samples displayed only one peak. The addition of the RDF to the coal blends led to a decrease in the ignition and volatile matter combustion temperature of the co-fired samples.

The calculated apparent activation energies for stage 2 increased as RDF was added to the blend due to the low temperature environment of the pyrolysis. The reduction in the  $E_a$  for the combustion of the char showed that the addition of RDF to low-quality coal results in a fuel which requires less energy and time to combust. The coal blend with RDF ( $\leq 30\%$ ) show the most similarity to the combustion profiles of 100% coal. Of these blends, the blend of discard coal (70%) and PL (30%) showed the lowest apparent activation energies of 55.8 kJ/mol and 54.2 kJ/mol for the volatile and char combustion, respectively, making this the most favourable blend (coal and plastic) for co-combustion. In summary, the addition of RDF composed of more than 85% plastic has been shown to improve the combustion profile of a high ash South African coal. This blend is considered to be an alternative fuel which could be used in an existing South African pulverized boiler.

#### Declarations

##### Author contribution statement

Kerina Isaac: Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Samson Bada: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

##### Funding statement

This work was supported by the National Research Foundation of South Africa's SARChI Clean Coal Technology Grant (Grant Number: 86421).

##### Competing interest statement

The authors declare no conflict of interest.

##### Additional information

No additional information is available for this paper.

##### Acknowledgments

The authors express their appreciation to Interwaste, Johannesburg, South Africa for providing the refuse derived waste used in this study.

##### References

- [1] WorldBank, Solid Waste Management, 2019.
- [2] Department of Environmental Affairs, State of Waste Report South Africa - Second Draft Report. Pretoria, 2018.
- [3] J. Malat'ak, J. Velebil, J. Bradna, Specialty types of waste paper as an energetic commodity, *Agron. Res.* 16 (2018) 534–542.
- [4] Eskom, Integrated Report, 2018.
- [5] A. Ko, N.-B. Chang, Optimal planning of co-firing alternative fuels with coal in a power plant by grey nonlinear mixed integer programming model, *J. Environ. Manag.* 88 (2008) 11–27.
- [6] R. Jeffrey, R. Falcon, A. Kinghorn, The benefits and challenges associated with coal in South Africa, *Cornerstone* 2 (2014) 66–70.
- [7] O. Vekemans, J. Chaouki, Municipal solid waste Co-firing in coal power plants: combustion performance, *Dev. Combust. Technol.* (2016) 118–142.
- [8] O. Aderoju, G. Dias, Z. Echakraoui, Assessment of renewable energy sources & municipal solid waste for sustainable power generation in Nigeria, *IOP Conf. Ser. Earth Environ. Sci.* 95 (2017) 1–10.
- [9] X. Chen, J. Xie, S. Mei, F. He, NO<sub>x</sub> and SO<sub>2</sub> emissions during co-combustion of rdf and anthracite in the environment of precalciner, *Energies* 11 (2018).
- [10] S. Zhang, X. Lin, Z. Chen, X. Li, X. Jiang, J. Yan, Influence on gaseous pollutants emissions and fly ash characteristics from co-combustion of municipal solid waste and coal by a drop tube furnace, *Waste Manag.* 81 (2018) 33–40.
- [11] E.C. Zabetta, V. Barišić, K. Peltola, A. Hotta, Foster wheeler experience with biomass and waste in CFBs, in: 33rd Clear Conf, 2008, pp. 1–15.
- [12] A. Sever Akdağ, A. Atımtay, F.D. Sanin, Comparison of fuel value and combustion characteristics of two different RDF samples, *Waste Manag.* 47 (2016) 217–224.
- [13] M. Muthuraman, T. Namioka, K. Yoshikawa, A comparative study on co-combustion performance of municipal solid waste and Indonesian coal with high ash Indian coal: a thermogravimetric analysis, *Fuel Process. Technol.* 91 (2010) 550–558.
- [14] J. Yanik, G. Duman, O. Karlstrom, A. Brink, NO and SO<sub>2</sub> emissions from combustion of raw and torrefied biomasses and their blends with lignite, *J. Environ. Manag.* 227 (2018) 155–161.
- [15] A. Iordanidis, A. Asvesta, A. Vasileiadou, Combustion behaviour of different types of solid wastes and their blends with lignite, *Therm. Sci.* 22 (2018) 1077–1088.
- [16] Department of Environmental Affairs, Municipal Solid Waste Tariff Strategy, 2012.
- [17] Interwaste Intergrated Waste Management, 2018. <https://www.inter-waste.co.za/integrated-waste-management>. (Accessed 20 September 2018).
- [18] Department of Minerals and Energy, National Inventory Discard and Duff Coal – Summary Report, 2011.
- [19] M. Belaid, R. Falcon, P. Vainikka, K.V. Patsa, Potential and technical basis for utilising coal beneficiation discards in power generation by applying circulating fluidised bed boilers, 2nd Int. Conf. Chem. Ecol. Environ. Sci. (2013) 260–265.
- [20] A. Álvarez, C. Pizarro, R. García, J.L. Bueno, A.G. Lavín, Determination of kinetic parameters for biomass combustion, *Bioresour. Technol.* 216 (2016) 36–43.
- [21] J. Wang, S.Y. Zhang, X. Guo, A.X. Dong, C. Chen, S.W. Xiong, et al., Thermal behaviors and kinetics of pingshuo coal/biomass blends during coprolysis and cocombustion, *Energy Fuel.* 26 (2012) 7120–7126.



- [22] M.V. Gil, D. Casal, C. Pevida, J.J. Pis, F. Rubiera, Thermal behaviour and kinetics of coal/biomass blends during co-combustion, *Bioresour. Technol.* 101 (2010) 5601–5608.
- [23] S. Bada, R. Falcon, L. Falcon, Characterization and co-firing potential of a high ash coal with *Bambusa balcooa*, *Fuel* 151 (2015) 130–138.
- [24] R.L. Blaine, H.E. Kissinger, Homer Kissinger and the Kissinger equation, *Thermochim. Acta* 540 (2012) 1–6.
- [25] O. Nam-Chol, P. Hyo-Song, S. Yong-Chol, R. Yong-Hyok, K. Yong-Nam, A feasibility study of energy recovery of RDF from municipal solid waste, *Energy Sources Part A Recover. Util. Environ. Eff.* 40 (2018) 2914–2922.
- [26] R. Rautenbach, C.A. Strydom, J.R. Bunt, R.H. Matjie, Q.P. Campbell, C. Van Alphen, Mineralogical, chemical, and petrographic properties of selected South African power stations' feed coals and their corresponding density separated fractions using float-sink and reflux classification methods, *Int. J. Coal Prep. Util.* (2018).
- [27] J.W. Cumming, J. McLaughlin, The thermogravimetric behaviour of coal, *Thermochim. Acta* 57 (1982) 253–272.
- [28] D. Porshnov, V. Ozols, L. Ansone-Bertina, J. Burlakovs, M. Klavins, Thermal decomposition study of major refuse derived fuel components, *Energy Proc.* 147 (2018) 48–53.
- [29] H. Yang, R. Yan, H. Chen, D.H. Lee, C. Zheng, Characteristics of hemicellulose, cellulose and lignin pyrolysis, *Fuel* 86 (2007) 1781–1788.
- [30] D. Vamvuka, S. Sfakiotakis, S. Saxioni, Evaluation of urban wastes as promising co-fuels for energy production - a TG/MS study, *Fuel* 147 (2015) 170–183.
- [31] E. Cardozo, C. Erlich, L. Alejo, T.H. Fransson, Combustion of agricultural residues: an experimental study for small-scale applications, *Fuel* 115 (2014) 778–787.
- [32] B. Arias, C. Pevida, F. Rubiera, J. Pis, Effect of biomass blending on coal ignition and burnout during oxy-fuel combustion, *Fuel* 87 (2008) 2753–2759.
- [33] S. Hu, X. Ma, Y. Lin, Z. Yu, S. Fang, Thermogravimetric analysis of the co-combustion of paper mill sludge and municipal solid waste, *Energy Convers. Manag.* 99 (2015) 112–118.
- [34] X. Fang, L. Jia, L. Yin, A weighted average global process model based on two-stage kinetic scheme for biomass combustion, *Biomass Bioenergy* 48 (2013) 43–50.
- [35] S.E. Smith, R.C. Neavel, E.J. Hippo, R.N. Miller, DTGA combustion of coals in the Exxon coal library, *Fuel* 60 (1981) 458–462.
- [36] G. Wang, J. Zhang, J. Shao, Z. Liu, G. Zhang, T. Xu, et al., Thermal behavior and kinetic analysis of co-combustion of waste biomass/low rank coal blends, *Energy Convers. Manag.* 124 (2016) 414–426.
- [37] K. Jayaraman, M.V. Kok, I. Gokalp, Thermogravimetric and mass spectrometric (TG-MS) analysis and kinetics of coal-biomass blends, *Renew. Energy* 101 (2017) 293–300.