TG-DSC investigation of co-combustion characteristics of blends sawdust and coal

D F Umar, I Monika and S Handoko

R&D Centre for Mineral and Coal Technology, The Republic of Indonesia
Corresponding author’s email: datin.umar@esdm.go.id

Abstract. Co-combustion of biomass and coal in coal fired power plant could reduce CO₂ emissions and utilize renewable energy resources. To understand the co-combustion characteristics of biomass and coal blends, thermogravimetry-differential scanning calorimetry (TG-DSC) analysis, as well as proximate, ultimate and heating value have been conducted. TG-DSC measures both weight changes (TG) and heat flow (DSC) in a material as a function of temperature or time in a controlled atmosphere. The combustion profiles can be used to study some combustion properties of fuels and fuel blends. The biomass that used in this study was sawdust in its origin and torrefied sawdust which blend with a low rank coal. The composition of the biomass and coal were 1:3; 1:1 and 3:1 in weight ratio. Results indicated that the blend of coal and torrefied sawdust in weight ratio of 1:3 was the best combustion performance compared to the other composition, indicated by the highest of ignition temperature (Tig), maximum combustion rate (Rmax) and heating value.

1. Introduction

Energy demand in Indonesia, increases year by year in line with the increasing of living standard of the people. Electricity is the most convenient form of energy carrier necessitating a large demand in the modern society. In spite of the limited reserve, the fossil fuels are likely to dominate (> 80 %) the electricity generating resources at least for the next few decades, about 60 % from coal, 22 % from natural gas, and 6 % from oil, and only 12 % of it generated by renewables. The dominance of the use of coal as fuel is caused by the abundance of coal which is relatively inexpensive due to easy and low-cost extraction, and less expensive infrastructure requirements compared to other energy resources.

Coal combustion for electricity generation is regarded as one of the major contributors of anthropogenic carbon emission in the environment [1]. Environmental and economic concerns of reducing green house gas (GHG), e.g. CO₂, have been motivating the utilization of biomass to substitute fossil fuels. Biomass co-combustion with coal is being recognised as a particularly attractive proposition for electricity generation since it provides an immediate and practical means of mitigating coal usage. It is confirmed that existing coal power plants of several hundred MW can be used as opposed to the < 100 MW capacity of contemporary biomass only plants [2].

Biomass is becoming an increasingly important contributor to the global energy mix, relatively carbon-neutral over its life cycle and renewable if grown sustainably. There is rising global concern regarding the use of non-renewable fossil fuels such as coal in thermal power stations, substituting coal with biomass is a very important aspect of future energy generation. Direct firing of the biomass, or co-combustion of biomass with coal to reduce the total usage of coal are both possible alternatives that show promise [3]. Another advantage of co-combustion biomass with coal involves the higher volatility of biomass. This has the effect of improving the reactivity and ignition characteristics of the fuel, compared to pure coal [4].
Consumption of biomass as the sole fuel resource for a large power station may not be an attractive alternative either economically or logistically. However, biomass can be used as a supplementary fuel along with the conventional fossil fuel in the plant, either in a co-firing mode or as a re-burning fuel [5-6].

According to Sarvaramini et al. [7], coal/biomass co-combustion for energy production is hampered by the limited biomass energy contribution. The most common hurdles are (1) low energy density of biomass (as compared to coal) due to the large moisture and oxygen contents cause flame instabilities in the combustion chambers, (2) low biomass flowability and fluidization properties leading to difficulties in feeding biomass into combustors, and (3) rigidity and mechanical strength of biomass structure attributed to the long crystalline cellulose fibers intertwined with non-crystalline hemicellulose resulting in higher grinding energy requirements and reducing grinding efficiency of coal-biomass feeds.

To overcome those shortcomings, torrefaction is one of the thermal treatment techniques to improve the fuel properties. Torrefaction is currently being considered as a biomass feedstock pretreatment particularly for thermal conversion systems [9]. During torrefaction, various permanent and condensable gases with high oxygen contents, are formed mainly due to hemicellulose degradation. As a consequence, the final solid product, so-called torrefied biomass, will be composed mainly of cellulose and lignin and characterized by increased brittleness, hydrophobicity, microbial degradation resistance, and energy density [9].

This paper discusses the effects of blend coal-biomass on its thermal and combustion behaviours which were studied using simultaneous thermal analysis (STA) methods. Simultaneous thermogravimetric and differential scanning calorimetry/differential thermal analysis (TGA-DSC/DTA) measures both heat flow (DSC) and weight changes (TG) in a material as a function of temperature or time in a controlled atmosphere. The characteristic parameters of each sample, including the ignition temperature (Tig), temperature maximum (Tmax), burnout temperatures (Tbo) and the combustion rate (Rmax), were investigated during the process to identify the thermal properties of blended coal-biomass.

2. Methodology
2.1. Materials
Coal used in this research was taken from Sorong Regency, West Papua Province. The coal is found in the southern region of the Regency in Salawati area. The coal carrier formation the Sele Conglomerate Formation, however part of this formation is covered by alluvial deposits [10]. The thickness varies from the thinnest 0.40 m to 2 m and the resources reach 100 million tons. Physically, coal has a brownish black color, slightly brittle and relatively mild. It is likely classified as young coal.

Coal exploitation activities are being conducted in the area though not optimally yet due to the small quantity of demand. Currently, the coal is used by the Maruni cement plant in Manokwari, and a mine mouth coal fired power plant will be built soon. Sawdust is a by-product or waste product of woodworking operations such as sawing, milling, planing, routing, drilling and sanding. It is composed of fine particles of wood. A major use of sawdust is for particleboard; coarse sawdust may be used for wood pulp.

In Sorong, West Papua, there are several major wood species that have been well known in the international market. Their uses are various, depending on their density; as materials for constructions, meubles and furniture. High production of these wood species in different stages of timber-processing industries has resulted in the generation of large amounts of waste, in forms of sawdust, chips, shavings, barks etc. Those solid wastes are dominantly disposed of, potentially posing detrimental impacts to the environment.
2.2. Torrefaction
To improve the sawdust properties as fuel, the sawdust was torrefied. It is a thermal pre-treatment to enhance chemical and physical properties to produce relatively dry sawdust and to reduce or eliminate its potential of organic matter decomposition. It was carried out under atmospheric pressure and in the absence of oxygen. After torrefaction process, the torrefied sawdust is expected to has higher calorific value, lower moisture content, less oxygen, more uniform properties, more brittle to reduce energy consumption during milling and enables higher co-combustion rates than its raw sawdust. There were five main stages in the total torrefaction process [8-9]:

- Initial heating: the biomass was initially heated until the stage of drying of the biomass was reached. In this stage, the temperature was increased, while at the end of this stage moisture started to evaporate.
- Pre-drying: at 100 °C the free water was evaporated from the biomass at a constant temperature.
- Post-drying and intermediate heating: the temperature of the biomass was increased to 200 °C. Physically bound water was released, while the resistance against mass and heat transfer was within the biomass particles. During this stage, some mass loss can occur as light fractions can evaporate.
- Torrefaction: during this stage, the actual process occurred. The torrefaction started when the temperature reached 200 °C and end when the process was again cooled down from the specific temperature to 200 °C. The torrefaction temperature was defined as the maximum constant temperature. During this period, most of the mass loss of the biomass occurred.
- Solids cooling: the torrefied product was further cooled below 200 °C to the desired final temperature, which was the room temperature.

2.3. Chemical characteristics
Each sample of the coal, sawdust (SD) and torrefied sawdust (TSD) was milled and sieved to the desired particle size (± 75 μm). The fine Sorong coal was blended with the fine sawdust and torrefied sawdust, respectively. Blending was conducted in a mortar and stirred constantly to form a homogeneous sample. The blending ratio of the coal to biomass (raw sawdust and torrefied sawdust) based on the mass fraction percentages were 1:3; 1:1 and 3:1.

To support the study of combustion behaviour, the samples were analysed to the proximate and calorific value. The proximate analysis covered the determination of inherent moisture (IM), ash (ASH) and volatile matter (VM) and the calculation of fixed carbon (FC) according to ASTM D3172-07a Standard Practice for Proximate Analysis of Coal and Coke (ASTM D3172-13, 2013).

The calorific value of the coal was determined according to the ASTM D 5865-04. Gross calorific value (gross heat of combustion at constant volume), Qv (gross) was the heat produced by complete combustion of coal at constant volume with all water formed condensed to a liquid under specified conditions. In this investigation, the adiabatic bomb calorimeter was used to determine the calorific value. Adiabatic calorimeter was a calorimeter that operated in the adiabatic mode and provided with microprocessor. The initial temperature before initiating the combustion and the final temperature were recorded by a microprocessor.

Ultimate analysis or elemental analysis is useful during mass balance calculations for a chemical or thermal process. According to Chen et al. [11], the main chemical elements from wooden pellets or sawdust consist of carbon (C), hydrogen (H), oxygen (O), and some secondary elements (usually negligible). Therefore, the ultimate analysis of coal and also biomass consists of carbon, hydrogen and oxygen.

The carbon presents in the organic coal/biomass substance and any carbon originally present as mineral carbonate. The hydrogen includes in the organic materials and in all water associated with the coal/biomass. Whilst the oxygen can be divided into organic oxygen and inorganic oxygen [12]. The oxygen concentration has a significant influence on the kinetics characteristics and kinetics parameters. The apparent activation energy was less than that in the low oxygen concentration under a high
oxygen concentration [13]. Ultimate analysis of C, H and O in this study were correlated with the results of proximate analysis of ASH, VM and FC in dry basis according to the formula of:

\[
C = 0.635FC + 0.460VM - 0.095ASH \quad (1)
\]

\[
H = 0.059FC + 0.060VM + 0.010ASH \quad (2)
\]

\[
O = 0.340FC + 0.469VM - 0.023ASH \quad (3)
\]

The average absolute errors of correlations given in the Equations are 3.17 %, 4.47 % and 3.16 %, with average bias errors of 0.19%, 0.34% and 0.19%, respectively [14-15].

2.4. Combustion characteristics

Combustion characteristics were determined using a thermogravimetric analyzer of LINSEIS High-Pressure STA TGA-DTA/DSC as shown in Figure 1. Sample of about 12-20 mg was placed in an alumina cell at an airflow rate of 25 mL/min and a heating rate of 10 °C/min [8]. The maximum experimental temperature was 800 °C. The weight loss of the sample and the rate of the weight loss were recorded continuously under dynamic conditions as functions of time or temperature, and all the experiments were performed at atmospheric pressure, under an inert air atmosphere.

Based on the weight loss curve derived from TGA-DTA/DSC, some combustion parameters were obtained (Figure 2). The ignition temperature (Tig) corresponds to the Tig of the volatile matter. Tig is an important characteristic of combustion, especially for low-rank coal due to its high intensity of spontaneous combustion [6]. Temperature maximum (Tmax) is the temperature at which the maximum rate occurred from the HDSC curve. Rmax relates to the maximum combustion rate was defined as \[d(TG)/dt\] at Tmax while char burnout temperature (Tbo) shows the end of combustion temperature at which the rate of heat flow is zero (dHDSC).

![Figure 1. High-Pressure TGA-DTA/DSC.](image1)

![Figure 2. Combustion parameters from the TG-DSC tests [16].](image2)

3. Results and Discussion

3.1. Chemical characteristics of proximate, calorific value and ultimate

Chemical characteristics of the samples (coal and biomass) were analysed through proximate analyses of inherent moisture, ash, volatile matter and fixed carbon, ultimate analysis of carbon, hydrogen and oxygen, as well as calorific value in dry basis. The results including blends coal-biomass at some ratios are listed in Table 1. The analyses were only conducted on coal, sawdust and torrefied sawdust samples. While the blends of coal and biomass, analyses results were obtained from calculation based on the coal and biomass ratio.
As seen in Table 1, inherent moisture of the coal is quite high of 26.76 %, consequently the calorific value is low of 4.073 cal/g (in adb). As physically appearance mentioned above, it is confirmed that the coal is classified as young coal or low calory coal with CV of <5,100 cal/g in adb.

In this study, the sawdust has relatively low inherent moisture content of 8.14 %, biomass generally has high moisture and volatile contents and low calorific value [17]. The low moisture of the sawdust in this study, could be due to the sawdust was not wrapped properly during storage. After torrefaction process, the moisture was decreased to 6.92 %. The slightly decrease of moisture content due to the torrefaction process is in accordance with the result that was carried out by Surest and teams [18]. In their research, the sawdust has moisture content of 11.62 % and slightly decreased to 9.85 % after torrefaction process.

Similarly with the ash content, here ash content was increased from 1.52 % to 5.03 %. According to the result of Surest et al., ash content is increased from 0.96 % to 6.93 %. It is also in line with the result of van der Stelt et al. research that was torrefied wood at temperature of 250 °C and 300 °C [19]. The ash content of raw wood was increased from 1.3 % to 1.5 % and 1.9 % after torrefaction process at temperature of 250 °C and 300 °C respectively. The increasing of ash could be understood due to the mass loss of the material. The process enriched the carbon content, so that the ash content of torrefied sawdust was substantially increased. The greater the mass loss of sawdust, the higher the ash content [20].

The volatile matter was significantly decreased after torrefaction process from 76.40 % to 12.44 %. It shows that torrefaction process was effective to reduce volatile matter. High volatile matter in sawdust could be an advantage for thermal chemical conversion processes: during the decomposition, it is evolved as gas instantaneously, leaving behind only a small amount of char, chemical energy is stored mainly in the form of fixed carbon and volatile matter, which can be released via direct or indirect combustion [16]. During the process of torrefaction, the sawdust partly devolatilizes leading to a decrease in mass. Mass losses obtained after thermal treatment were due to decomposition of the main chemical compounds of sawdust: cellulose, hemicellulose, and lignin. Decompositions begin at temperatures of 180 °C [21].

Torrefaction destructs not only the fibrous structure and tenacity of biomass, but also increases the calorific value [22]. The calorific value of the raw sawdust was significantly increased after torrefaction process. The calorific value of raw sawdust was increased from 3,793 cal/g to 6,973 cal/g (adb). According to van der Stelt et al. [19], the initial energy content of the torrefied biomass is mainly preserved in the solid product so the energy density of the biomass becomes higher than the raw biomass.

Table 1. Analysis results of proximate, ultimate and calorific value.

| Sample        | IM % adb | Ash % dry | VM % dry | FC % dry | C % dry | H % dry | O % dry | CV cal/g adb |
|---------------|----------|-----------|----------|----------|---------|---------|---------|-------------|
| Coal          | 26.76    | 9.48      | 52.68    | 37.84    | 62.33   | 7.93    | 26.69   | 4,073       |
| Sawdust (SD)  | 8.14     | 1.52      | 76.40    | 22.08    | 48.64   | 5.90    | 43.30   | 3,793       |
| Torrefied sawdust (TSD) | 6.92   | 5.03      | 12.44    | 82.53    | 57.59   | 5.11    | 33.78   | 6,973       |
| Coal 1:SD 3   | 12.80    | 3.19      | 71.42    | 25.39    | 52.06   | 6.41    | 39.15   | 3,863       |
| Coal 1:SD 1   | 17.45    | 5.05      | 65.88    | 29.07    | 55.48   | 6.92    | 35.00   | 3,933       |
| Coal 1:SD 3   | 22.11    | 7.13      | 59.67    | 33.20    | 58.91   | 7.42    | 30.84   | 4,003       |
| Coal 1:TSD 3  | 11.88    | 5.95      | 20.80    | 73.25    | 58.78   | 5.82    | 32.01   | 6,248       |
| Coal 1:TSD 1  | 16.84    | 6.99      | 30.16    | 62.85    | 59.96   | 6.52    | 30.23   | 5,523       |
| Coal 3:TSD 1  | 21.80    | 8.15      | 40.71    | 51.14    | 61.14   | 7.23    | 28.46   | 4,798       |

Note: adb: air dried basis
After torrefaction process, the carbon content of the sawdust was increased from 48.64 % up to 57.59 %, while hydrogen and oxygen contents were decreased from 5.90 % to 5.11 % and from 43.30 % to 33.76 %, respectively (Table 1). The increasing of carbon content is in line with the increasing of fixed carbon due to the release of volatile rich in hydrogen and oxygen, such as water and carbon dioxide. This change in the chemical composition of the sawdust improves its quality as an energy source through an increase in energy density since more oxygen than carbon is lost in the form of volatile.

3.2. Combustion characteristics
TG-HDSC curves of the coal, sawdust, torrefied sawdust include the blends of coal-sawdust and coal-torrefied sawdust in some compositions are illustrated in Figure 3 (a) to (i) and the combustion characteristics determined from these curves are summarized in Table 2.

![Figure 3. TG-HDSC curves of coal sawdust, torrefied sawdust, coal-sawdust and coal torrefied sawdust blends.](image-url)
Different from the proximate, ultimate and calorific value analyses, the combustion behaviour of the blends of coal and biomasses cannot be directly correlated based on the weight composition of them. Combustion characteristics are not only influenced by chemical composition, but also influenced by several factors, such as particle size, combustion temperature, etc.

The ignition temperature (Tig) is defined as the lowest bed temperature required for stable combustion in boiler which corresponded to the starting point of the devolatilization of volatile matter. If the coal is fed into a furnace at a temperature lower than Tig, the coal will not burn and the furnace temperature will decrease even more. While feeding the coal at temperatures higher than Tig, is safer but consumes time and oil [23].

The lowest Tig of the blend of coal and sawdust at the weight ratio percentage of 1:3 is related to the volatile content within the samples. The higher volatile content contributes to the release process of volatile matter. The faster devolatilization rate and oxidation rate of the volatile matter leads to lower particle ignition temperatures [24]. In accordance with the previous research by Umar et al. [8], the Tig increases with the increase of fixed carbon and calorific value. The fixed carbon is the solid fuel that is left in the furnace after the volatile matter is distilled off. The exponential trendline of Tig is higher with the higher amounts of the fixed carbon and calorific value (Figure 4).

Temperature maximum (Tmax) is the temperature at which the maximum rate occurred from the DSC curve. It relates to the reactivity defined as the rate at which the fuel reacts in an oxidizing/reducing atmosphere, subsequently its de-volatilization, describes the easiness of the fuel to reacts with the gasification agent (e.g. oxygen). The reactive fuels have a lower Tmax. The lower the Tmax, the more reactive the coal at low-temperature oxidation causes spontaneous combustion. The Tmax has no definite correlation with the Tig or the Rmax [8]. The coal has the lowest Tmax of 391.4 °C compared to those of sawdust and torrefied sawdust of 472.5 and 456.1°C, respectively. It could be understood because the coal is classified as low rank coal with high moisture content which affects low temperature oxidation due to the easiness to react with oxygen. The highest Tmax of the blend of coal and biomass was reached by the blend of coal and sawdust at the weight composition percentage of 3:1, i.e. 481.9 °C.

Rmax relates to the maximum combustion rate. The highest Tmax was reached by the blend of coal and torrefied sawdust at the weight ratio percentage of 1:3 of 0.0075 mg/s. This result is in line with the results of moisture and calorific value analyses. The Rmax will be high if the moisture content is low and the fixed carbon and heating value are high. Similarly with the Tig, the exponential trendline of Rmax is higher with the higher amount of the fixed carbon and calorific value as shown in Figure 5 while the relation between Rmax with Tig and Tmax is shown in Figure 6.

Char burnout temperature (Tbo) reflects the char characteristics of the fuel and end of combustion. The lowest Tbo of the blend coal with torrefied sawdust at the weight composition of 3:1 can be understood because its combustion rate of Rmax is relatively high. Figure 7 shows that the Tbo has no definite correlation with the Tig, Tmax or Rmax. It shows that the char burnout of the coal,
biomasses and the blends of coal with the biomasses changes in a wide region. Besides the effects on the burning parameters such as the Tig, Rmax and Tmax, on the other hand, macromolecular ingredients of biomass such as hemicelluloses, celluloses, and lignin have significant effects on the combustion behavior of biomass [25].

Figure 4. Relation between Tig with fixed carbon and calorific value.

Figure 5. Relation between Rmax with fixed carbon and calorific value.

Figure 6. Relation between Rmax with fixed carbon and calorific value.

Figure 7. Relation between Tbo with Tig and Tmax.

4. Conclusion
The coal used in this research was categorized as low calory coal of 4,073 cal/g in air dried basis. Experiment results indicated that torrefaction process was effective to increase the fixed carbon and calorific value of the sawdust due to the decrease of moisture and volatile matter contents. The
calorific value affected the combustion performance, i.e., higher calorific value, higher Tig, Tmax and Rmax. The blend of coal with torrefied sawdust at the weight composition percentage of 1:3 has the best combustion performance compare to the other composition with the Tig, Tmax, Rmax and Tbo of 336.6 °C, 456.1 °C, 0.0075 mg/s and 644.9 °C respectively. There is no direct correlation between Tbo and other combustion parameters of Tig, Tmax or Rmax. It can be stated that the combustion behaviour of blends of coal and the biomass is basically complex. Clearly, more tests are needed to investigate the effect of coal and biomasses properties both physically and chemically in more detail.

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