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Investigation of co-combustion characteristics of low quality lignite coals and biomass with thermogravimetric analysis

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ABSTRACT

In this study, combustion and co-combustion characteristics of three biomass fuels and three Turkish lignite coals were investigated by using a thermo gravimetric analyzer. There are just a few studies investigating the co-combustion characteristics of coal and biomass, and the synergistic effect of their various combinations on the peak temperatures and burnout times.

Results of this study have shown that low rank coals can be burned with biomass very beneficially. As the VM content of the coal increases, the ignition temperature decreases and the maximum combustion rate is reached at lower temperatures. About 80–90% of the fuel is combusted as the combustion of volatile matter. As the biomass content of the fuel mixture increases, the ignition temperatures of the mixtures are found to be very close to that of the biomass. Therefore, it can be said that biomass in the mixture starts to burn first and then coal follows.

1. Introduction

The energy demand of the world is continuously increasing in parallel with population increase and industrial development. According to the "Key World Energy Statistics-2008" published by the International Energy Agency, total primary energy supply has increased from 6 115 Mtoe in 1973 to 11 741 Mtoe in 2006 [1]. This demand has been met by fossil fuels particularly from coal until now. The share of fossil fuels (coal/peat, oil and gas) on the total primary energy supply was 80.9% in 2006. Out of this amount 26% belonged to coal/peat [1].

Biomass energy is one of the renewable energy sources. When the huge biomass potential of the world is considered, biomass is a candidate fuel to play a supplementary but active role for meeting part of the world's energy demand. Particularly, within the European Union (EU) biomass is seen as the most relevant renewable energy source besides hydropower. Thus, it is expected to contribute substantially to the CO_2 emission reduction targets defined in the Kyoto protocol [2]. Biomass utilization in energy production is very important to decrease the fossil fuel usage in energy sector. It is also seen a very effective way of removal of biowaste materials which occupy great volumes when they are disposed to a landfill. Co-combustion of biomass with coal in fluidized bed combustors to get cleaner energy is a promising application. However, there can be some operational problems because of the alkali and chlorine content of the biomass fuel. Agglomeration of bed material, fouling, and corrosion of superheater tubes are commonly seen when biomass containing high alkali and chlorine content is burned in fluidized bed combustors [3]. These operational problems may be ended by burning biomass fuels with high-sulfur containing lignite coals. The reason could be the sulfur in the coal may react with alkalis coming from biomass and forming alkali sulfates [3]. Therefore, it is necessary to study the co-combustion characteristics of biomass fuels with coals.

Combustion characteristics of a fuel before it is used in energy production can be determined by using thermo-analytical techniques such as TG, DTG, DTA, DSC and TMA which cover a wide range of applications in research, development and economic assessment of fuels. They have been used in a wide variety of areas related to proximate analysis, coal reactivity, and heat effects associated with coal pyrolysis, combustion and heat of hydrogenation [4]. Thermogravimetric analysis (TGA) is the simplest and the most effective technique to observe the burning profile of a fuel. A short review of the studies done on the combustion characteristics of several fuels with thermogravimetric analysis is given in Table 1.

Xiao et al. [5] studied the combustion behavior of coal, straw, sewage sludge and their mixtures in a thermogravimetric ana-

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Abbreviations: TG, thermogravimetry; TGA, thermogravimetric analysis; DTG, differential thermogravimetry; DSC, differential scanning calorimetry; DTA, differential thermal analysis; TMA, thermomechanical analysis; FC, fixed carbon; VM, volatile matter; O, Orhaneli lignite; S, Seyitömer lignite; T, Tunçbilek lignite; HS, Hazelnut shells; OC, olive cake; W, wood chips; IT, ignition temperature; PT, peak temperature; BT, burnout temperature.

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Table 1
A summary of literature review.

Fuel type	Working temperature	Characterization technique used	Gases used	Ref.
Coal, straw, sewage sludge and their mixtures	30–1000 °C with a heating rate of 40 °C/min	TGA and DTG	Five different atmospheres used 80% N_2/20% O_2, 70% N_2/30% O_2, 60% N_2/40% O_2, 40% N_2/60% O_2, 30% N_2/70% O_2	Xiao et al. [5]
Treated waste wood samples (medium density fibers, plywood and particleboard); one untreated pine sample	25 °C up to 900 °C with 10, 20 and 30 °C/min heating rates	TGA	Air atmosphere	Yorulmaz and Atimtay [6]
Sewage sludge (SS), animal manure, and organic fraction of municipal solid waste	20–627 °C at a four different heating rates; 5, 10, 25, and 50 °C/min	TGA	Air atmosphere	Sanchez et al. [7]
Cotton, forest residues, olive kernel, and wood chars, lignite and a hard coal char and their blends	25–850 °C and at a heating rate of 10 °C/min	Non-isothermal thermogravimetry	Air atmosphere	Kastanaki and Vamvuka [8]
Seventeen coal samples from the Thrace basin of Turkey	20–600 °C at a heating rate of 10 °C/min	DSC and TG/DTG	Air atmosphere	Kök [9]
Biomass materials (sunflower shell, colza seed, pine cone, cotton refuse and olive refuse)	20–1000 °C at a heating rate of 20 °C/min	Non-isothermal thermogravimetry	Air atmosphere	Açma [10]
Four coal samples (peat, lignite, bituminous coal, and anthracite)	20–1000 °C with a heating rate of 40 °C/min	Non-isothermal thermogravimetry	Air atmosphere	Açma et al. [11]
Lignite coal samples from Thrace basin of Turkey	22–622 °C at a heating rate of 10 °C/min	TGA	Air atmosphere	Kök [12]

lyzer. Five different atmospheres were used with a flowrate of 100 mL/min. Five different atmospheres were used in order to investigate the effect of oxygen concentration on combustion. It was observed that the onset temperature for volatile release, weight loss and the final temperature detected at the stabilization of weight, decreased as the oxygen concentration in the combustion atmosphere increased. The maximum weight loss rate of sample was also observed to increase with the increase of heating rate. In another study Yorulmaz and Atimtay [6] studied the thermal kinetics and combustion mechanisms of three treated waste wood samples (treated medium density fiber, plywood and particleboard) by TGA. One untreated (untreated pine) sample was also used for comparison. The results of TG analysis showed that thermal decomposition of treated samples takes place at lower temperatures as compared to the untreated pine sample because of the catalyzing effects of the chemicals in the samples. Therefore, there were less flammable products, lower weight losses in the main oxidation region, and decrease in the maximum weight loss temperatures and formation of more char for treated samples as compared to untreated pine sample. Thermal kinetic constants for the samples were calculated by using Coats–Redfern method. In contrast to the other studies with untreated wood, treatment of wood with different additives and glues seemed to alter the thermal oxidation process and change the effective oxidation mechanisms. The studies carried out by Sanchez et al. [7] on thermogravimetric analysis in order to study combustion characteristics of sewage sludge, animal manure, and organic fraction of municipal solid waste. Activation energies of the materials studied were found to be in the range of 140 and 174 kJ/mol.

Kastanaki and Vamvuka [8] studied the combustion behavior and kinetics of four biomass chars, lignite and a hard coal char and their blends. Kinetic evaluation was performed using a power law model. Reaction kinetic parameters were obtained by modeling the combustion of biomass and coal chars as a single reaction, with the exception of lignite and olive kernel chars, the combustion of which was modeled by two partial reactions. A single reaction model was used in the case of coal–wood char blends, while for the lignite–biomass char blends two partial reactions were used. Reactivity was assessed using the specific reaction rate, as a function of conversion. Biomass chars were found generally more reactive than those of hard coal and lignite. The combustion behavior of the blends was greatly influenced by the rank of each coal (hard coal or lignite) and the proportion of each component in the blend. Alteration in reactivity was seen to be more pronounced in the case of lignite–biomass chars than coal–wood chars. This was an important result. Kök [9] performed differential scanning calorimetry (DSC) and thermogravimetry (TG/DTG) experiments for 17 coal samples which were from the Thrace basin of Turkey. Reaction intervals, peak and burnout temperatures of the coal samples were determined. Two different kinetic methods known as, Arrhenius and Coats–Redfern, were used to analyze the kinetic data. It was observed that the reaction intervals of the coal samples studied were varied between 265 and 500 °C depending on the properties. It was also observed that the activation energies of the samples were varied in the range of 54–92 kJ/mol. However, these values of activation energies were much lower than the activation energies found for the biomass materials used by Sanchez et al. [7].

Açma [10] investigated the combustion characteristics of five biomass materials (sunflower shell, colza seed, pine cone, cotton refuse and olive refuse). The derivative thermogravimetry (DTG) technique was applied in order to determine the burning profiles of biomass samples. Ignition temperatures and peak temperatures were determined for all samples. The ignition temperatures were found in a temperature range of 150 and 200 °C. The maximum combustion rates of the sunflower shell, pine cone, cotton refuse, olive refuse and colza seed were calculated as 5.5, 5.2, 3.7, 3.4 and 2.8 mg/min, respectively. It was observed that the investigated biomass materials showed different combustion characteristics. Also Açma et al. [11] studied the combustion reactivity of four coal samples (peat, lignite, bituminous coal, and anthracite). Non-isothermal thermogravimetry was used to determine the reactivity of the samples. Activation energies of samples were calculated by using Coats–Redfern method. The activation energies were found as 71, 97, 158, 191 kJ/mol for peat, lignite, bituminous coal, and anthracite samples, respectively. The first two activation energies for peat and lignite were in the range of activation energies that Kök [9] has found. The others are higher than the range. It was stated as a conclusion that activation energy of samples increased with increasing carbon content and decreasing volatile matter content on the dry mineral matter free basis. The results showed that the higher is the rank of the coal, the longer is the burnout time. These studies were looking at the combustion characteristics of single materials, but not co-combustion of coal and biomass.

Table 2
Proximate analysis, ultimate analysis and heating values of fuel samples.

Fuel sample	Proximate analysis (dry basis), % by wt.			Heating values (dry basis), kcal/kg	
	VM[a]	Ash	FC[b]	HHV[c]	LHV[d]
Tuncbilek (T)	26.17	52.34	21.49	3029	2912
Seyitömer (S)	34.24	46.29	19.47	3315	3196
Orhaneli (O)	36.07	32.25	31.68	4206	4031
Wood chips (W)	82.75	0.90	16.35	4711	4395
Olive cake (OC)	70.20	10.65	19.15	5245	4950
Hazelnut shells (HS)	73.54	1.73	24.73	5518	5215

Fuel sample	Ultimate analysis (dry basis), % by wt.				
	C	H	N	S_{total}	O
Tuncbilek	33.62	2.23	1.65	1.23	8.93
Seyitömer	36.61	2.27	1.32	1.43	12.08
Orhaneli	45.25	2.66	0.87	4.43	14.54
Wood chips	44.93	5.88	0.32	0.03	47.94
Olive cake	54.72	5.24	1.14	0.14	31.98
Hazelnut shells	56.34	5.35	0.51	0.01	36.06

[a] Volatile matter.
[b] Fixed carbon.
[c] Higher heating value.
[d] Lower heating value.

Kök [12] investigated the thermogravimetric characteristic of 17 lignite coal samples which were from Thrace basin of Turkey. It was observed that some coal samples had two separate peaks due to combustion of volatile matter within the coal. The proximate analysis of coal samples was also performed and it was concluded that the combustion profile of coal samples with high fixed carbon content generally showed two separate peaks, but the combustion profile of coal samples with low fixed carbon content showed one peak. This point needs further clarification.

As can be seen from the results of the above mentioned studies in the literature, none of the studies investigated the co-combustion characteristics of coal and biomass, and the effect of their various combinations on the peak temperatures and burnout times. This study will mainly consider these points. In this study, combustion characteristics of three biomass fuels and three Turkish lignite coals were investigated by using a thermo gravimetric analyzer. The effect of co-combustion of biomass fuels with Turkish lignite coals was also investigated to see the interaction and possible synergistic effects between biomass and coal during combustion.

2. Experimental

Three lignite coals (Tuncbilek, Orhaneli and Seyitömer) and biomass fuels (wood chips (oak), olive cake and hazelnut shells) and several mixtures of lignite coal and wood chips (25%, 50% and 75% by wt.) were used in the experiments. These coals and biomasses were selected due to their high reserve and high production potentials in Turkey. Sampling was carried out carefully in order to represent the original fuel as much as possible. Then, the samples were dried, crushed and sieved under 250 μm for the analyses.

Proximate analyses of the fuel samples were performed according to ASTM D 5142-04 standard test method with LECO-TGA701 thermogravimetric analyzer. Ultimate analyses of the fuel samples were performed according to ASTM D 5373-02 (for carbon, hydrogen and nitrogen contents) and ASTM D 4239-05 (for sulfur content) standard test methods using LECO Truspec CHN-S ultimate analysis instrument. Results of proximate and ultimate analysis are given in Table 2.

Calorific values of the fuel samples were detected according to ISO 1928:1995 standard test method with LECO AC350 bomb calorimeter. Calorific values of the fuel samples are also given in Table 2.

As can be seen from the table, the coal samples (T, S and O) are low rank coals. The lower heating values are between 2900 and 4000 kcal/kg on dry basis. They are even lower on the wet basis because air dried coals usually contain about 10–20% by wt. moisture. The lignite coals usually have higher VM content than bituminous coals. VM content of these coals vary between 26% and 36% by wt. The coal having the highest VM content is Orhaneli lignite.

The biomasses used in this study are wood chips (W), olive cake (OC) and hazelnut shells (HS). If the VM content of biomasses is compared with that of coals used in this study, it is seen that biomass contains about 2–3 times as much VM as the coal. Ash contents of the coals (on dry basis) are pretty high. However, the ash content of the biomass used is very low except the olive cake, even negligible.

Thermal behavior of the fuel samples was analyzed according to thermogravimetric analysis method using Mettler Toledo-TGA851 instrument. 50 mg of fuel sample was used for each experiment. Each sample was thoroughly mixed and homogenized before the analysis. Samples were heated from room temperature (25 °C) to 1100 °C at a heating rate of 20 °C/min in a dry air atmosphere of 40 mL/min. Then, they were kept waiting at 1100 °C in a dry air atmosphere for 30 min. Analysis of each sample was repeated twice and repeatability was checked. The repeatability of the experiments was more than 99%. Thermogravimetric (TG) and derivative thermogravimetric (DTG) curves of each fuel sample were obtained as an output. These curves were used in order to assess the thermal characteristics of fuel samples.

3. Results and discussion

3.1. Combustion results of coal and biomass separately

Burning characteristics obtained from a TGA analyzer may be a good guide in order to compare the reactivity and combustibility of the fuels which will be used in combustors.

According to TGA results, three regions were determined on thermographs. These regions were determined according to the approximate starting and end points of the DTG curve which shows thermal breakdown of the organic matters and volatiles in the samples. The first region on the DTG curve was due to the moisture and low boiling point organic matters in the sample. The second

Table 3
The ignition, peak and burnout temperatures of lignite coals and biomasses.

Fuel sample	Ignition temp. (T_o), °C	1st peak temp. (T_{p1}), °C	2nd peak temp. (T_{p2}), °C	Burnout temp. (T_b), °C	Burnout time, min	Max. comb. rate, mg/min	VM (dry basis), %
Tuncbilek1	265	595	–	–	63	1.578	26.17
Tuncbilek2	265	595	–	–	62	1.619	26.17
Seyitömer1	225	490	–	–	62	1.030	34.24
Seyitömer2	225	490	–	–	62	0.992	34.24
Orhaneli1	215	490	–	–	54	1.310	36.07
Orhaneli2	210	490	–	–	56	1.388	36.07
Wood chips	180	310	360[a]	730	35.5	8.460	82.75
Olive cake	190	330[a]	440, 770	880	43	5.290	70.20
Hazelnut shells	185	330	370[a], 440, 760	860	42	4.706	73.54

[a] Temperature of the main peak.

region where the main weight loss occurred was due to oxidation and removal of the volatile matters of the samples. The third region was due to oxidation of the char remaining after the volatiles were removed from the samples [6].

The ignition, peak and the burnout temperatures are important temperatures obtained from thermographs. The ignition temperature (IT) is the temperature at which a sudden decrease is seen in the DTG curve. The peak temperature (PT) represents the place where the rate of weight loss is at maximum due to rapid volatilisation accompanied by the formation of carbonaceous residue. The point on the DTG curve where the combustion rate is maximum corresponds to the peak temperature (PT) and the rate at this temperature is called the maximum combustion rate ($(dm/dt)_{\max}$). The peak temperature is the measure of the combustibility. Lower the peak temperature, easier is the ignition of the fuel. The burnout temperature (BT) is the temperature on the DTG curve where the oxidation is completed. The ignition and peak temperatures and burnout times of all fuel samples are given in Table 3.

As can be seen from Table 3, the most easily ignited coal is Orhaneli lignite, because it has the highest VM content. The ignition temperature is found as 213 °C on the average. The next easily ignited coal is Seyitömer lignite and then comes Tuncbilek lignite with ignition points as 225 and 265 °C, respectively. The VM contents of the coals go in the same order. From these results, we can conclude that as the VM content of the coal increases, the ignition temperature decreases and coal is more reactive.

TG and DTG curves of lignite coals (T, S, and O) are given in Fig. 1, respectively. It is seen from the figures that the burning characteristics of these three lignite coals are all different. Since Tuncbilek (T) lignite has the lowest VM, the ignition temperature is high (around 265 °C) and the first peak (after the moisture peak) temperature which shows the maximum combustion rate has been reached at 595 °C. However, for the other lignites (S and O) the ignition temperatures are lower than that of T (around 225 and 210 °C, respectively), because the VM content of these coals are around 34% and 36% by wt. The first peak (after the moisture peak) temperatures which show the maximum combustion rate have been reached at 490 °C which is earlier than the T lignite. The FC content of O lignite is higher than the T lignite.

In conclusion it can be said that for the more reactive coals the maximum combustion rate is reached at lower temperatures.

If the combustion characteristics for biomasses under investigation are concerned, a very different DTG curves are seen. Instead of one peak, two or more peaks are seen after the moisture peak. Among the biomasses investigated, wood chips are the most possible biomass which is readily available for co-combustion with lignite and also which will make the largest contribution to the country's economy.

TG and DTG curves of biomasses, namely wood chips (W), olive cake (OC) and hazelnut shells (HS) are given in Fig. 2, respectively. From the figures, it is seen that the burning characteristics of these biomass fuels are quite different than coals. Since the VM content of these fuels are much higher than coals (between 70.2 and 82.75% by wt. on dry basis), the ignition temperatures are lower than coals (around 200 °C). After the moisture is volatilized, the VM content starts to leave the material and burns very rapidly. The major peak is for the combustion of volatiles. After the moisture peak, wood chips give two peaks for combustion of volatiles. The first peak is combined with the second peak and it is like a shoulder to the second peak. The temperature of the first peak is 310 °C and that of the second peak is 360 °C. Combustion of about 90% of the sample

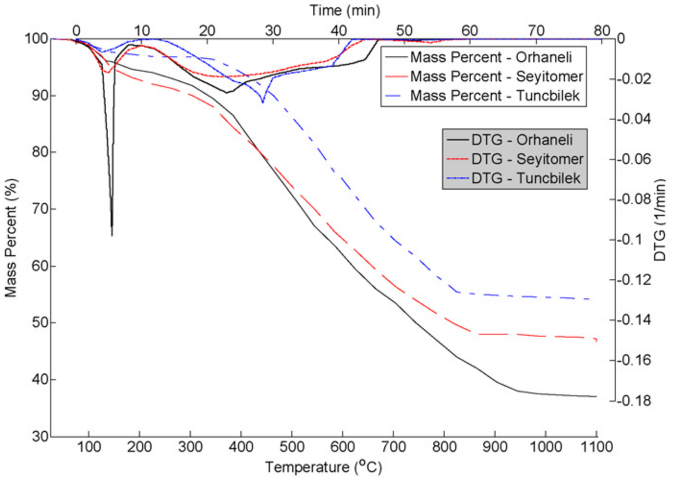

Fig. 1. TGA curves of coal samples (Tuncbilek lignite, Seyitömer lignite and Orhaneli lignite).

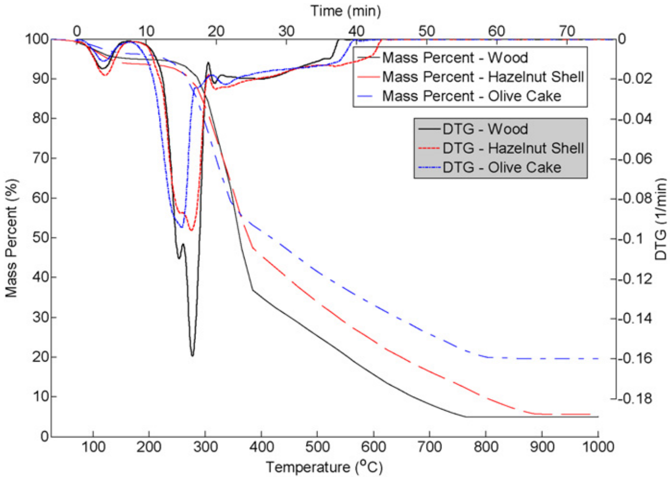

Fig. 2. TGA curves of biomass samples (wood chips, olive cake and hazelnut shells).

Table 4
The ignition, peak and burnout temperatures, and maximum combustion rates for co-combustion experiments.

Fuel sample	Ignition temp. (T_o), °C	1st peak temp. (T_{p1}), °C	2nd peak temp. (T_{p2}), °C	Burnout temp. (T_b), °C	Burnout time, min	Max. comb. rate, mg/min	VM (dry basis), %
25%W + 75%T	210	356	600	1100	56.0	2.410	40.32
50%W + 50%T	200	356	590	820	39.5	4.818	54.46
75%W + 25%T	190	356	580	760	37.0	6.843	68.61
25%W + 75%O	200	356	490	840	42.0	2.671	47.74
50%W + 50%O	195	356	485	800	38.3	5.038	59.41
75%W + 25%O	200	355	485	750	36.0	7.258	71.08
25%W + 75%S	215	356	–	1100	56.5	2.705	46.37
50%W + 50%S	210	356	–	1100	55.0	5.015	58.50
75%W + 25%S	195	356	–	750	36.5	7.100	70.62

is completed in 18 min. Then the char formed continues its combustion and the sample burnout is reached at 730 °C in 35.5 min.

DTG curve of the OC is a little different than that of W. After the moisture peak there is one major peak for the combustion of volatiles and it is seen at 330 °C. After the combustion of the 85% of the sample is completed in 19 min, 2 more peaks are seen during the char combustion at 440 and 770 °C, respectively. The total burnout of the sample is completed at 880 °C in 43 min.

DTG curve of the HS is similar to that of wood chips probably both materials have similar compositions and rich in lignin. After the moisture peak, HS also gives 2 peaks for combustion of volatiles. The first peak is combined with the second peak and it looks like a shoulder to the second peak. The temperature of the first peak is 330 °C and that of the second peak is 370 °C. Combustion of about 80% of the sample is completed in 18.5 min. Then the char formed continues its combustion and the sample burnout are reached at 860 °C in about 42 min. The rest 20% of the material burns more slowly and there are two minor peaks during this combustion similar to that of OC.

After these observations it can be said that biomass fuels are more reactive than lignite coals studied here. They ignite at much lower temperatures. About 80–90% of the fuel is combusted as the combustion of volatile matter. Then the combustion of the char formed takes time. The amount of the char formed depends on the amount of the FC% in the fuel.

Another important point to be considered is the combustion mechanism of coal samples with high ash content. In these coal particles, combustion follows the "shrinking core model" because of the high amount of ash material in coal. Oxygen and the gaseous compounds produced during their combustion must diffuse to the remaining particle. This may be the reason for the first peak temperature to be higher for lignite than for biomasses. The ash content of biomass is quite low as compared to coal. Therefore, a shrinking core model will not represent the combustion mechanism for biomass.

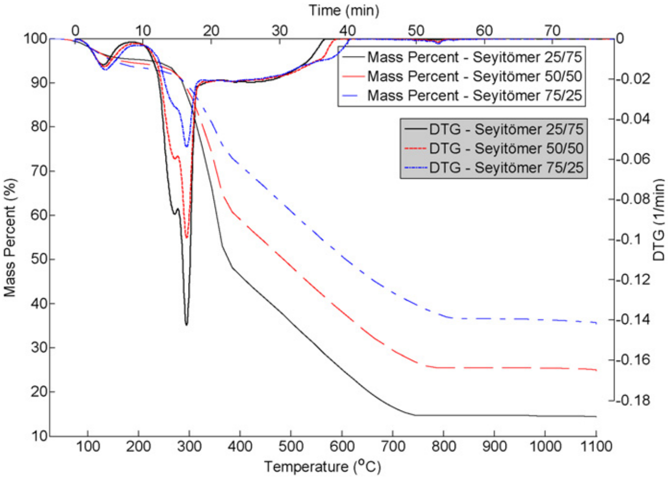

Fig. 4. TG and DTG curves of Seyitömer lignite and wood chips mixtures (75%S + 25%W, 50%S + 50%W and 25%S + 75%W).

3.2. Co-combustion results of coal with biomass

Co-combustion of Tuncbilek, Seyitömer and Orhaneli Lignites with wood chips was tried in this study. The wood chips are produced in very large quantities in Turkey and they can have a considerable contribution to the Turkish economy if the energy is

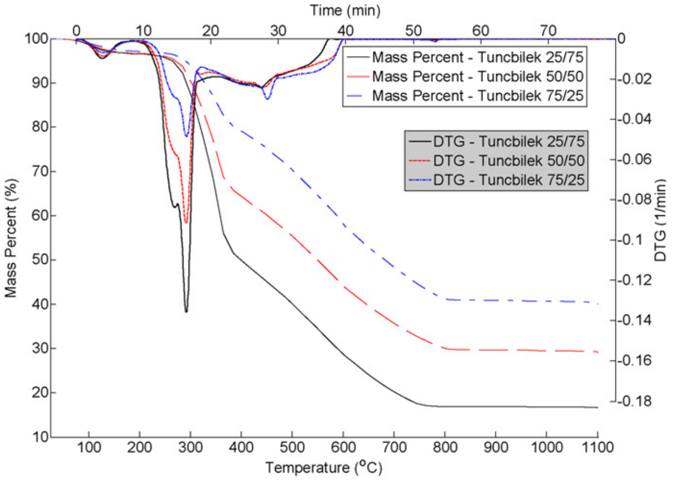

Fig. 3. TG and DTG curves of Tuncbilek lignite and wood chips mixtures (75%T + 25%W, 50%T + 50%W and 25%T + 75%W).

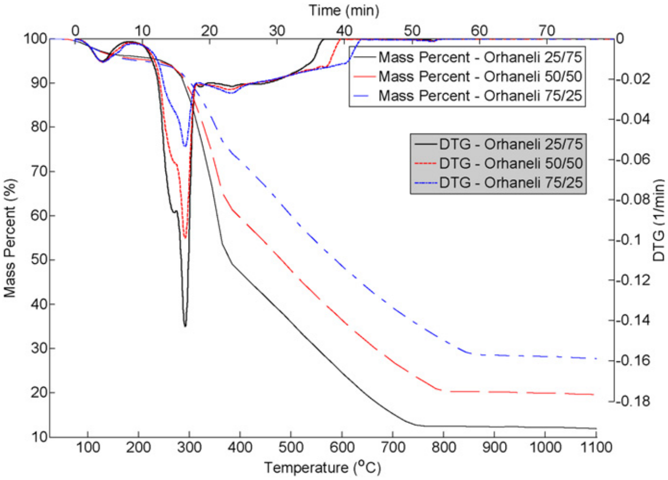

Fig. 5. TG and DTG curves of Orhaneli lignite and wood chips mixtures (75%O + 25%W, 50%O + 50%W and 25%O + 75%W).

Table 5
Burnout characteristics of fuel samples.

Fuel sample	Temperature, °C									
	200	300	400	500	600	700	800	900	1000	1100
% Burnout										
Tuncbilek	1.67	1.54	3.15	9.81	21.00	31.05	39.12	45.34	47.90	47.92
Seyitömer	6.04	7.65	13.24	21.52	29.91	37.12	40.53	40.61	40.63	40.64
Orhaneli	5.72	7.42	14.14	24.70	34.60	43.18	51.79	59.78	62.87	62.87
Wood chips	5.09	14.17	64.94	74.67	84.42	91.88	95.12	95.12	95.11	
Olive cake	4.00	21.20	48.32	58.49	66.90	74.23	79.96	80.39	80.40	
Hazelnut shells	6.46	16.95	54.46	66.20	76.01	83.62	90.16	94.36	94.42	
25%Woodchips + 75%Tuncbilek	2.91	6.05	20.92	29.68	41.78	51.60	58.70	59.16	59.31	59.66
50%Woodchips + 50%Tuncbilek	3.33	9.56	35.64	44.63	55.76	64.24	69.99	70.37	70.48	70.76
75%Woodchips + 25%Tuncbilek	3.45	12.39	50.03	59.93	71.23	79.75	83.09	83.13	83.18	83.32
25%Woodchips + 75%Seyitömer	6.50	11.16	28.63	39.15	49.23	57.47	62.80	63.48	63.72	64.32
50%Woodchips + 50%Seyitömer	5.58	12.35	40.96	51.60	61.86	70.54	74.46	74.51	74.60	75.00
75%Woodchips + 25%Seyitömer	4.77	14.11	53.59	64.21	74.90	83.42	85.38	85.39	85.40	85.56
25%Woodchips + 75%Orhaneli	4.98	9.71	27.56	39.98	51.35	60.71	68.20	71.54	71.84	72.28
50%Woodchips + 50%Orhaneli	4.59	11.53	40.40	52.36	63.54	72.93	79.55	79.85	80.09	80.48
75%Woodchips + 25%Orhaneli	4.10	13.47	52.74	64.12	75.42	84.75	87.61	87.67	87.81	88.10

extracted from wood chips. In previous studies in the literature, combustion characteristics of some agricultural wastes have been determined [10,13]. However, wood chips were not tried and as we know from the General Directorate of Forestry (GDF) that the most available biomass for energy production with co-combustion is wood chips.

Therefore, co-combustion of lignite coals with wood chips has been mainly experimented in this study. As it is known, wood chips are renewable materials, they are waste of forest products and they are CO_2 neutral. In order to get CO_2 credit for a country, CO_2 emissions and the use of fossil fuels should be decreased as much as possible. Therefore, in this study 25%, 50% and 75% by wt. of the coal has been replaced with wood chips in the fuel mixture to see the full spectrum of combustion characteristics.

Tuncbilek lignite is a very widely used coal in Turkey. The reserves are high. There is already a power plant established in this area burning only coal. However, the possibilities are searched to make co-combustion of coal and wood chips in this power plant. The fuel mixtures with the given compositions were tried for the TGA analysis. The ignition, peak and burnout temperatures of all fuel mixtures are given in Table 4.

As can be seen from the table, the ignition temperature of the fuel mixture decreases because as the biomass content of the mixture increases the VM content of the fuel mixture increases. The

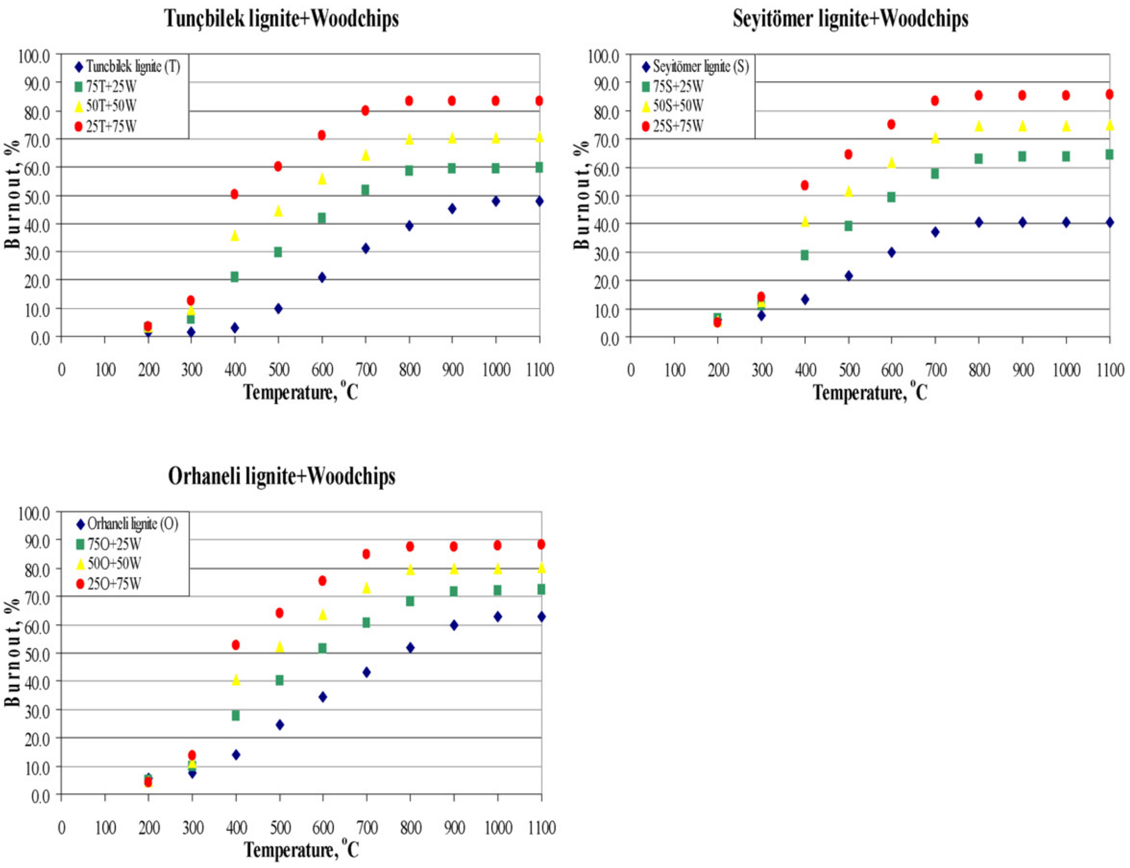

Fig. 6. Burnouts of lignite and woodchips mixtures.

ignition temperatures of the mixtures are very close to that of the biomass. Therefore, it can be said that biomass in the mixture starts to burn first and then coal follows.

The first peak temperatures are all the same for all fuel mixtures. The first peak temperature of the wood chips when burned alone was 360 °C as shown in Table 3. Only the shoulder temperature was 310 °C. In Table 4, this temperature has been found as 356 °C, very close to 360 °C. The maximum combustion rates also increase with the increase of biomass addition to the fuel mixture as can be seen in Table 4.

TG and DTG curves of Tuncbilek (T) lignite and wood chips mixtures are shown in Fig. 3. It is quite obvious from this figure that DTG curves of wood chips and T lignite are overlapped. The first part of the DTG curve belongs to wood chips and the second part of the curve belongs to T lignite. The VM of the coal has been added to the VM of the lignite and a synergy has happened between them and they started to burn together.

TG and DTG curves of Seyitömer (S) lignite and wood chips mixtures are shown in Fig. 4. A similar situation has been observed with the S lignite as seen with the T lignite. DTG curves show the similar characteristics.

TG and DTG curves of Orhaneli lignite and wood chips mixtures are shown in Fig. 5. When Fig. 1 is examined, it is seen that Orhaneli lignite has a maximum combustion rate of 1.388 mg/min. This rate corresponds to the peak temperature of 490 °C and it is attributed to the high volatile matter content of Orhaneli lignite. While volatile matter content of Orhaneli lignite is 36.07% by weight, this ratio becomes 47.74%, 59.41%, and 71.08% for the fuel mixtures containing 25%, 50%, and 75% wood chips, respectively. The volatile matter content of wood chips was given in Table 2 as 82.75%.

The burnout characteristics of fuel samples used in this study are given in Table 5 and the data is plotted in Fig. 6. As can be seen from Fig. 6, the % burnout amount increases as the temperature increases. Among the fuel mixtures tested in this study, the most reactive mixture is the one which has the highest % of wood chips in it, namely 75% wood chips and 25% coal. Lignite coals by itself are not as reactive as the mixture. However, with Orhaneli lignite the highest burnout (88.1%) is reached because the VM content of the Orhaneli lignite was higher and the ash content was lower than that of the other coals. The total burnout percentages of Tuncbilek and Seyitömer lignites with 75% wood chips are very close to each other, 83.3% and 85.5%, respectively.

4. Conclusions

From the results obtained in this study, it can be concluded that as the VM content of the coal increases, the ignition temperature decreases. For the more reactive coals the maximum combustion rate is reached at lower temperatures. Biomass fuels are more reactive than lignite coals studied here. They ignite at much lower temperatures than coals. About 80–90% of the biomass is combusted as the combustion of volatile matter. Then the combustion of the char formed takes place. The amount of the char formed depends on the amount of the FC% in the fuel.

For the co-combustion of lignite coal with wood chips, the most reactive mixture is the one which has the highest % of wood chips in it. Lignite coals by itself are not as reactive as the mixture. Therefore, these results show that the combustion characteristics of low rank lignite coals can be improved by addition of biomass materials like wood chips to coals and the energy in waste biomass will be recovered while some CO_2 reduction benefit is obtained.

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References

[1] Key World Energy Statistics, International Energy Agency (IEA), 2008.
[2] I. Obernberger, TUE in http://alexandria.tue.nl/extra2/redes/obernberger2005.pdf, 2005 (access date: 23.05.08).
[3] M. Hupa, Interaction of fuels in co-firing in FBC, Fuel 84 (2005) 1312–1319.
[4] L. Fangxian, L. Shizong, C. Youzhi, Thermal analysis study of the effect of coal-burning additives on the combustion of coals, J. Therm. Anal. Calorim. 95 (2009) 633–638.
[5] H. Xiao, X. Ma, Z. Lai, Isoconversional kinetic analysis of co-combustion of sewage sludge with straw and coal, Appl. Energy 86 (2009) 1741–1745.
[6] S.Y. Yorulmaz, A.T. Atimtay, Investigation of combustion kinetics of treated and untreated waste wood samples with thermogravimetric analysis, Fuel Process. Technol. 90 (7–8) (2009) 939–946.
[7] M.E. Sanchez, M. Otero, X. Gomez, A. Moran, Thermogravimetric kinetic analysis of the combustion of biowastes, Renew. Energy 34 (2009) 1622–1627.
[8] E. Kastanaki, D. Vamvuka, A comparative reactivity and kinetic study on the combustion of coal–biomass char blends, Fuel 85 (2006) 1186–1193.
[9] M.V. Kök, Temperature-controlled combustion and kinetics of different rank coal samples, J. Therm. Anal. Calorim. 79 (2005) 175–180.
[10] H.H.H. Açma, Combustion characteristics of different biomass materials, Energy Convers. Manage. 44 (2003) 155–162.
[11] H.H. Açma, A.E. Meriçboyu, S. Küçükbayrak, Combustion reactivity of different rank coals, Energy Convers. Manage. 43 (2002) 459–465.
[12] M.V. Kök, An investigation into the combustion curves of lignites, J. Therm. Anal. Calorim. 64 (2001) 1319–1323.
[13] H.H. Açma, S. Yaman, Effect of biomass on burnouts of Turkish lignites during co-firing, Energy Convers. Manage. 50 (2009) 2422–2427.