Temperature Measurements of Single Burning Pulverized Particles

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ABSTRACT – The main aim of this work is to measure the temperature of single particles of coal and biomass burning in air using a two-color pyrometer. A Brazilian bituminous coal with particles size below 150 µm and a Portuguese wheat straw with particles size in the range 150-200 µm were used as fuels. The combustion took place in an electrically heated drop tube furnace with a wall temperature of 1373 K. The drop tube furnace was fitted with a central, transparent, 82 cm long quartz tube with an internal diameter of 6 cm. The single solid fuel particles were injected from the top of the drop tube furnace with the help of a syringe needle. A two-color pyrometer was used to measure the particle temperature. The device was placed perpendicular to the direction of the flow. The particle temperature was measured along the drop tube furnace in order to obtain axial profiles. The present method produced satisfactory results that are in agreement with previous studies.

1. INTRODUCTION

The demand of energy is on the rise from last few decades since the industrialization and urbanization has increased dramatically. The global primary energy consumption (in Mtoe) has increased by 53% from 1995 to 2015 (BP, 2017). A lot of successful efforts are being done by improving the energy efficiency and advancements in available technologies to hinder this growth, which can be reflected from the fact that the rate of primary energy consumption has slowed down in recent years, being only 1.1% in 2014 and 1% in 2015 (BP, 2016). But it is still expected that the energy consumption will increase by 31% from 2015 to 2035 (BP, 2017).

Fossil fuels have been the foremost important source of energy and will remain so because the energy generated by renewable sources is still insufficient to keep up with the growing energy consumption rate. Coal is still the most abundantly used fossil fuel in power plants on world scale. Although, the use of fossil fuels has decreased (4% in production and 1.5% in consumption in 2015), they are still considered to be the most stable, cheap and abundant source of energy in the whole world (BP, 2016). Coal still has the highest reserves-to-production ratio as compared to other fossil fuels and it is said to have enough stocks available to power the world for the next 114 years (BP, 2016).

There are also a lot of concerns related to the burning of fossil fuels due to the emission of pollutants. Currently, the major concern of using the fossil fuels is to minimize their environmental effects. The main pollutant gas species emitted to the environment from the combustion of fossils are CO_2, CO, NOx, SOx and particulate matter. Although CO_2 is essential for the photosynthesis process, its excess release in the ambient is responsible for the greenhouse effect and ultimately global warming. The CO_2 emitted by burning the fossil fuels increased by 0.1% in 2015 alone (BP, 2016).

To overcome these environmental concerns, a lot of efforts are being done to minimize the pollutants such as co-firing of biomass with coal or use of biofuels. This is done not only to reduce pollution but also to decrease the dependency on imported fossil fuels and increase employability (Saidur et al., 2011). One of the main renewable sources is biomass that has a great potential to be used in future to minimize gas pollutants. One of the biggest reason of its great potential is its neutrality of CO_2 emissions, which means that the CO_2 emitted during its combustion cannot be more than its consumption during photosynthesis. This is the reason why it can play a key role not only just to fulfil the global energy demand but also to cater the industrial and agricultural waste and improve the social and economic aspect of the community.

A recent investigation by (Haykiri-Acma et al., 2010) revealed that coal/biomass blends can be used to utilize the excess heat generated by oxy-fuel combustion of coal. They used a TGA-DSC technique at 1173 K to burn mixtures of a lignite coal and two biomass fuels, at high oxygen partial pressures. It was found that heat flux during burning of lignite was increased dramatically when the dry air in the oxidizing medium was replaced with neat oxygen. However, in case of co-firing of lignite with biomass, this excess heat flux was reduced when the oxidizing medium was replaced and thus, the temperature of the combustion chamber was controlled. So, it was concluded that co-firing of coal/biomass in enriched oxygen environments can be an alternative to recycling of CO_2 in future oxy-fuel systems.

Although co-firing biomass can be really useful, it still is a novel technology and a lot of technical aspects need to be worked upon as coal and biomass have different burning characteristics, ignition times and temperatures. Therefore, knowledge of technical and economic aspects is mandatory as it will directly affect the combustion process, furnace shape and size, efficiency and ultimately the cost.

Among all the parameters needed for fuel combustion, temperature is the most important parameter in all the combustion processes because every part of a combustion process such as devolatilization, ignition and burnout are related to it. Therefore, it is always a centre of interest for researchers to measure the particle temperature of fuel during combustion, either surface temperature or inside the particle. Few important reasons for such extensive research on temperature, as stated by (Joutsenoja et al., 1999), are as follows:

a) The kinetics of carbon residue oxidation depends strongly on particle temperature, so its measurement constitutes the key element for the determination of combustion reaction rates.

b) Particle temperature is the most important parameter in the calculation of heat flow to/from the particle, both by convection, as well as by radiation.

c) It can also play a detrimental role in the identification of problems appearing during coal utilization, such as fly ash formation and slagging, and its deposition on the boiler walls.

There are a lot of studies regarding the combustion profiles, ignition and delay times, effects of oxy-fuel conditions on combustion process but there is a gap in literature regarding the temperature of single fuel particle of coal or biomass when burning in air. So, in this context, this work is focused on estimating the single particle temperature of coal and biomass burning in air.

2. LITERATURE REVIEW

In recent years, biomass has gained a massive interest in co-firing it in coal-based power plants with just minor modifications in the design rather than building a new biomass-specific power plant. Usually biomass has lower heating value and less carbon, but higher volatile content and oxygen as compared to coal (Riaza, Gibbins and Chalmers, 2017). So, biomass has been the centre of interest from past few years and a lot of research is going on.

Fuel burning profile is an important factor in co-firing biomass and coal as it directly affects the design of the combustion chamber and ultimately the cost. Hence fuel particle temperature, being the most important aspect of the burning profile, comes out as the centre of interest for many researchers.

(Khatami et al., 2012) assessed the combustion behaviour of single fuel particles burning in different environments such as O_2/N_2 and O_2/CO_2, with oxygen mole fractions ranging from 20-100%. Four pulverized coals from different ranks (a high-volatile bituminous, a sub-bituminous and two lignites) as well as a biomass residue (pulverized sugarcane-bagasse) were used. High oxygen mole fractions in N_2 was also employed for comparison purposes. All the solid fuels were burned in a laboratory scale, electrically heated, vertical drop tube furnace with a fitted quartz tube. Single particle combustion was observed by using a 3-color pyrometer and high-speed cinematography simultaneously.

The drop tube furnace with a radiation cavity, 25 cm long, was heated up to 1400 K by hanging molybdenum disilicide elements. The gas mixtures were introduced from a water-jacketed stainless-steel injector equipped with a flow straightener into a transparent quartz-tube having ID of 7 cm. The particles were introduced through a port at the top of the nozzle by a syringe-needle system to ensure single particle entry. The gas temperature profiles of all the gas mixtures were also measured by suction thermometry along the centreline of quartz tube. With replacement of N_2 with CO_2 and increasing percentage of O_2, all fuels tended to burn in one-mode (simultaneous volatile and char combustion) while it turned to be two-mode behaviour when the coal rank was increased from lignite to bituminous. The temperature and the burnout times of coal, for one-mode combustion, were found to be in between the volatile and char (two-mode) temperatures and burnout times of similar particles under similar conditions. Moreover, particle burnout temperature and luminosity were increased, and burnout time was decreased with increasing O_2 concentration.

(Riaza, Khatami, Yiannis A Levendis, et al., 2014) studied the combustion behaviour of four different pulverized biomasses which included sugar cane bagasse, pine sawdust, torrefied pine sawdust and olive residue. Single particles of these solid fuels were burned in a DTF at 1400 K, in both air and O_2/CO_2 atmospheres containing 21, 30, 35 and 50% oxygen mole fractions. High-speed camera and a pyrometer were also used for temperature-time histories. Results showed that all the fuels burned in two-phases. In the first phase, volatiles were evolved and burned in a spherical envelope flame with low luminosity. In the second phase, char residues were ignited and burned with brief time periods. Moreover, changing from air to oxy-fuel atmosphere, intensity of combustion was impaired, combustion temperatures were reduced, and burnout times were increased at 21% O_2 mole fraction. Increasing the mole fraction of O_2 from 28-35% restored the combustion intensity of single biomass particles.

(Rodriguez and Raiko, 2009) also studied the effect of oxy-fuel conditions on coal char particles in a DTF using a high-speed camera and two-colour pyrometer. Particles sizes used were 100-125 μm and 180-200 μm at three different temperatures. The results were in agreement with the previous study of (Khatami et al., 2012) that increasing the O_2 concentration increased the particle temperature and decreased the burnout duration and the effect was reversed in case of CO_2.

(Timothy and Sarofim, 1982) measured the burning history of a single coal particle using a two-color pyrometer. Two lignite and three bituminous coal particles ranging from 38-45 μm and 90-105 μm were used at furnace temperature of 1250 K and 1700 K in atmosphere containing 15-100% oxygen. The apparatus had an astro model furnace with a two-stage feeding system together with a top-mounted pyrometer to get the particle radiations against the dark background. The model was developed to simulate the combustion of coal particles. Results showed that the burning temperature and effect of O2 increment were in agreement with values predicted by the model till 3000 K (50% O_2) but the further increase in O_2 resulted in overprediction of temperature.

(Maloney et al., 2013) also measured the changes in the particle temperature and size during the early stages of heating and devolatilization using a radiation source and a single wavelength pyrometer. It was found out that the measured values exceeded the predicted model values (over 50 percent) owing to the uncertainty in assigning the thermodynamic and heat transfer properties as well as particle shape factors.

(Bejarano and Levendis, 2008) investigated the combustion behaviour of the single particles of bituminous and lignite coal as well as the spherical and monodisperse synthetic chars at increasing O_2 mole fraction in N_2 and CO_2 environments. The experimental setup had a DTF at temperatures of 1400 K and 1600 K and the particle temperature was measured by three-color pyrometer. It was found out that coal particles burned at higher mean temperatures and shorter combustion times in O_2/N_2 than in O_2/CO_2 environment keeping the same O_2 mole fraction in both. Similarly, bituminous coal volatile and char temperatures comparable to air (21% O_2) were obtained in CO_2 atmosphere when the oxygen content was 30%.

(Riaza et al., 2014) conducted another investigation involving four different coal ranks; anthracite, semi-anthracite, medium-volatile bituminous and high-volatile bituminous coal. The experimental setup had an electrically heated DTF at 1400 K, three-color pyrometer and a high-speed high-resolution camera. The combustion environments used were air (21% O_2/79% N_2) and four different oxy-fuel conditions: (21% O_2/79% CO_2), (30% O_2/70% CO_2), (35% O_2/65% CO_2), (50% O_2/50% CO_2). It was deduced that the ignition temperatures increased with the increasing coal ranks and decreased with the increasing oxygen concentration. Secondly, replacement of N_2 with CO_2 (changing from air to oxy-fuel condition) impaired the combustion intensity but increasing the oxygen concentration to 35%, restored its intensity.

3. MATERIALS AND METHODS

3.1. Drop tube furnace

Figure 1 shows the schematics of the DTF and all the auxiliaries. This DTF is suitable for the present experiments since it has a relatively simple configuration and can reproduce the conditions encountered in practical systems. The combustion studies of pulverized coal and biomass were carried out in this electrically heated, vertical DTF at a wall temperature of 1100 ̊C that was continuously monitored by two type-S thermocouples. The DTF has two opposed rectangular quartz windows with 2 cm width and 20 cm height for viewing. The DTF is fitted with a cylindrical quartz tube with a length of 1 m and an inner diameter of 66 mm. The radiation cavity of DTF is 30 cm long. The feeding unit consists of a nozzle to inject the solid fuel particles with the help of a syringe and a rotameter to measure the air flow rate. The fuel particles, stored in the syringe, are injected in the water-cooled injector by gravitational force. Gentle pushes and rotation of the syringe help to inject the single particles of fuel inside the injector without clogging.

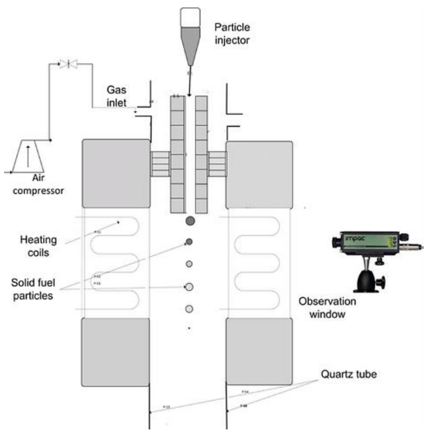


Figure 1: Schematics of drop tube furnace.

The temperature measurements of the solid fuel particles were performed with a two-colour pyrometer, which was aligned perpendicularly with the quartz tube axis. The temperature profiles of the burning particles were obtained by taking several readings along the axis of quartz tube. Radiations from the burning particles were detected by the pyrometer and then processed by a computer software called SensorTools. Table 1 shows the DTF test conditions during all the experiments.

Parameter	Value
Temperature	1373 K
Airflow	1 L/min
Air pressure	1 bar

Table 1: DTF test conditions.

3.2. Solid fuels

The solid fuels used for this work include a Brazilian bituminous coal with a particle size below 150 µm and a Portuguese wheat straw of particle size in between 150-200 µm. Table 2 shows the main properties of the both solid fuels (Branco and Costa, 2017) (Rabacal et al., 2017).

		Wheat straw	**Brazilian coal**
Proximate analysis (wt.%, as received)	**Volatiles**	64.9	27.8
	Fixed carbon	12.4	38.5
	Ash	14.7	33.7
	Moisture	8.0	5.3
Ultimate analysis (wt.%, dry ash free)	**Carbon**	41.1	50.8
	Hydrogen	5.3	3.8
	Nitrogen	0.7	0.9
	Sulfur	<0.2	0.9
	Oxygen	52.6	9.8

Table 2: Properties of solid fuels

3.3. Two-color pyrometer

A two-colour SensorTherm GMBH pyrometer was used to undertake the temperature measurements. It was placed on a vertically movable stand to get the temperature profiles along the axis of the quartz tube. The distance between the DTF and pyrometer was kept minimum (~340-360mm) since it provided the smallest focus point of 0.8 mm that enabled us to capture the radiations from the smaller fuel particles (Studios and Reserved, 2010). The pyrometer had the effective wavelengths of 0.7 and 1.1 µm. The measurements were done starting from a distance of 10 cm from the injector tip till 15 cm in downward direction. The reason for choosing this distance range was that the pyrometer could not catch the significant radiation before that distance because the particle velocity was too high to be captured by the pyrometer. Also, due to airflow of 1 L/min, particles were carried away from the injector tip quite swiftly making it difficult for the pyrometer to get a stable reading. Table 3 shows the pyrometer parameters used.

Parameter	Value
Measurement distance	340 - 360 mm
Emissivity ratio	1.00 – 1.40
Spot size	~0.8 mm
Buffer interval	2, 16 ms

Table 3: Pyrometer parameter used.

4. RESULTS AND DISCUSSION

4.1. Gas temperature

In all experiments, the fuel particles were combusted in air (21% O_2/79% N_2). The gas temperature in the heated quartz tube with a DTF wall temperature of 1373 K was measured with Pt-Rh thermocouples. The temperature of the air was measured at the same distances from the injector tip at which particle temperature was measured. Figure 2 shows the gas temperature profile along the axis of quartz tube.

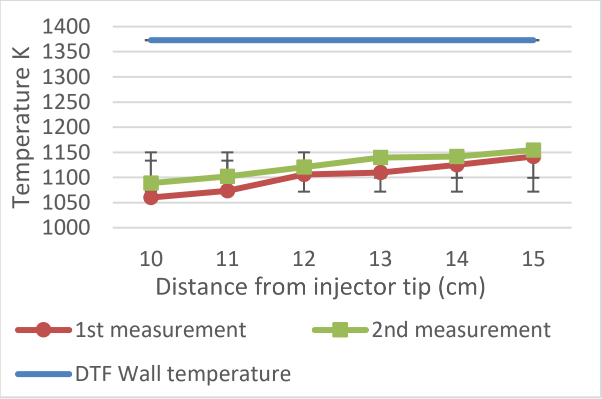


Figure 2: DTF gas temperatures.

The measurements were repeated twice to verify the results. In both the cases, it is evident that the temperature of the air increased as the distance to the injector tip increased. This trend was similar to that observed by Khatami (Khatami et al., 2012) and Riaza (Riaza, Khatami, Yiannis A. Levendis, et al., 2014) in figure 3.

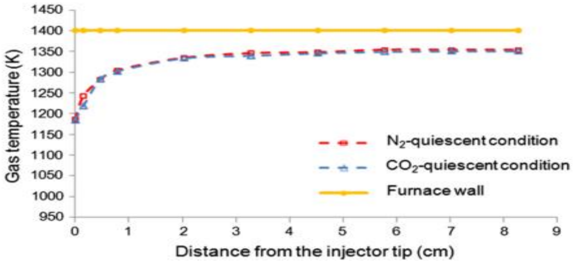


Figure 3: Centerline gas temperature inside the drop-tube furnace.

4.2. Bituminous coal particle temperature

Mean particle temperature of Brazilian bituminous coal particles with size below 150 µm was measured using the pyrometer using the method described before. Figure 4 shows the particle measurements for two different pyrometer settings. In the “1st measurement”, a buffer rate of 16 ms was used and, as mentioned before, there was the possibility of skipping many particles as they passed through the focal point of pyrometer and hence, affecting the final measurements. After discussing with the pyrometer supplier, it was decided that the buffer rate should be decreased to 2 ms that would increase the number of readings taken by the pyrometer per second.

The experiment was repeated with this new parameter and it can be seen in 2nd measurement that there was improvement in the results.

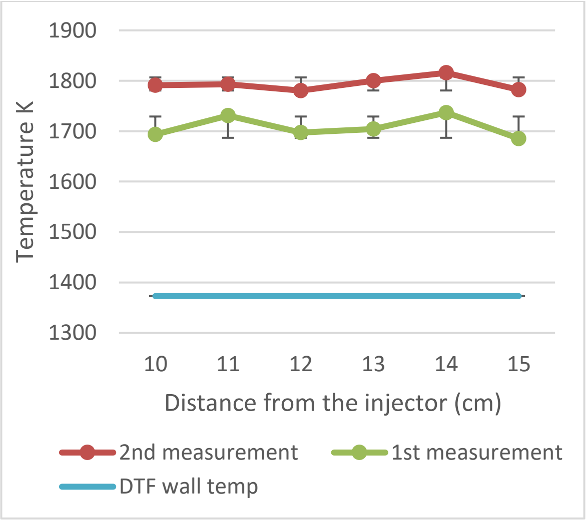


Figure 4: Mean particle temperature of bituminous coal particles.

The temperature range observed in these experiments for bituminous coal is in close agreement with the temperature range obtained by (Riaza, Khatami, Yiannis A Levendis, et al., 2014). Figure 5 and 6 show the results obtained by Riaza and Levendis, respectively, for the combustion of a bituminous coal in air at a DTF wall temperature of 1400 K. They used a bituminous coal of 90 µm at a DTF wall temperatures of 1400 K and their results showed temperature in the range 1600-1800 K which is in close agreement with the present results.

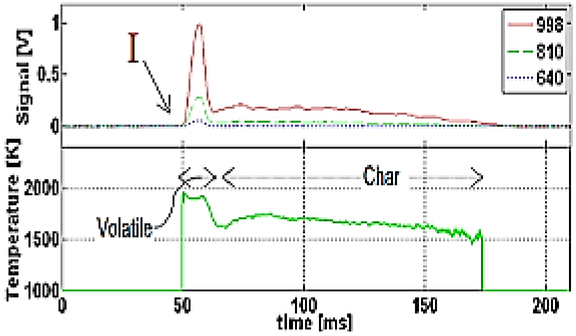


Figure 5: Temperature of bituminous coal particles (75–150 µm) [1].

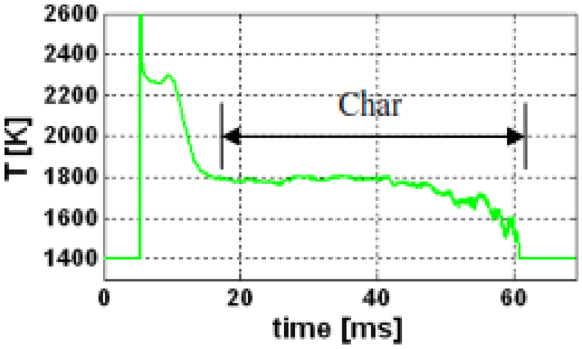


Figure 6: Temperature of bituminous coal particles (75–90 µm) (Riaza *et al.*).

4.3. Wheat straw particle temperature

The Portuguese wheat straw biomass with a particle size in between 150-200 µm was burned in the drop-tube furnace and the temperature was measured using the pyrometer. During all these measurements with biomass, the buffer rate was kept at 2 ms to get the maximum number of temperature readings per second, which as it was seen in the previous experiments with bituminous coal, improved the results significantly. Figure 7 shows the results obtained from this experiment.

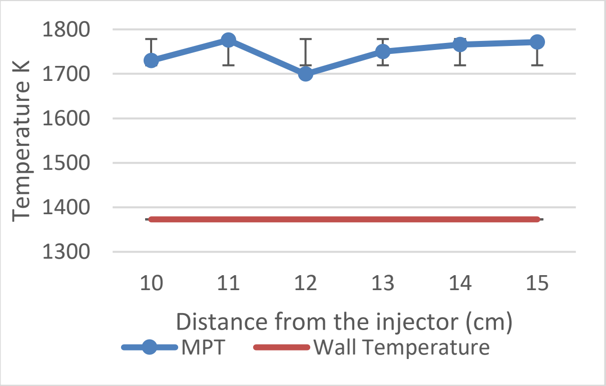
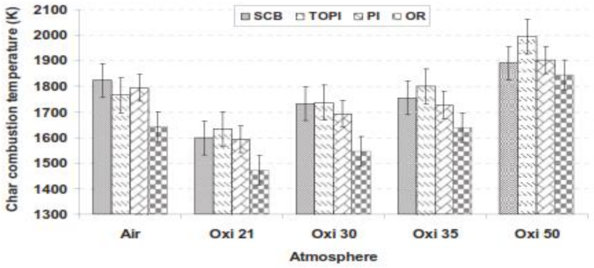


Figure 7: Mean particle temperature of wheat straw biomass (150-200 µm).

Figure 8 shows the results obtained by Khatami and Levendis using a three-color pyrometry. It can be seen that for all types of biomass fuels used, the single particle temperature for combustion in air lies in the range of 1700-1800 K, which endorses the test results obtained in this work



OR	Olive residue
SCB	Sugarcane bagasse
PI	Pine sawdust
TOPI	Torrefied pine sawdust

Figure 8: Temperature profiles of different biomasses under different conditions.

The temperature range of Portuguese wheat straw is quite similar to that obtained in the case of Brazilian bituminous coal as evident from Figure 9.

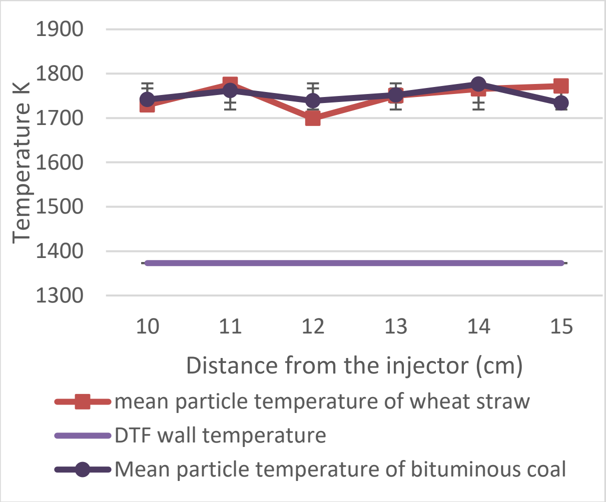


Figure 9: Temperature comparison of bituminous coal and wheat straw.

5. Summary

A two-color pyrometer was used to measure the single particles temperature of two fuels: a Brazilian bituminous coal with a particle size below 150 µm and a Portuguese wheat straw with a particle size in the range 150-200 µm. The combustion environment was air with a flowrate of 1 L/min and 1 bar pressure. The particles were introduced through the injector with the help of a syringe needle from the top of a DTF. the DTF, electrically heated at 1373 K, was provided with an 82 cm long quartz tube with a radiation cavity of 30 cm. Two windows were available sideways for optical access that were used for the pyrometric measurements. Measurements were taken at a distance of 10-15 cm from the injector tip in each case to make the temperature profiles of the solid fuel particles. The results can be summarized as follows:

- In both the cases with bituminous coal and wheat straw, the temperature profiles of particles obtained were comparable to previous studies.
- Both the bituminous coal particles and wheat straw particles burned in a temperature range of 1700-1800 K in air environment.
- The results obtained seem to be satisfactory and this method can be used further to measure particle temperatures of more solid fuels.

6. Future work

This particular work established the method of pyrometric measurements of solid fuels particle temperatures along the axis of a DTF. Now more solid fuels can be studied. Furthermore, this same study can also be repeated by changing the combustion environments such as oxy-fuel conditions to compare the results with previous studies.

7. REFERENCES

BP, “BP Energy Outlook Energy 2017,” BP Stat. Rev. World Energy, p. 52, 2017.

BP, “Statistical Review of World Energy,” BP Stat. Rev. World Energy, no. June, pp. 1–48, 2016.

R. Saidur, E. A. Abdelaziz, A. Demirbas, M. S. Hossain, and S. Mekhilef, “A review on biomass as a fuel for boilers,” Renew. Sustain. Energy Rev., vol. 15, no. 5, pp. 2262–2289, 2011.

J. Koppejan, L. Baxter, “Global operational status on cofiring biomass and waste with coal Experience with different cofiring concepts and fuels,” Biomass, vol. 2, pp. 1–14, 2013.

H. Haykiri-Acma, A. Z. Turan, S. Yaman, and S. Kucukbayrak, “Controlling the excess heat from oxy-combustion of coal by blending with biomass,” Fuel Process. Technol., vol. 91, no. 11, pp. 1569–1575, 2010.

T. Joutsenoja, P. Heino, R. Hernberg, and B. Bonn, “Pyrometric temperature and size measurements of burning coal particles in a fluidized bed combustion reactor,” Combust. Flame, vol. 118, no. 4, pp. 707–717, 1999.

J. Riaza, J. Gibbins, and H. Chalmers, “Ignition and combustion of single particles of coal and biomass,” Fuel, vol. 202, pp. 650–655, 2017.

R. Khatami, C. Stivers, K. Joshi, Y. A. Levendis, and A. F. Sarofim, “Combustion behavior of single particles from three different coal ranks and from sugar cane bagasse in O_2/N_2 and O_2/CO_2 atmospheres,” Combust. Flame, vol. 159, no. 3, pp. 1253–1271, 2012.

M. Rodriguez, R. Raiko, “Effect of O_2 and CO_2 content on particle surface temperature and size of coal char during combustion,” no. January, pp. 28–29, 2009.

M. Flower, J. Gibbins, “A radiant heating wire mesh single-particle biomass combustion apparatus,” Fuel, vol. 88, no. 12, pp. 2418–2427, 2009.

L. D. Timothy, A. F. Sarofim, “Characteristics of single particle coal combustion,” Department of Chemical Engineering, in International Combustion Symposium, 1982.

H. Kobayashi, J. B. Howard, and A. F. Sarofim, “Coal devolatilization at high temperatures,” Symp. Combust., vol. 16, no. 1, pp. 411–425, 1977.

D. J. Maloney, E. R. Monazam, S. D. Woodruff, L. Lawson, and W. Virginia, “Temperature measurements of single coal particles during the early stages of heating and devolatilization,” vol. 84, no. 1–2, pp. 721–729, 1991.

M. Momeni,"Fundamental study of single biomass particle combustion," Ph.D Thesis, Department of Energy Technology, Aalborg University,2013.

P. A. Bejarano, Y. A. Levendis, “Single coal particle combustion in O_2/N_2 and O_2/CO_2 environments,” Combust. Flame, vol. 153, no. 1–2, pp. 270–287, 2008.

J. Riaza et al., “Single particle ignition and combustion of anthracite, semi-anthracite and bituminous coals in air and simulated oxy-fuel conditions,” Combust. Flame, vol. 161, no. 4, pp. 1096–1108, 2014.

V. Branco, M. Costa, “Effect of particle size on the burnout and emissions of particulate matter from the combustion of pulverized agricultural residues in a drop tube furnace,” Energy Convers. Manag., vol. 149, pp. 774–780, 2017.

R. B. Kops, F. M. Pereira, M. Rabaçal, and M. Costa, “Effect of steam on the single particle ignition of solid fuels in a drop tube furnace under air and simulated oxy-fuel conditions,” accepted for presentation at 37th International Symposium on Combustion, 2018.

J. Riaza et al., “Combustion of single biomass particles in air and in oxy-fuel conditions,” Biomass and Bioenergy, vol. 64, pp. 162–174, 2014.