Experimental Study of Radiative Properties of Charcoal Combustion in Grills

by

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Abstract

This research focuses on the heat transfer characteristics of charcoal combustion in grills. Experiments were performed to observe the effects of fuel type, fuel amount, and fuel arrangement on the various thermal characteristics of charcoal. The experiments were conducted in a natural draft uncontrolled ventilation atmosphere. Two commercially available charcoals, and a hardwood lump charcoal were observed during combustion while thermal measurements were recorded and are presented here. A single wavelength pyrometer was used to measure the temperature of charcoal as a black body source, whereas the true temperature measurements were done by several thermocouples. A model for calculating the emissivity was developed, and the variation of emissivity as a function of temperature was studied for the black and gray-ash surface conditions of the charcoals. The end goal of this study was to obtain correlations for emissivities of these fuels at different surface conditions. Additionally, these results are beneficial in the design of grills and also for benchmarking CFD and other combustion models with observed experimental data.

The results showed that one of the commercially available charcoals had higher emissivities and also higher rates of combustion than the other two fuels tested. Emissivity was observed to increase with an increase in the amount of fuel. It was found that the emissivities varied greatly and were highest at the center of the fuel arrangement, but also depended on how tightly the fuel was arranged. The average emissivity values of black and gray surface conditions of one of the commercially available charcoals were 0.77 and 0.80 respectively.

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List of Symbols

e – Overall emissivity of the surface of charcoal

j_* – Total energy radiated per unit area (W).

KTG – Kettle-type Grill

LCG – Large Chamber Grill

MC – Mini-Chimney

Q" – Heat Flux generated by the charcoal (W/m2)

t – Elapsed time (of the experiment) (mm:ss)

T – Surface Temperature of the charcoal (K)

T_{corr} – Corrected Temperature

T_{meas} – Measured Temperature

T_P – Temperature readings by the pyrometer (K)

T_{ck1}, T_{ck2}, and T_{ck3}– Temperature readings by the three thermocouples (K)

ρ – Bulk Density of the charcoal (g/l)

σ – Stefan's Boltzmann Constant

$\Delta\in$ – Uncertainty

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Chapter 1
INTRODUCTION

Charcoal is a light, black residue, consisting of carbon and any remaining ash, obtained by removing water and other volatile constituents from animal and vegetation substances. Charcoal is usually produced by slow pyrolysis, the heating of wood or other substances in the absence of oxygen. Commercial charcoal is found in either lump, briquette, or extruded forms:

Lump charcoal is made directly from hardwood material and usually produces far less ash than briquettes.

Pillow shaped briquettes are made by compressing charcoal, typically made from sawdust and other wood by-products, with a binder and other additives. Some briquettes may also include brown coal (heat source), mineral carbon (heat source), borax, sodium nitrate (ignition aid), limestone (ash-whitening agent), raw sawdust (ignition aid), and other additives.

Hexagonal sawdust briquette charcoal are made by compressing sawdust without binders or additives. It has a round hole through the center, with a hexagonal intersection. Mainly for barbeque uses as it does not emit odor, no smoke, and little ash, high heat, and long burning hours (exceeding 4 hours).

Extruded charcoal is made by extruding either raw ground wood or carbonized wood into logs without the use of a binder. The heat and pressure of the extruding process hold the charcoal together. If the extrusion is made from raw wood material, the extruded logs are then subsequently carbonized.

Japanese charcoal removes pyroligneous acid during the charcoal making. Therefore, when burning, there are almost no stimulating smells or smoke.

Charcoal has been used since earliest times for a large range of purposes including art and medicine, but by far its most important use has been as a metallurgical fuel. Charcoal is the traditional fuel of a blacksmith's forge and other applications where an intense heat is required. Charcoal was also used historically as a source of carbon black by grinding it up. In this form charcoal was important to early chemists and was a constituent of formulas for mixtures such as black powder. Due to its high surface area charcoal can be used as a filter, and as a catalyst or as an adsorbent.

Charcoal has been made by various methods. The traditional method in Britain used a clamp. This is essentially a pile of wooden logs (e.g. seasoned oak) leaning against a chimney (logs are placed in a circle). The chimney consists of 4 wooden stakes held up by some rope. The logs are completely covered with soil and straw allowing no air to enter. It must be lit by introducing some burning fuel into the chimney; the logs burn very slowly and transform into charcoal in a period of 5 days' burning. If the soil covering gets torn (cracked) by the fire, additional soil is placed on the cracks. Once the burn is complete, the chimney is plugged to prevent air from entering. The true art of this production method is in managing the sufficient generation of heat (by combusting part of the wood material), and its transfer to wood parts in the process of being carbonized. A strong disadvantage of this production method is the huge amount of emissions that are harmful to human health and the environment (emissions of unburnt methane). [1]

Understanding the charcoal combustion process is essential for the development of more efficient fuel utilization processes. Thermal property values such as specific heat, thermal conductivity, and emissivity vary with moisture content, temperature, and degree of thermal degradation by one order of magnitude. The carbon content of wood varies from about 47 to 53% due to varying lignin and extractives content [2]. The ash layer formed at the burning surface is found to play a major role in establishing the combustion characteristics of charcoal. There are basically two steps involved in charcoal combustion: The pyrolysis and oxidation of the liquid and volatile matter, followed by the oxidation of the residual char reactions. Char oxidation takes 5-10 times longer than devolatilization to end the combustion process. A brief description of these processes is given below:

Devolatilization: As mentioned earlier, the devolatilization process is the initial phase of particle heating. It is a process in which coal at increasing temperatures is transformed to split into gaseous, char and tar compounds. This temperature rise occurs during combustion process by radiation and convention.

Char Oxidation: As the name suggests, char oxidation means the diffusion of oxygen into the pores of the particle and reaction with the fixed carbon. The main driver for the rate of this chemical kinetics is the temperature. At temperatures below 850 K, the reaction rate is comparatively slow and the oxygen can completely penetrate into the pores of the particle. At high temperatures, the velocity of oxygen diffusing into the pores becomes the limiting factor. During the burning process at the outer surface the particle shrinks over the time because of the oxidation of the bound carbon.

Volatile Reaction: Volatile matters are the organic decomposition products which emerge as gas or steam during heating up of coal substance under the exception of air. The reference temperature on this phase is 1050 K. Basically, the volatile matter consists of different hydrocarbons such as carbon monoxide (CO), Carbon Dioxide (CO_2), Water (H_2O), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), and tar.

Fig. 1.1 is the schematic representation of the different mechanisms during charcoal combustion [3]. When carbon burns, the bulk of the mineral matter in coal remains as ash residue. In high-temperature pulverized charcoal combustion, the minerals may melt. As the carbon surface falls back due to oxidation, ash dribs sticking to the carbon surface come into contact and may combine to form larger particles. At the same time, oxidation of the porous microstructure leads to the breakdown of the physical form of the char structure, and in the end, the formation of a number of fragments from each particle.

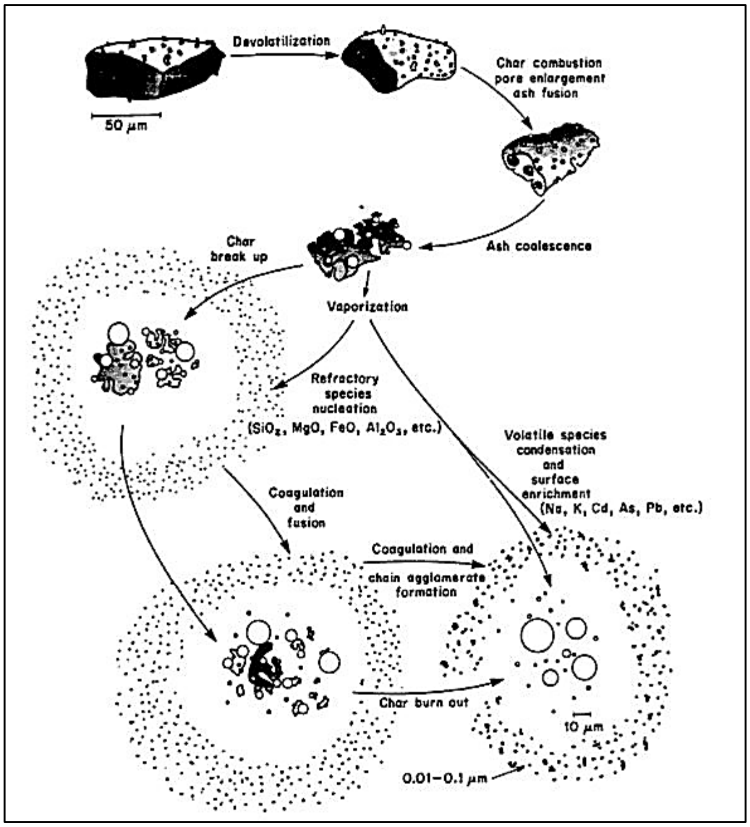

Figure 1.1 Schematic Representation of Different Mechanisms of Charcoal Combustion [4]

Coal is a naturally occurring mineral that is formed under the earth's crust due to the prolonged decay of plant and animal matter due to the heat and pressure. Charcoal is man-made, and is prepared by burning wood and sometimes animal matter and extinguishing the fire just before they turn ash.

Table 1.1 below shows the proximate analysis of a commercially used charcoal, in comparison with anthracite coal. [4]

Parameter \ Fuel	Anthracite Coal	Commercial Charcoal
Moisture Content (%)	0.2	16
Ash Content (%)	8.5	5
Volatile Matter (%)	2.7	14
Fixed Carbon (%)	88.6	65

Table 1. 1 Proximate Analysis Comparison of Coal and Charcoal

1.1 Scope of this study

This research focusses on the heat transfer characteristics of charcoal combustion in grills. Testing was done on different types of test rigs, built at the sponsor's Facility. Experiments were performed to observe the effects of fuel type, fuel amount, and fuel arrangement on the various burning characteristics of charcoal. The experiments were conducted in a natural draft uncontrolled ventilation atmosphere. There is a high amount of thermal radiation in grills. The emittance of charcoal is highly dependent on the deposit composition, morphology, temperature, and on the conditions under which the combustion takes place. Emissivity measurements for various coals under a variety of conditions are highly desirable. In the thermal design of charcoal grills, knowledge of thermal radiation characteristics is important, since the heat transfer due to combustion of coals is highly unsteady in nature. Regarding temperature dependence, emissivity increases with temperature and is expected to exceed 0.9 [6, 7]. Visible emission from charcoal flames can develop from various sources, including coal, char, ash, and soot. In the infrared spectral region, the ash and soot can contribute significantly during combustion. Relatively small quantities of soot particles can be expected to dominate emission due to their high absorbing and emitting properties. Therefore the applications involving charcoal as a fuel must be carefully designed and controlled so that uneven radiation distributions over loads are minimized. The associated literature being very limited, this experimental study will provide us the thermal characteristics of charcoal that can be used in any heat transfer application of these fuels, and also gives the opportunity for benchmarking Computational Fluid Dynamics (CFD) and other combustion models with observed experimental data. Currently, there is no research available on the study of combustion characteristics of charcoal in grills. This study is aimed at obtaining the correlations for emissivity under different surface and fuel type conditions. This gives us the idea of characterizing the performance of charcoal, and how the radiation plays an important role in charcoal combustion.

1.2 Charcoal

There are two major types of charcoal, hardwood lump and briquettes. Hardwood charcoal is pretty much the way charcoal has been made for centuries. Hardwoods are set to smoldering in a closed environment with very little oxygen until it turns to lightweight carbon. Hardwood charcoal when ground up and mixed with binders and additives, form briquettes. There is still a question among grilling enthusiasts on what type of charcoal is best for grilling. Charcoal briquette users consider the importance of the uniformity in size, burn rate, heat creation, and quality represented by briquettes. On other hand, all-natural lump charcoal users emphasize on the subtle smoky aromas, high heat production, and lack of binders and fillers often present in briquettes.

1.3 Grills

A barbecue grill is a device for cooking food by applying heat directly from below. Grills can be any of the three categories: gas-fueled, charcoal-fueled, or electric grills. Gas-fueled grills typically use propane (LP) or natural gas (NG) as their fuel source, with gas-flame either cooking food directly or heating grilling elements which in turn radiate the heat necessary to cook food. Charcoal grills use either charcoal briquettes or all-natural lump charcoal as their fuel source. The charcoal, when burned, will transform into hot fragments radiating the heat necessary to cook food. Charcoal grills have a number of advantages and are the most common type of grills for domestic use in the U.S. They are often desired for the charcoal flavor they impart to the cooked food. Charcoal cooking is considered to be ritual in the southern part of the U.S. They are cheaper to purchase than gas grills. They are portable and can be carried anywhere unlike the gas and electric grills. Three types of charcoal which are commonly used as domestic cooking fuels have been experimented in this research.

Disadvantages of Charcoal grills:

Typically the heat necessary to barbecue the meat in medium or large grills is generated by burning charcoal briquettes. These charcoal grills efficiently generate heat, but unwanted side effects may occur. For example, briquette lighter fluid is sometimes used to ignite charcoal briquettes, and the flames produced may be dangerous in small enclosures such as porches or balconies. For this reason, apartment buildings or condominiums often ban the use of charcoal grills on porches or balconies. Moreover, the hot briquettes cannot always be cooled quickly and so it may be impossible to put away or leave a briquette grill immediately after a cooking session. Furthermore, disposing of briquette ash can be troublesome and messy.

Chapter 2
LITERATURE REVIEW

Charcoal is an important source of energy for mankind. Charcoal combustion has been identified in some of the earliest recorded history. Nowadays, direct charcoal combustion is extensively utilized for industrial and domestic purposes because of the large scale reserves and low cost of charcoal. The following is some literature available on the combustion properties of both coal and charcoal.

2.1 Combustion and Gasification Kinetics

Combustion of coal involves a complex series of different reactions. Coal being an organic fuel, when heated, the organic matter of coal is pyrolyzed, and then evolves as volatile. The remaining solid is a mixture of carbon and mineral matter, which is referred to as "char." The combustion of coal is primarily the combustion of carbon as well as the volatile matter. The principal combustion process of coal occurs in three basic stages: [8]

1. Devolatilization: The release of the volatile matter resulting from the heating of coal,
2. Char Oxidation: The burning of the released volatile matter and
3. Volatile Reaction: The burning of the remaining char.

Depending upon specific combustion conditions, the burning process of volatile matter and coal char may take place simultaneously, sequentially, or with some overlapping.

Laboratory scale testing provides useful and necessary information on solid fuel behavior during combustion and gasification. The chemical kinetics of coal char combustion and gasification were studied at low temperature levels and high heating rates by Tolvanen et al. [9]. A drop-tube reactor (DTR) was used for experiments, and measurements of particle velocity and surface temperature were done by a charge-coupled device (CCD) camera and a two color pyrometer respectively. During the measurements, the pyrometer's optics were exposed to the combusting particles' radiation. The pyrometer allowed measuring the particles' radiation with two narrow wavelength bands. The temperature of the combusting particle could then be determined from the ratio of these wavelength measurements. The selection of the wavelengths is mainly dependent on the following factors: there has to be enough spectral radiation at the selected wavelengths and at the concerned temperatures, and absorption of thermal radiation into the gas atmosphere has to be minimized. The wavelength bands used were 1.0 and 1.6μm for the main signals, and 1.25μm for the reference signal. The size of char particles was 100-125μm and its oxidation and gasification were studied in a mixture of oxygen in nitrogen, and oxygen in carbon dioxide with varying oxygen concentrations (2,3,6, and 8%-Vol) in each case.

It was concluded that the diffusion of gas particles into the char particles' surface through the boundary layer is impacted by both char porosity and ash layer diffusion, thus governing the rate of reaction. The kinetics observed were that:

- At high combustion temperatures, ash can deform and melt forming an ash layer on the surface of the coal particle. The molten ash adds resistance to the gas diffusion to and from the particle surface.
- The reactant gas after diffusing through the boundary layer makes its transition through the pores to reach the reactive surface in the particle. Hence porosity has an effect on rate of reaction. There are three kind of pores: micropores, mesopores and macropores.

The oxygen concentration clearly had an effect on particle surface temperatures. In nitrogen atmosphere, at the highest concentration of oxygen, the temperature peak was much higher and it was reached sooner when compared to lower concentrations of oxygen. The results showed that with the oxygen concentrations used, replacing nitrogen with carbon dioxide in the reactor atmosphere had a notable decreasing effect on the surface temperature of the char particle. The carbon conversion and surface temperatures increased with the growing oxygen concentration.

2.2 Burning Characteristics of Pulverized coals

Thermal radiations of pulverized-coal from the gases and the ash and char particles is much more complex than a regular gas-oil flame. Lou et al. [10] took measurements of the flame radiation in a 1025 t/h pulverized-coal-fired boiler furnace. The flame emissivity, temperature and radiative energy of a cross-section upon the burners were calculated using visible image processing technique according to the procedure mentioned by Solomon et al. [11]. From the images, it was observed that with the increase in load, the flame images became brighter indicating the increase in both flame emissivity and temperature. This is because more fuels are fed into the furnace, so the concentration of the suspended particles in the furnace increases, which enhances the radiation of the flame. Same trend was observed with the carbon content, there was an increase in flame radiation and a slight increase in the flame temperature as the carbon content increased in the coals.

The effects of particle heating rate and pyrolysis gas composition on the intrinsic reactivity of chars were examined by Gale et al. [12]. Three coals were chosen to provide a range of reactivities, volatile yields, swelling behavior, and surface area properties of coals and chars: Pittsburgh No. 8, Utah Blind Canyon, and North Dakota (Zap) coals. Experiments were conducted in a high pressure controlled profile drop tube reactor (HPCP), which was an electrically heated, laminar flow reactor. It had the capability of independently varying the temperature, pressure, gas atmosphere, particle and gas velocities, and residence time. Coal was injected with a small amount of inert gas at a feed rate of 1 g/h. For comparing the results, experiments were also conducted in a flat flame burner (FFB) with almost same heating rates (7 x 10^4 K/s) as in HPCP. As a result from few other experiments, intrinsic reactivity decreased with either increasing pyrolysis temperature (from 850K to 1627K) or increasing heat rate (between 104 and 2 x 105). Also, the char reactivity decreased as the residence time increased, due to the affected mass release. The mass release increases with increasing temperature and heating rate as a result of which, true density increases. By this, it can also be said that the intrinsic reactivity decreases as the true density and mass release increase. So consistent with the fact that the reactivity decreases as maximum particle pyrolysis temperature, heating rate, and residence time increase, correlations for reactivity were developed for these coals. The intrinsic rate was expressed both as a function of particle temperature and mass release. It was concluded that the mechanism that causes the decrease in reactivity during devolatilization was ordering, flattening, or smoothing (decreasing active carbon sites) of carbon-layered planes during depletion of non-aromatic compounds in the char matrix, thereby increasing the relative concentration of aromatic compounds as mass is released.

Gale et al [13] observed the effect of pyrolysis temperature, heating rate, residence time, and mass release on the surface area using the same coals. If the CO2 surface area of these chars contributed to their reactive surface, then increasing the CO2 surface area would likely encourage an increase in the intrinsic reaction rate. A research by Gale [14] focused on 1. The effects of maximum particle temperature, heating rate and residence time on the physical properties, i.e. N_2 and CO_2 surface areas and porosities, of chars prepared from the same coals as discussed earlier; 2. The effects of different reactive gas atmospheres on internal surface areas, true densities and porosities of these same coal chars and 3. The effects of total mass release on densification or graphitization, as indicated by the true density of the chars.

Many experimental investigations of the combustion of pulverized fuels are being conducted in large-scale laboratory apparatus. The study of effect of various parameters on the rate of combustion of pulverized coals has attracted much research interest in recent time. For some time, the Battelle Memorial Institute has conducted an experimental investigation of the combustion of pulverized fuels in a large-scale laboratory apparatus. The object of this investigation was to determine the relation of the rate of burning of pulverized fuels and of the radiation from their flames to the type of fuel and the fineness of pulverization. Sherman [15]-[16] determined the relation of the pulverized fuels and of the radiation from their flames, to the type of coal and the fineness of pulverization. Four types of coals were tested in this work namely, Pocahontas, Hocking, Illinois No. 6, and Pittsburgh No. 8 coals. A furnace was used to conduct the experiments. An air supply was provided separately to observe its effect on combustion. With increase in excess air, the rate of unburned carbon decreased, and the effect was the least in Hocking coal, followed by Pocahontas coal. Similar was the case with fineness. As the fineness increased, the amount of unburned carbon decreased. Fuel type markedly increased rate of combustion. Pocahontas coal burned the slowest followed by Illinois coal, the rest burned rapidly. A special apparatus was used to measure the radiation from the flame. Of all the four, the emissivity of the Illinois coal was greatest and Pocahontas coal had the least. The emissivity decreased as moving away from the burner as the carbon burned out. It was observed that the maximum radiation of the flame can be at any point in the furnace, and not necessarily at the region of highest temperature. Another conclusion was that the type of the coal most effected the radiation and emissivity, whereas no great differences were observed by varying size of coal, excess air and rate of heat input.

2.3 Measurement of Temperature-Time Histories

In 1988, Sahu et al. [17] measured the complete temperature-time histories of single burning char particles with a two-color pyrometer using wavelengths in the near infra-red. A bituminous coal (PSOC 1451) was chosen for conducting the experiments in a combustion environment of 1450-1600K. Two color Pyrometer's main advantage lies in the fact that it has a fast response time and can therefore gather data during transient processes. The burning particles were in the view of the pyrometer detector during the entire duration of combustion. The pyrometer was aligned along the direction of flow of the particles. The radiation from the burning particles was actually focused onto a bifurcated optical fiber which transmitted the signal to two silicon photodetectors. Two medium band (70nm) filters centered at 800 and 1000 nm were used to pass only the desired spectral signals to the detectors. The resulting voltage signals from each detector channel were then read by a high speed, computerized data acquisition system. By using Planck's law of radiation, the temperature of each particle was deduced from the ratio of the two signals as a function of time. The experiments were carried out with char particles of different sizes at various wall temperatures and in different ambient environments. Wall temperature was varied from 1000K to 1500K. In all cases the gas velocity was roughly 0.1 m/s. The coal was pyrolyzed in an electrically heated drop tube furnace. Coal particles were entrained in a stream of nitrogen at rates of 2 g/h using the syringe pump feeder arrangement. Furnace wall temperatures (1650K) were measured by thermocouples attached to the outside of the alumina tube. Gas temperatures (1600K) were measured using a suction pyrometer. After the coal was pyrolyzed, the chars were collected on a filter and then dried at room temperature for 1 hour. The temperature-time plots showed widely different qualitative behavior from particle to particle. While some burnt at almost constant temperature, many particles showed temperature maxima or even monotonic behavior, both increasing and decreasing.

2.4 Radiative Properties of Charcoal

The emittance of an object is highly dependent on the condition of the object surface, which can change from day to day [18]. Precise knowledge of the surface temperature of the object must be known [19]. Other considerations include accounting for the reflections from the surroundings [20]. The radiative properties of charcoal vary as their temperature, size and shape change as they travel through the furnace. In a set of experiments, Lou et al. [21] measured the temperature, emissivity and other radiative properties of coal particles burning in three boilers. Along the height of the boiler, eight image detectors were mounted. Each detector comprised of a lens, an image guide and a CCD camera. From the images, by knowing the wavelengths of the acquired colors, temperature was expressed as a function of the intensity and wavelength of the bands. Emissivity, then, was expressed as a function of temperature and wavelength. The calibration constants were obtained from the assumption of a black body source. Because the emissivity was only due to the particulate medium, it was less than the total flame emissivity which includes particle radiation and the infrared radiation by the gaseous medium. It was observed that as the load was increased, the flame emissivity in the different layers of the furnace increased. This was due to the increase of concentration of the suspended particles, which enhanced the radiation of the flame. From the images, it was found that the maximum emissivity occurred within the upper half of the burner zone along the height of the furnace. The next highest emissivity was recorded in the lower half of the burner zone. Also, in the burner zone, the concentration of the flue gases was the highest. Beyond the burner zone, the flame emissivity decreased with the increase in height. This was because the number density of coal and char particles decreased as the degree of burnout of coal increased. Due to the lowest concentration of char and residual ash, the lowest emissivity was recorded. The emissivities of the flames in three boilers were compared and a conclusion was made. At the highest layer near the outlet of the furnace, the emissivity in one boiler was higher than the other. The reason was due to the more concentration of ash and flue gas in the higher emissivity recorded boiler. Because the soot concentration is directly proportional to the volatile matter concentration, the boiler in which coal with high volatile content was fired had the highest values of flame emissivity recorded. Flame emissivity can also be affected by ash content. The boiler in which coal with more ash content was fired, there were higher emissivity values calculated. It was concluded that the size distributions of the pulverized coal was the major factor which determined the size of char and ash particles. The larger the size of ash and char particles, the lower was the flame emissivity. Experiments with varying loads were also conducted and the change in radiative properties like intensity was found to be directly proportional to the load of the furnace.

2.4 Miscellaneous

China has its abundant coal resources ranking from anthracite to lignite with very wide differences in property. In pulverized coal fired boilers, as the residence time of coal particles in combustion chamber is very short, the combustion efficiency is very sensitive to the combustion characteristics of the coal burned. Xian et al. [22] presented the test procedures and the models used to calculate combustion kinetic parameters. Four coals were used for testing: The SLT lignite, the DT bituminite, and two low volatile anthracites LY and YA. The experiments are carried out in a drop tube furnace system, where the coals were pyrolyzed in the presence of Nitrogen at 1523K. The solid products collected were analyzed to determine the ash contents. As a result of which, burn-off efficiency was calculated.

More studies about how fuel type effects heat transfer results are available in literature, including the gas fuels. Ingason et al. [23] studied heat transfer results with using three different gas fuels: carbon monoxide (CO), propane (C_3H_8), and propylene (C_3H_6). The effects of 1. Fire heat release rate 2. Fuel type and 3. Wall separation distance (controlled by flues) on flame dimensions and wall heat fluxes were studied in this paper. The fuel with more sootiness produced greater heat fluxes. Moreover, CO flames had their maximum heat flux at about 55% of the flame height, whereas, C_3H_8 and C_3H_6 had their maxima close to 40% of their flame heights. The CO flames, being non-luminous (e.g. blue), had no soot and, consequently, minimal heat transfer by radiation was observed. On the other hand, C_3H_8 flames were quite luminous, released considerably more radiation and produced greater heat fluxes. The same result was deduced from the results of ray-radiometers measured during the experiment. Therefore, solid/liquid fuels which have even more soot can produce even large values of heat fluxes. The current study is focused on using charcoal for observing the effect of various fuel and surface condition parameters on the heat transfer properties of charcoal.

Chapter 3
EXPERIMENTAL SET-UP

All the materials used for testing are explained in this chapter.

3.1 Fuels

The approximate dimensions of a briquette is 2.25” × 2.25” × 0.75”. These dimensions vary from one manufacturer to another and may not be the same always because they are subjected to wear and tear while using them. The briquettes were always stored in a cool, dry place for preserving the product performance. Three types of fuel were tested in the experiments:

1. Fuel 1: Kingsford Matchlight Briquettes - These briquettes are easy and quick for ignition because they are pre-treated with lighting enhancement oils.
2. Fuel 2: Kingsford Original Briquettes – These briquettes burn slower compared to Matchlight charcoal, usually made for achieving longer times of cooking.
3. Fuel 3: Hardwood Lump Charcoal– These briquettes are unevenly shaped.

For measuring the charcoal content, the analytical balance having the following specifications was used:

- Denver Instrument Company, Model # TC-4102.
- Readability=0.01g; Linearity=0.02g; Repeatability=0.01g; Stabilization time=2s.

3.2 Thermocouples

A Thermocouple is a sensor used to measure temperature. Thermocouples consist of two wire legs made from different metals. The wires legs are welded together at one end, creating a junction. This junction is where the temperature is measured. There are several types of thermocouples depending on the accessibility. Thermocouples were used in this research to measure the surface temperature of the solid fuels. The best ways of positioning them on the surface of the briquettes was determined, to minimize the errors. For most of the experiments, type 'K' thermocouples having the following specifications were used to measure the surface temperature of the briquettes:

- Type 'K' thermocouples; Provider: Omega Engineering
- Error: ± 2.2 C or ± 0.75% whatever is higher;
- Temperature range: -200 TO 1000 C
- Data acquisition system: Agilent 34972A
- Software: Agilent Benchlink Datalogger

Trials were also done using Type 'J' thermocouples, but they were not best suitable for this application due to the nature of their response and the fact that they are mostly used for reading temperatures in gaseous mediums. For the data acquisition from thermocouples, Agilent DAQ system was used for obtaining the data in a computer. Thermocouples were changed at a regular basis in order to preserve accuracy of the results.

3.2.1 Positioning of Thermocouples

The positioning of thermocouples on the briquettes had to be tricky enough to measure the most accurate temperatures possible. If they were held perpendicular to the charcoal briquette, the surface of contact had less oxygen reaching the briquette at that spot, and the thermocouples would read low temperatures. On the other hand, if the thermocouples were fixed in such a way that they lie on the surface of the briquette and the tip is exposed to air, the problem would be that over course of time during combustion, when ash forms on the surface and the briquette shrinks in size, the thermocouples would still lie at the initial position and not touching the briquette anymore. To overcome these problems associated with the arrangement of thermocouples, a system of manually holding them was adopted which gave us more accurate results. But this method was only implemented in the experiments associated with the Mini-Chimney (Discussed in section 3.5). On the other test rigs, the thermocouples were fixed in such a way that throughout the combustion, they remain in contact with the surface of the briquette.

3.3 Pyrometry

When there is anything burning in suspension in a gas stream, the only practical way to measure the particle temperature is by making use of some form of radiation pyrometry. Pyrometry measures the temperature of objects without touching them. It is considered to be a standard procedure in many industries today. Every object whose temperature is above absolute zero (-273.15 °C) emits radiation. This emission involves heat radiation and is temperature-dependent. Infrared radiation is important because the wavelengths of the majority of this radiation lie in the electro-magnetic spectrum above the visible red light, in the infrared domain. Therefore, the energy emitted by an object is utilized by remote (i.e. non-contact) temperature measuring devices. The instruments which determine an object's temperature in this fashion are called radiation thermometers, radiation pyrometers, or simply pyrometers. There are three basic classes of radiation pyrometers, namely, total radiation, spectral band, and two-color or ratio pyrometers.

The advantages of noncontact pyrometry are:

- It records temperature within fractions of seconds (fast response time).
- It does not influence the temperature and material of the target.
- Requires less maintenance and hence the longer life time.
- It can measure the temperature of the moving object.
- Measurements can be taken for hazardous or physically inaccessible objects (e.g. high-voltage parts and great measurement distance).
- As it is not in direct contact with target, high temperatures can be measured.

A pyrometer is a type of remote-sensing thermometer used to measure the temperature of a surface. Depending on the operation type, they are classified as optical, infrared and digital pyrometers. In terms of wavelength, they can be single, dual, and multi-wavelength depending on the source of emission. The following are the specifications of the pyrometer used in the research:

- Williamson Pyrometers Company Single Wavelength Traditional Style Pyrometer.
- Uncertainty: $\pm 2°C$ or $\pm 0.25\%$, whatever is higher
- Model: SW-16-30C-FOV2ft/100-D-VALA-IM-SB-WC-AP-CF020- NSO322
- Specs: Spectral Response: 1.6 μm; Temperature range: 400-1800 C
- Software used for data acquisition: ProView

The pyrometer's lens was covered whenever there was high amount of fumes or soot being generated by charcoal. This is because formation of soot on the lens may result in the malfunctioning of the instrument. Fig. 3.1 shows a picture of the pyrometer (on the left) and its interface module (on the right) in use during an experiment.

Figure 3. 1 Williamson SW Pyrometer (on the left) and Interface module (on the right)

3.4 Briquette-of-focus

This terminology is used to describe a briquette chosen in the charcoal pile, which is subjected to the data acquisition. This can be any briquette, depending on the target of temperature zones. In the Fig. 3.2 below, we can see that a briquette from the bottom most layer was considered to be the briquette-of-focus.

Figure 3. 2 Briquette-of-focus

3.5 Description of Set-up

The experimental set-up was at a location outside, where there is no harm to safety of other personnel. It was made sure that the test rig was placed 25 feet away from the building. Also, a charcoal disposal bin was provided to dump the ash heap and other solid fuel left over at the end of experiments. This set-up is different from an indoor set-up in terms of the climate control. Although radiation and convection effects of the sun and wind have an impact on the combustion behavior, precautions were made to ensure that most of these effects were negated. For minimizing the wind effects, the combustion chamber was surrounded by cylindrical walls made of steel.

Additionally, air channels were built on the test rig whenever the air-supply had to be regulated. An anemometer was used for measuring the air flow, which was carefully made to sit through the probe holes provided on the air intake channels. The specifications of the anemometer are listed below:

- Model: TSI Alnor CompuFlow Thermo-anemometer
- Velocity Range=0-30m/s
- Velocity resolution=0.01m/s; Accuracy=3% of RDG or ±0.015m/s

3.6 Testing Apparatus

Three kinds of test rigs were used for performing the experiments:

1. Mini-Chimney (MC) or, Small-fire testing.
2. Kettle-type Grill (KTG) or, Medium-fire testing
3. Large Chamber Grill (LCG) or, Large-fire testing
4. The Mini-Chimney is basically a hollow square cross-section made of steel. Briquettes were made to sit along the cross-section, ensuring that they are most tightly packed. The top briquette was used for temperature measurements. While performing the experiments, this device was surrounded by a cylindrical wall (Firebox top of LCG) to minimize heat losses due to convection and radiation. The Mini-Chimney had holes on all sides, allowing oxygen to reach the combustion chamber. The holes were randomly sealed depending upon the governance of air-supply into the combustion chamber. For achieving longer times of combustion during the black-surface-condition of the briquettes, this device was built and temperature measurements were done by manually holding the thermocouples. The pyrometer was made to point at spot on the top-most briquette, and the spot was adjusted

in such a way that the thermocouples focused at the immediate proximity. Figs. 3.3 and 3.4 show us the side view, 3D view and the air setup of the Mini-Chimney.

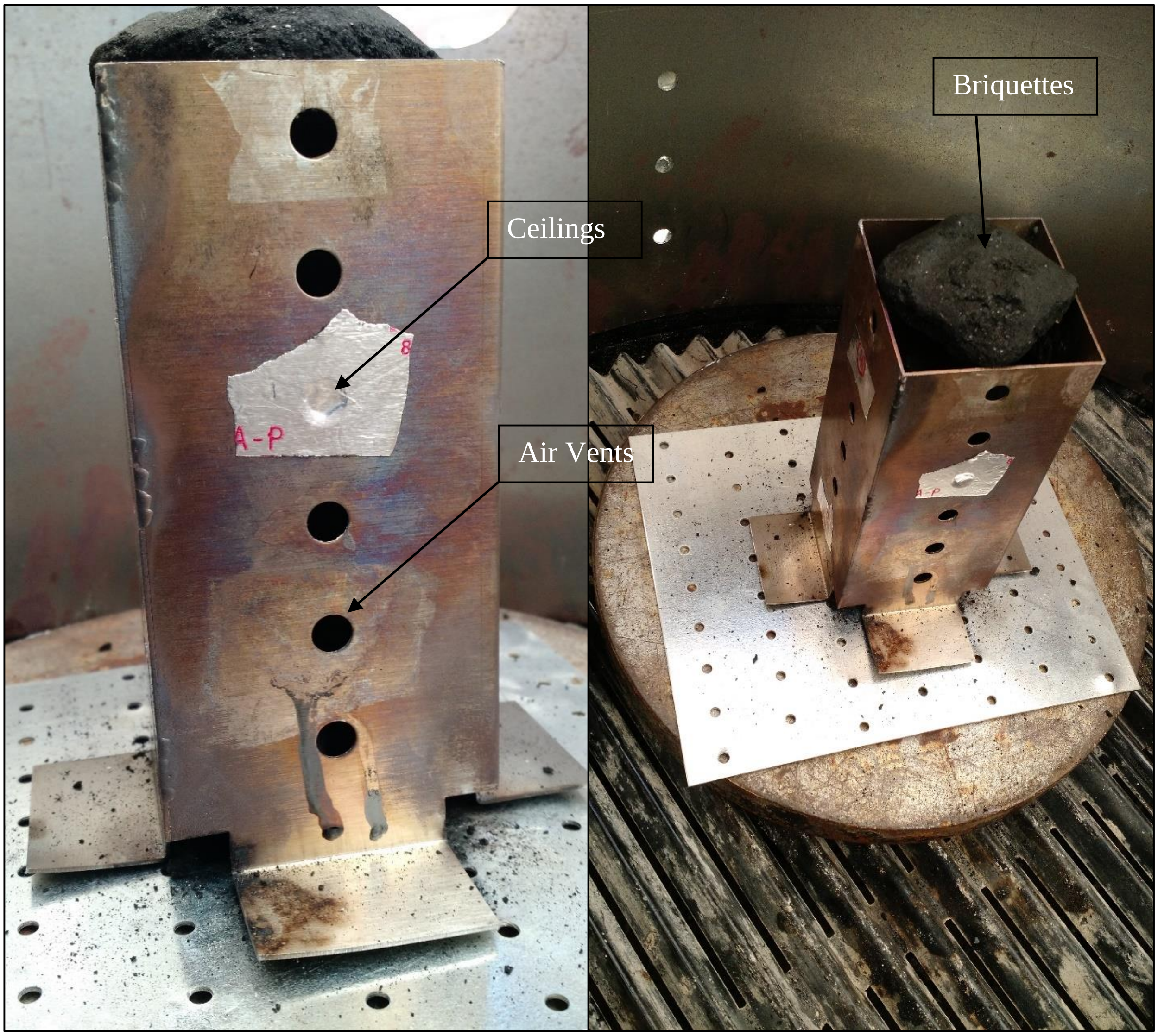

Figure 3. 3 Side view (on the left) and 3D view (on the right) of the Mini-Chimney

Figure 3. 4 Air setup (cylindrical wall) around the Mini-Chimney

The Kettle-type Grill (KTG) is the one which looks similar to domestic grills used for cooking purposes. The top lid of this grill was replaced by a component of LCG, i.e. the firebox top. In order for the oxygen to reach charcoal from the outside, and for easy arrangement of thermocouples, the firebox top was chosen as a surrounding wall on the KTG. It has a removable ash-bowl to easily clean up, and the grate is porcelain-coated to prevent flare-ups. This grill was used to record the data for ash or ‘Gray’ surface conditions of the briquettes.

A Large Chamber Grill (LCG), made of steel, was built to facilitate testing of different charcoal parameters. Although KTG could handle combustion up to 2 kgs of charcoal, it did not facilitate for testing larger amounts. After obtaining the correlations for emissivity, testing was done on LCG to observe the effect of fuel type, fuel amount, fuel arrangement, and air supply on the combustion characteristics of charcoal. The schematic for the LCG is shown in Fig. 3.5.

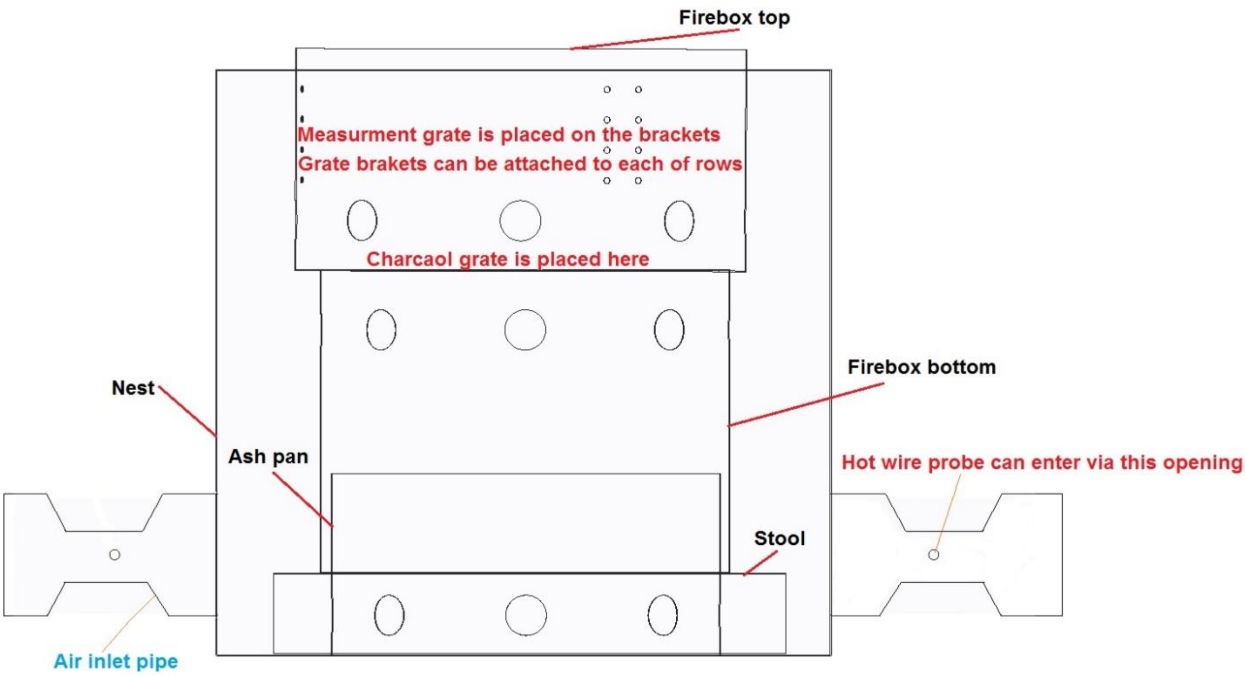

Figure 3. 5 Schematic of the LCG

It consists of an ash pan, firebox bottom, firebox top, stool and a nest. The following are the description of all the parts in detail:

1. Ash Pan: Made of steel, gauge 19, and painted black. It has a diameter of 19" and is 10" tall. There are 8 circular openings under the pan for keeping the floor from overheating. The ash pan sits inside the firebox bottom. Ash pan is used to collect the left over ash after the experiments. The ash is hot for a while after the experiments, so sometime was given for ash to cool down in the ash pan and then to dispose it safely. Wetting the ash pan would make the pan dirty and hard to remove the ash. The circular openings are 2" in diameter Fig. 3.5 shows the schematic of the ash pan.

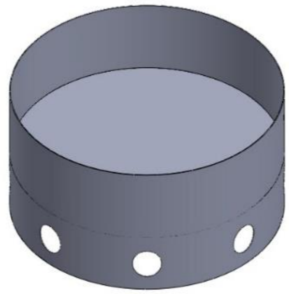

Figure 3. 6 Ash pan of the LCG

2. Firebox Bottom: Made of steel, gauge 19, and painted black. It has a diameter of 19” and 10” tall. There are 8 circular openings for air inlet. Each inlet is a 2” diameter circle at 12” from the bottom. The firebox bottom is attached to the firebox top by 4 screws. The charcoal grate will sit on the top end. If needed, the air inlets can be restricted by covering the holes with aluminum tapes.
3. Firebox Top: Made of steel, gauge 19, painted black. It has a diameter of 20” and is 11” tall. There are 8 circular openings for air inlet. Each inlet is a 2” diameter circle at 8.5” from the top. The firebox top is attached to the firebox bottom by 4 screws. The charcoal grate sits inside the firebox top at its lower end. The measurement grate sits inside the firebox top near to its top. It can be placed at different heights according to the experiments, with the help of brackets. The brackets are attached to the firebox top by screws. This firebox top is used as the surrounding wall on the KTG, which acts as a barrier for air and radiation from reaching the combustion chamber.
4. Stool: Made of steel, it is a 25”X25”X4” part with two openings on sides for facilitating air flow into the ash pan. The circular opening is 19.5” in diameter, for the ash pan to sit inside. The firebox bottom sits on the stool.

5. Nest: Made of steel, gauge 18. It is a cube with 30”X30” cross-section and is 29” tall. There are two openings for air inlet. The top circular opening is for the firebox. The inside of firebox can be viewed from the top through this opening.
6. Air Supply Pipes: The air inlets are 10” channels with inlet and exit diameters of 5” and throat diameter of 2.5”. The small openings on the throat are for the hot wire probe of the anemometer to sit in. The hot wire anemometer is placed carefully through the probe hole provided on the intake air channel. Fig. 3.6 shows the schematic of the air channel.

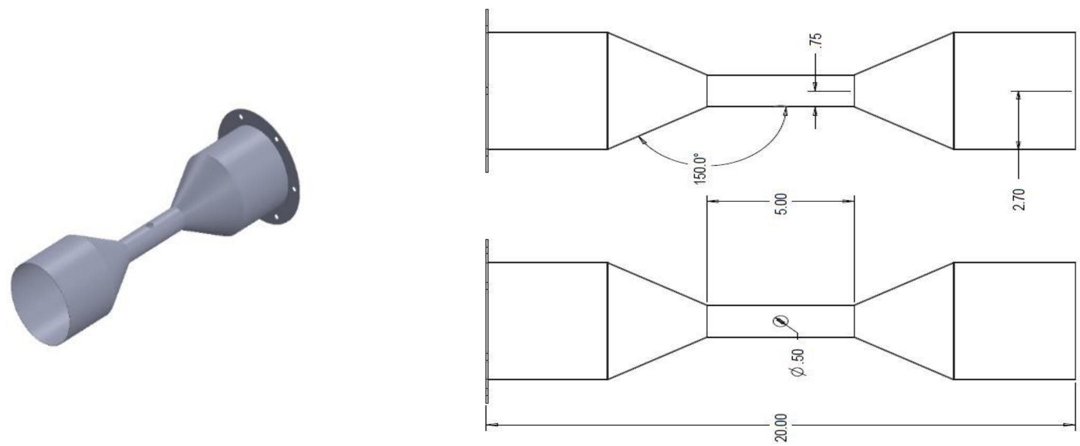

Figure 3. 7 Air channel - 3D View and Dimensions

Chapter 4
EXPERIMENTAL PROCEDURE

To make sure that the experiment proceeds with minimal human errors possible, a standard procedure was adopted to perform the experiments. The Mini-Chimney was used to accomplish the emissivity correlations for the black surface conditions of charcoal, whereas the Kettle-type-Grill was used for the gray surface conditions. For the rest of the miscellaneous experiments involving the parametric studies of combustion, the Large Chamber Grill was used. For obtaining the emissivity correlations, the air velocity was not taken into consideration, and alternatively, the experiments were carried out under controlled air-supply conditions. A test matrix was created in Microsoft Excel to record all the data obtained from the experiment. The steps listed below are followed from the beginning through the end of experiment:

1. The test rig is placed at a location outside, where there is no harm to safety of other personnel. It is arranged at a distance 25 feet away from the building to ensure safety.
2. A canopy is set up right above the grill, and positioned in such a way that the grill is least impacted by sun’s radiation.
3. The air intake openings on the test rig are sealed according to the inlet conditions of the experiment. Aluminum tapes are used for this process.
4. If performing the experiment on the LCG, the anemometer is inserted in the air cone hole, and made sure that the hot wire of the device is faced normal to the airflow.
5. The thermocouples are connected to the connectors of the data acquisition system. If it is a type ‘K’ thermocouple, then yellow adapters are used and if it is a type ‘J’ thermocouple,

black adapters are used. The connections are cross-checked to make sure they are tightly linked. This prevents errors in thermocouple readings.

6. The thermocouples are either fixed on stands with the help of clamps or manually held depending on the type of experiment.
7. The pyrometer is connected to the data acquisition module and placed facing the test rig. If the ambient condition is hot and humid, then the coolant (water) pipe is connected to the pyrometer on one end and the water hose on the other. The water outlet pipe is left on the ground making sure that it is away from the test rig.
8. The value of emissivity is set as '1' on the pyrometer by the help of the adjusting knob.
9. The fuel amount is measured on the weighing balance and then arranged on the grill according to the experiment. Simultaneously, the bulk density is calculated by the formula: $= \frac{Total\ amount\ of\ the\ fuel}{Volume\ of\ the\ container}$, where ρ is the bulk density of the charcoal.
10. The lighter fluid is added to the charcoal pile if necessary.
11. A briquette-of-focus is chosen in the arrangement and at a spot on the briquette where the topography appears good, the thermocouples are arranged and at a location midway between the thermocouple beads, the pyrometer is focused. This arrangement is similar to a small circle on the surface of the briquette, where tips of the thermocouples lie on the perimeter whereas the pyrometer is focused at the center.
12. The experiment number, date, type of fuel, amount of fuel, bulk density, air setup, fuel arrangement, lighter fluid, and positioning of thermocouples are all updated in the test matrix. A new sheet in the workbook is created for every experiment.
13. A cold run of all the measuring instruments is done to make sure everything works properly.

14. Using matchsticks, the ignition of the briquettes is began at the click of the stopwatch.
15. The flame is allowed to settle and then the data acquisition is started. This start-up time varies in each experiment depending on the ambient conditions, fuel amount, fuel type, addition of lighter fluid, air supply, and the surface temperature of the briquettes. Since lower temperature limit of pyrometer is 648K, readings below that are avoided.
16. The data is collected at an interval of 10s. During the experiment, all the observations are noted down.
17. The experiment is ended when the pyrometer reads less than 648K. All the data is saved and uploaded in the cloud database.
18. The raw data acquired through the DAQ software or through individual read-outs is then read into a post-processing package like MATLAB for determining calibrated output data and performing further calculations.

Fig. 4.1 shows the complete experimental set-up.

Figure 4. 1 Test rig set up at a location outside

Chapter 5
METHOD OF APPROACH

Thermal radiation is energy transfer by the emission of electromagnetic waves which carry energy away from the emitting object. The relationship governing the net radiation is given by the Stefan-Boltzmann law.

The Stefan–Boltzmann law states that the total energy radiated per unit surface area of a black body across all wavelengths per unit time (also known as the black-body radiant exitance or emissive power), j^*, is directly proportional to the fourth power of the black body's thermodynamic temperature T.

$$j^* = \sigma T^4 \tag{5.1}$$

The constant of proportionality σ, is known as the Stefan–Boltzmann constant or Stefan's constant. The value of the constant is

$$\sigma = 5.670373 \times 10^{-8}\, W\, m^{-2} K^{-4}$$

A body that does not absorb all incident radiation emits less total energy than a black body and has an emissivity < 1.

$$j^* = \varepsilon \sigma T^4 \tag{5.2}$$

The emissivity of different types of charcoal has to be determined for each surface condition. The radiative heat from the solid fuel is more dominant than convective heat due to the fourth degree temperature proportionality. However, the convective losses due to air are minimized by setting up a cylindrical wall around the combustion chamber.

The net radiative power from the briquette-of-focus per unit surface area is expressed as:

$$P = \varepsilon_s \sigma {T_s}^4 \tag{5.3}$$

Where ε_s is the emissivity and T_s is the surface temperature of the briquette-of-focus.

The surface temperature of the briquette is measured by two devices: 1. Pyrometer 2. Thermocouples. Hence equation 5.3 can be expressed in two forms:

$$P = \varepsilon_s \sigma {T_p}^4 \tag{5.4}$$

$$P = \varepsilon_s \sigma {T_c}^4 + Q_a \tag{5.5}$$

Where T_p and T_c are the temperature readings by the pyrometer and thermocouples. Q_a is the additive heat generated from the adjacent briquettes, from all directions. T_c is treated as the average value of all the thermocouples. For instance, if three type 'K' thermocouples (T_{ck1}, T_{ck2}, and T_{ck3}) are used in an experiment, then for every data point measured, T_c would be:

$$T_c = \frac{1}{3}(T_{ck1} + T_{ck2} + T_{ck3}) \tag{5.6}$$

The power expressed from both the equations 5.4 and 5.5 are equal since the pyrometer and thermocouples experience the same effective radiation from the charcoal. Hence, the resulting expression is:

$$\varepsilon_s \sigma {T_p}^4 = \varepsilon_s \sigma {T_c}^4 + Q_a \tag{0.1}$$

In a flat type of arrangement, when the thermocouples are focused on the top briquette, Q_a is almost negligible. Hence equation 5.7 becomes

$$\varepsilon_s \sigma {T_p}^4 = \varepsilon_s \sigma {T_c}^4 \tag{5.8}$$

The preconditioning followed for the emissivity calculations is as follows:

1. A spot on the briquette is chosen and the pyrometer and thermocouples are focused at that spot. This spot can be on any briquette, depending upon the arrangement of briquettes.
2. The value of emissivity is set as '1' on the pyrometer by the help of the adjusting knob and the temperature is read as T_p.
3. The readings from the thermocouples surrounding the same spot are recorded.
4. Average value of T_c's is computed from equation 5.6

In equation 4.8, the Stefan constant is same on both sides of the equation so they cancel out. The emissivity on the RHS of the equation is 1, because we have set ε_s =1 on the pyrometer. Hence the effective emissivity is expressed as:

$$\varepsilon_{eff} = \left(\frac{T_c}{T_p}\right)^4 \tag{5.9}$$

The emissivity expressed in Eqn. 5.9 is the proposed equation for emissivity as a function of temperature. The uncertainty analysis for the same is shown in Chapter. 7 (discussions).

Chapter 6
RESULTS

While testing the briquettes, the input parameters taken into condition were: fuel type, fuel arrangement, amount of briquettes, and air supply.

For the black-surface condition testing of Matchlight and Original briquettes, Mini-Chimney was used. The list of experiments are as follows:

1. MC13-MC19 (7 Experiments) – for testing the black surface properties of Matchlight Briquettes (Fuel 1)
2. K01-K04 and MC14-MC19 (10 Experiments) – for testing the gray (ash) surface properties of Matchlight Briquettes (Fuel 1)
3. MC20-MC24 (5 Experiments) – for testing the black surface properties of Original briquettes (Fuel 2)
4. K05-K08 (4 Experiments) - for testing the gray surface properties of Original briquettes (Fuel 2)

Miscellaneous Experiments:

1. MC01-MC12 (12 Experiments) – for testing black surface properties of Fuel 1. In this set of experiments, the positioning of thermocouples, air supply, type of thermocouples, and fuel amount were varied to observe their effects on the thermal properties of briquettes.

2. P01-P10 (10 Experiments) – for testing the gray surface conditions of Fuel 1. This set of experiments is similar to K01-K04. Additionally, the red-zone conditions were observed and the thermal performance of charcoal under different conditions was analyzed.

For each experiment, temperature-time histories were recorded to examine the intervals at which maximum temperature occurred. A test matrix showing all the details of the experiment was created, and the obtained data was processed both in Microsoft Excel and MATLAB. A sample test matrix for is shown in Appendix 1.

The data acquisition was made at an interval of 10sec for every experiment. Once the set-up is done and cold test had been run, the briquettes were fired on the click of the stopwatch. After firing up the briquettes, the flame was allowed to settle down for a few minutes before starting the data acquisition. This settling time varied form one experiment to another, depending on the fuel type and weather conditions. For example, the oiled briquettes (Fuel 1) took somewhat a lesser time to light up than the other fuels. On the other hand, if the ambient temperature was very less, then the briquettes burned at a slow rate, in contrast to a sunny day. Testing was not encouraged when humidity in the ambience was high. This is because when the humidity in air increases, the susceptibility to spontaneous combustion in the charcoal is decreased [24], thereby decreasing the performance and causing deviation in the results.

6.1 Fuel 1 Testing

6.1.1 Black Surface Condition

The first set of experiments (MC13-MC19) were focused at obtaining the correlations for emissivity for the black-surface conditions of fuel 1. Since this fuel comes oiled, there was no use of a lighter fluid for almost all the experiments. The air set up for these experiments was Firebox top on kettle, and holes were left open for air supply into the combustion chamber. The Mini-

Chimney was placed at a position most convenient for holding the thermocouples. Along the cross-section of the chimney, briquettes were arranged. The bottom four briquettes were placed perpendicular to the ground, in order to achieve an improved support to the top briquettes. The briquettes were ignited with the help of match sticks from the bottom space provided on the Mini-Chimney. On an average, 7 briquettes were used for testing the black-zone properties. The number of thermocouples used for measuring the surface temperature varied between 2 and 4. At a location midway between the thermocouples, the pyrometer was spotted. This arrangement is similar to a small circle on the surface of the briquette, where tips of the thermocouples lie on the perimeter whereas the pyrometer is focused at the center.

During the course of combustion, as ash forms, the briquettes collapse. This is why the thermocouples had to be adjusted or re-positioned throughout the experiment. Thermocouples were always placed at an angle anywhere between 0° and 75° to the surface of the briquette. Beyond 75°, the readings would be effected due to the insufficient supply of oxygen to the briquette. Data acquisition was performed until the angle of thermocouples was reasonably good. In all the experiments, Mini-Chimney proved to be a very good source of retaining the combustion period for a longer time. Fig. 6.2 shows a Temperature-time plot of an experiment (MC13) using Fuel 1. In this experiment, 6.5 briquettes were arranged in the Mini-Chimney, and the ambient condition was sunny, less humid and no wind.

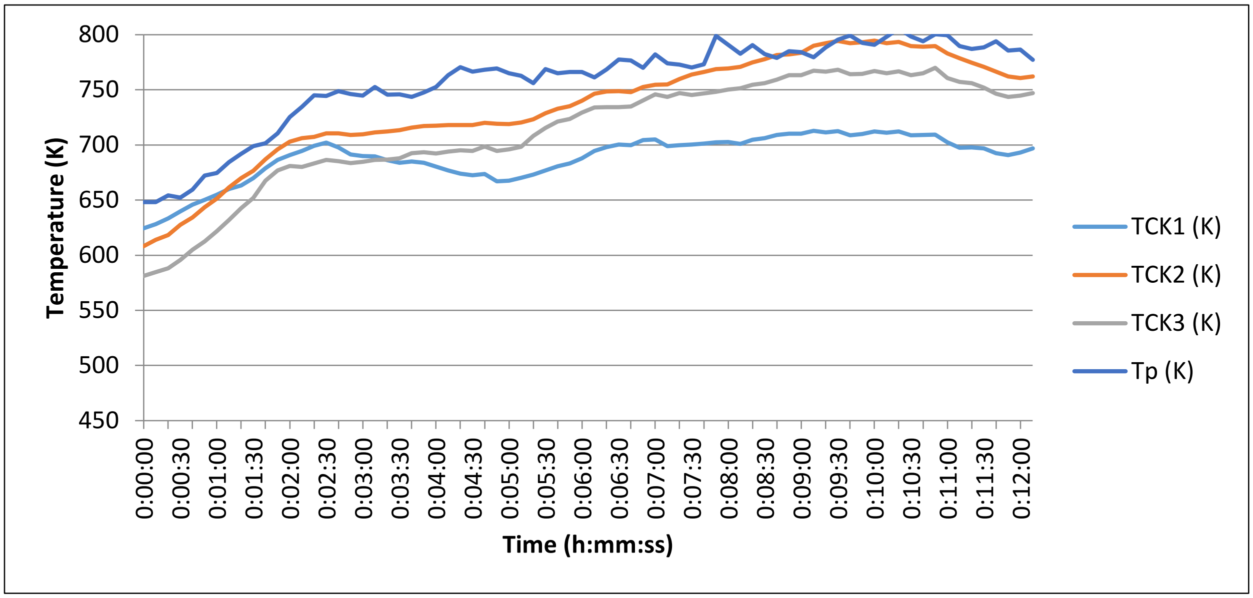

Figure 6. 1 Temperature-Time Plot of an Experiment on Black Using Kingsford Matchlight Charcoal

The data acquisition started 12 minutes after firing up the briquettes, after all the flame had disappeared. T_{CK1} (K), T_{CK2} (K), T_{CK3} (K) are the surface temperature readings (in Kelvin) as recorded by the three thermocouples. T_P (K) refers to the temperature readings (in Kelvin) as recorded by the Pyrometer. For post-processing, the average of TCK1, TCK2 and TCK3 was determined and used for further calculations. The plot shows the temperatures when the briquette's surface condition was black. In the above experiment, at 11:30 (mm:ss), the surface condition changed to all ash (gray). The wavy nature of the curves is due to the unsteady nature of combustion. The graph shows that the maximum temperature read by the thermocouple is 760K (considering the average of all thermocouples), while that of the pyrometer is 805K. Other experiments performed under the same conditions resulted in temperatures quite similar to the above. However, the e-T graphs are presented in the further sections taking all the experimental results into account.

6.1.2 Gray Surface Condition

The second set of experiments (K01-K04 and MC14-MC19) were performed using the same fuel, and the data was collected when the briquette condition was gray. Experiments K01-K04 indicate medium-fire experiments, where the fuel amount was around 1kg, whereas the amount of fuel used while testing in MC14-MC19 (small-fire) was between 6 and 8 briquettes. Fig. 6.3 shows the ash (gray) condition of all the briquettes.

Figure 6. 2 Gray Surface Condition of the Kingsford Matchlight Briquettes

For testing on KTG, thermocouples were fixed in a constant position throughout the experiment. A lot of effort was put in to make sure that they remain in contact with the surface of the briquette till the end of the experiment. Even if ash collapse occurred, the thermocouples would go down along with the rigid surface of the briquette and still read the surface temperature.

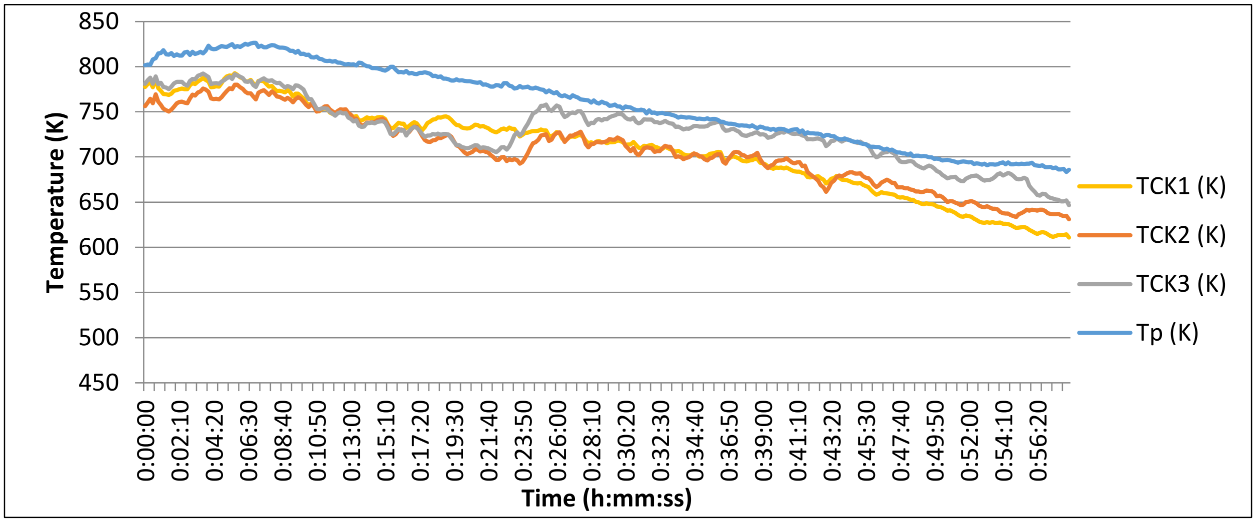

Figure 6. 3 Temperature-Time Plot of an Experiment on Gray Condition Using Kingsford Matchlight Charcoal

The arrangement of briquettes on the grill was either of the flat or volcano or semi-volcano type. To observe the thermal behavior in different sections of the combustion chamber, the position of thermocouples was changed in each experiment. For instance, in one experiment, the temperature measurements were done on the top most briquette which was exposed to air, whereas in another experiment, a briquette from the bottom layers of the pile was considered. Fig. 6.4 shows the temperature-time plot of an experiment (K04) performed on KTG. 1kg of fuel was used, arranged flat on the grill. With the firebox top on Kettle, air was let into the chamber through the holes. The weather conditions being less windy, no sun and 21°C ambient temperature, radiation losses were negligible in this experiment. The data acquisition started 18:40 (mm:ss) after firing up the briquettes, and 5 minutes after that, the briquette-of-focus surface condition was all ash.

The graph shows that the maximum temperature read by the thermocouple is 795K (considering the average of all thermocouples), while that of the pyrometer is 826K. The experiment terminated at 56:00 (mm:ss), when the briquettes transformed completely into powdered ash. Similar temperature distributions were observed in other experiments having the same set-up.

The data for black and gray conditions was used for emissivity calculations. The emissivity formulation has been discussed in Chapter 5. The emissivity of charcoal at different temperatures was calculated and its variation with temperature was studied for each experiment. Figs 6.4 and 6.5 show the emissivity vs temperature plots for two individual experiments on the black surface conditions. Temperatures lower than 615K were not recorded because of the presence of flame on charcoal at the initial stages of combustion. As a result of this, the thermocouple measurements could be affected greatly.

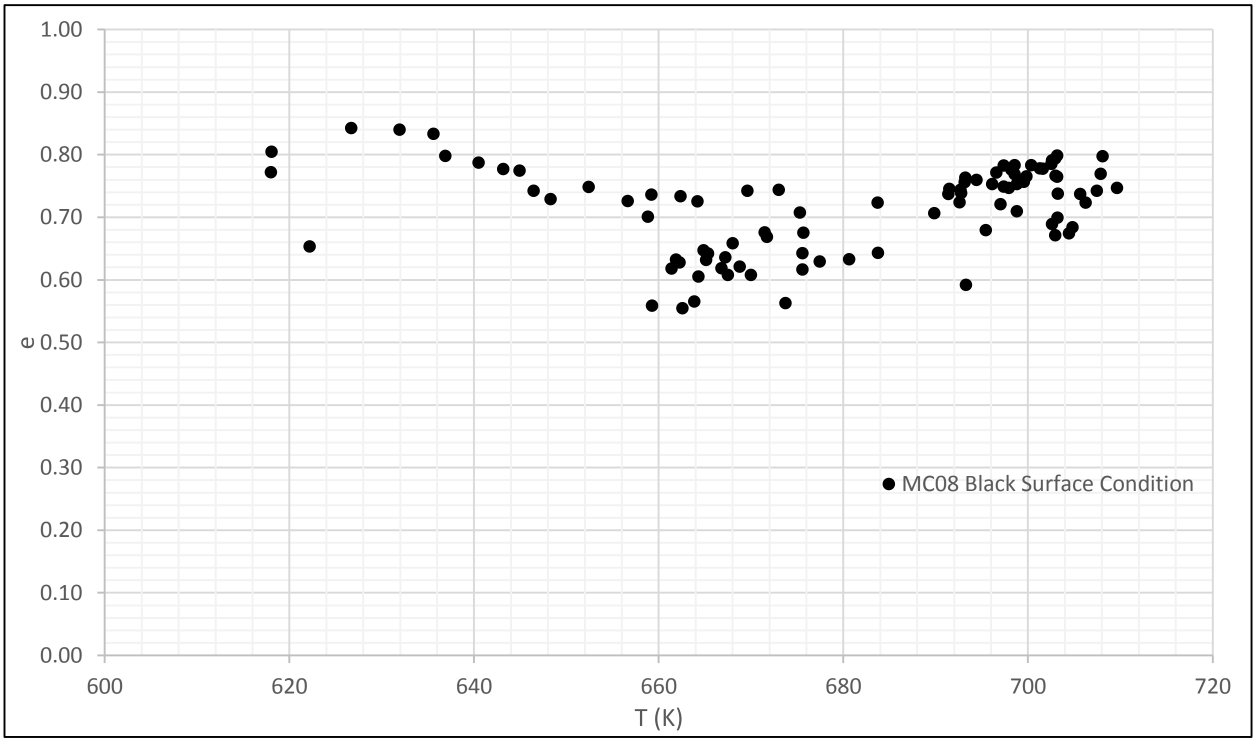

Figure 6. 4 Emissivity vs Temperature Plot of Black Surface Condition - Experiment MC08

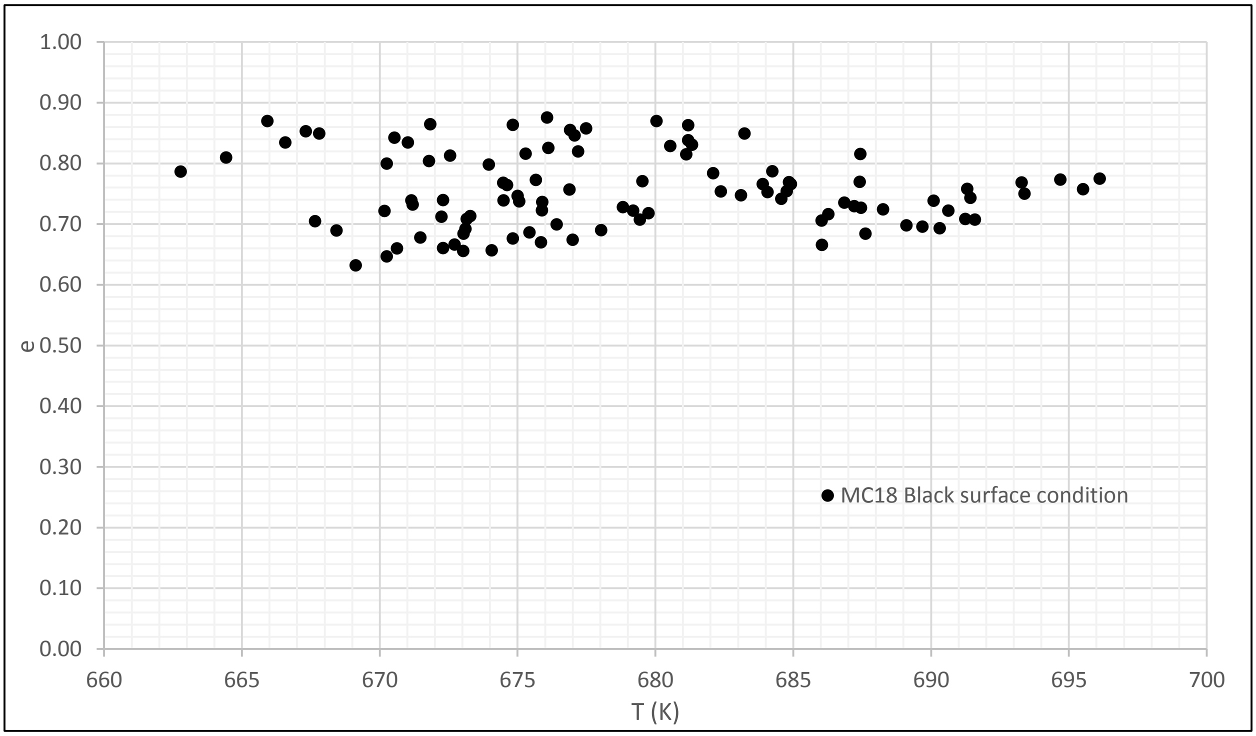

Figure 6. 5 Emissivity vs Temperature Plot of Black Surface Condition - Experiment MC18

Similarly, data for the gray (ash) conditions of the briquettes from 3 individual experiments is shown in Figs. 6.6, 6.7 and 6.8.

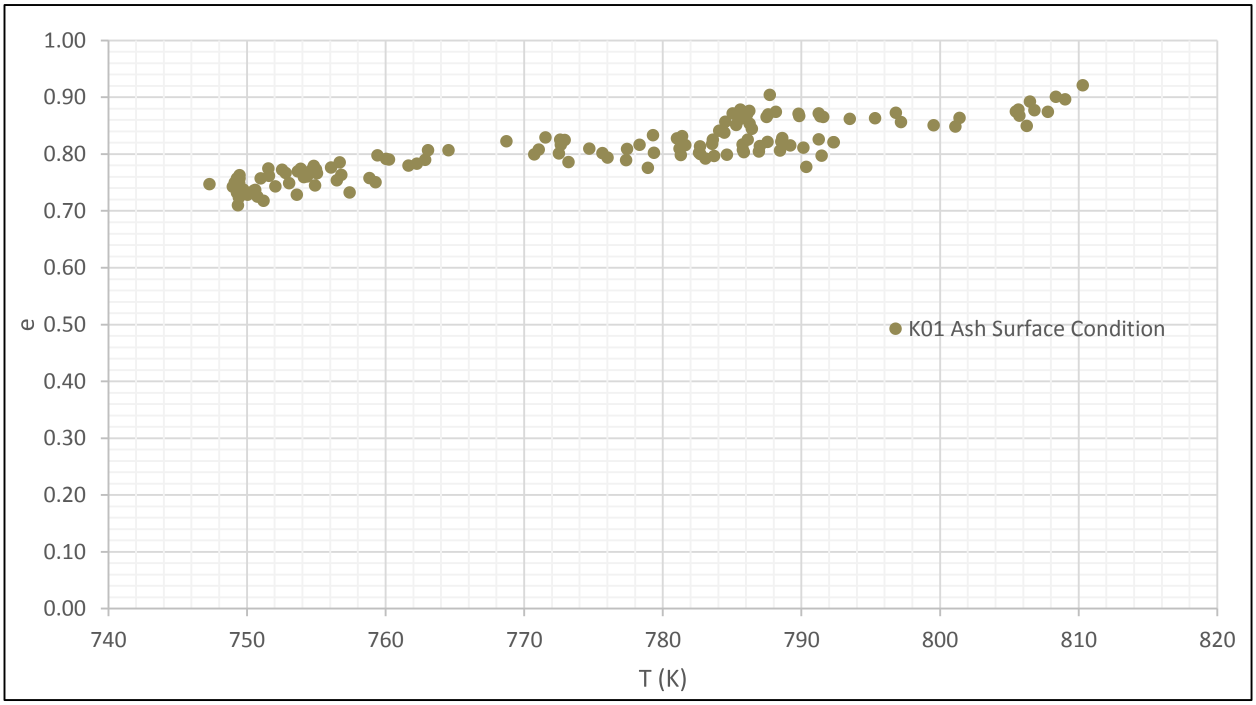

Figure 6. 6 Emissivity vs Temperature Plot of Gray Surface Condition - Experiment K01

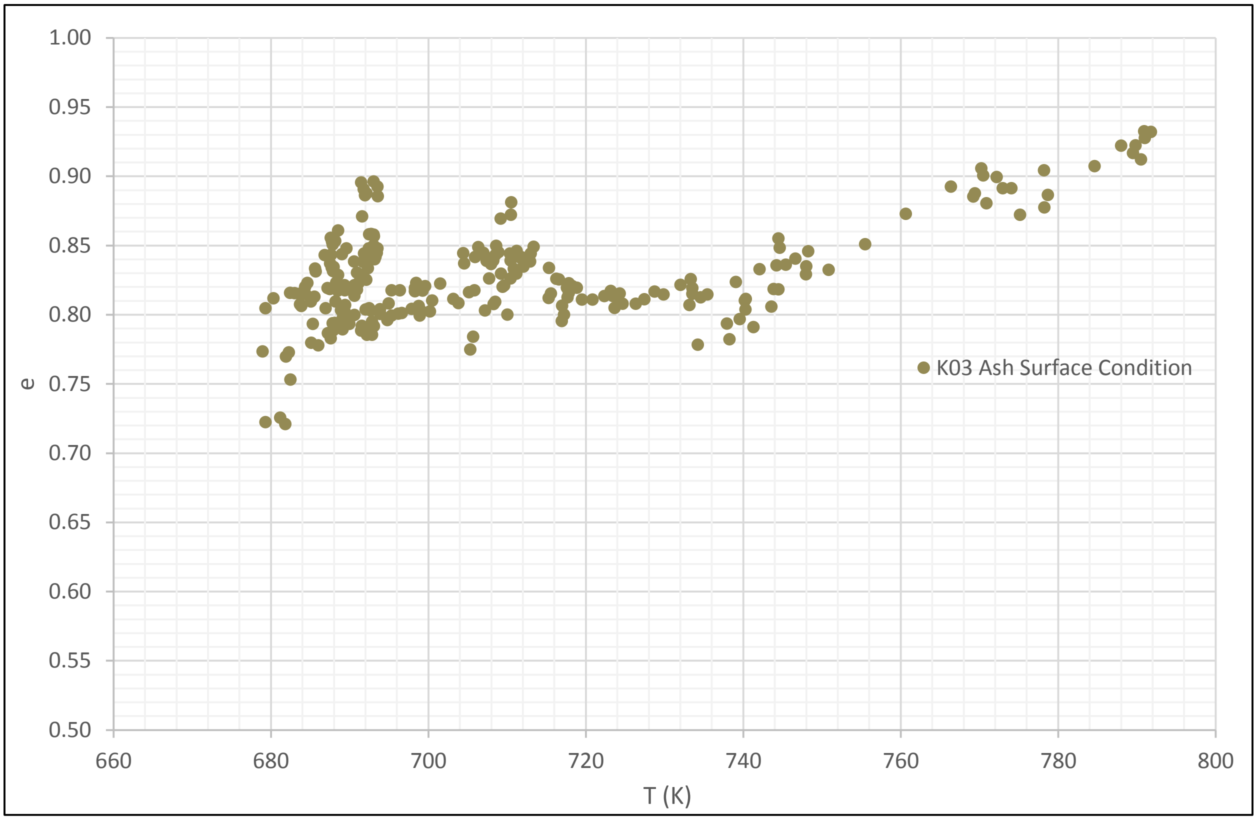

Figure 6. 7 Emissivity vs Temperature Plot of Gray Surface Condition - Experiment K03

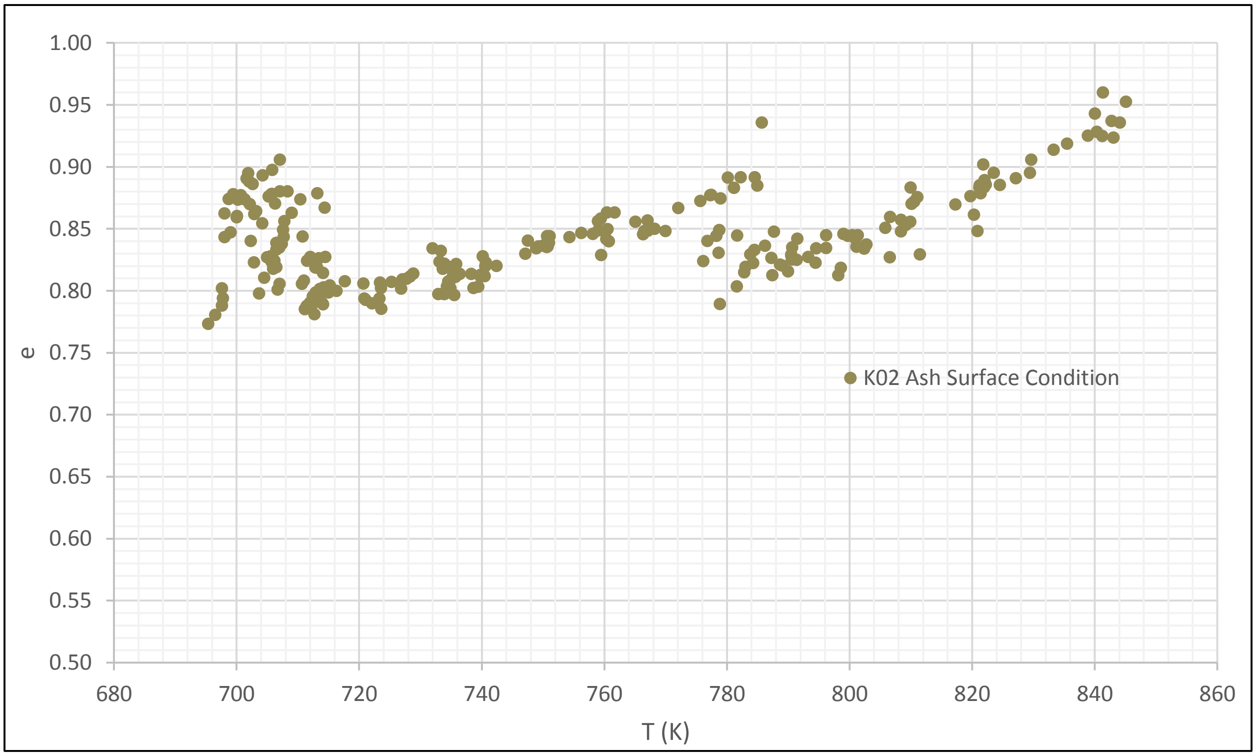

Figure 6. 8 Emissivity vs Temperature Plot of Gray Surface Condition - Experiment K02

The deviation in the trends might be due to changes in the boundary conditions of the briquette, such as ash collapse, or the top layer of ash being blown away by wind, or thermocouples reading the ash temperature instead of rigid surface temperature. It can be concluded from the plots that the average emissivity at low temperatures (660K) is 0.8 and the same at higher temperatures (up to 840K) is 0.95. This high emissivity is a result of the radiative heat generated from the adjacent briquettes which are at the same or higher temperatures than the briquette-of-focus. Hence the thermocouples pick up heat from the neighborhood along with the heat from briquette-of-focus, thereby reading higher temperatures.

Combining the data from all the experiments, central averaging technique was adopted to reduce the noise in the readings. Fig. 6.9 shows the variation of emissivity with temperature for the black surface condition of the briquettes between 615K and 760K.

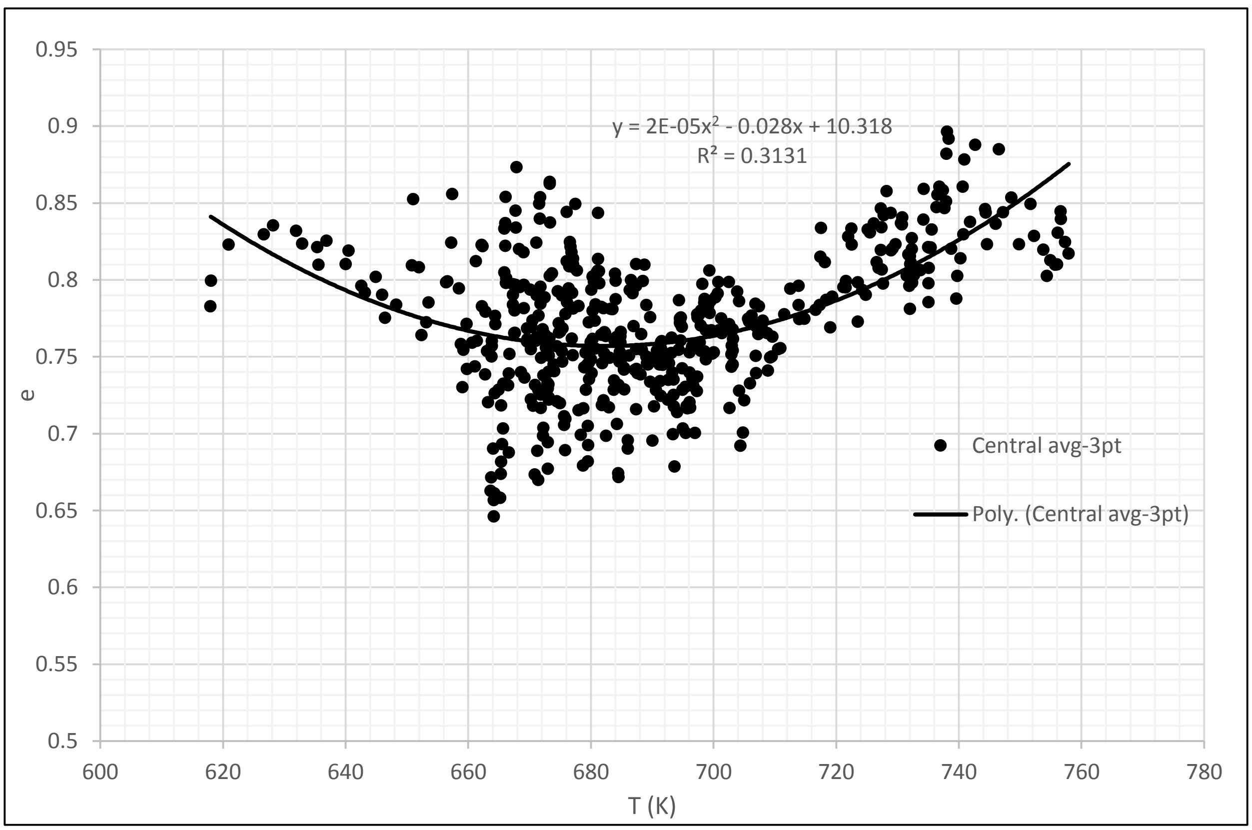

Figure 6. 9 Emissivity vs Temperature of Black Surface Condition of Fuel 1 (Kingsford Matchlight Charcoal)

The emissivity decreases from 0.85 at 618K to 0.76 at 680K and then increases until it reaches 0.87 at 758K. Beyond this temperature, it was observed in the experiments that black surface condition of the briquettes completely transforms into ash. The plot appears dense in the 660-710K region because the combustion survives for a longer time in this temperature zone. A curve fit for the data is also shown in the plot. The curve fit is a second order polynomial with an R squared value of 0.3161. This equation can be used for emissivity calculations in further experiments, which can be done without the use of a pyrometer. The emissivity is high in the beginning as the surface is black and also there is less heat radiated from the surroundings at the initial stages of combustion. Fig. 6.10 shows the e-T plot for the ash or gray conditions of the fuel using the central averaging techinque. The data is retrieved from all the experiments on the small as well as medium-fire testing. The average amount of fuel used in medium-fire testing was 1Kg, whereas in small-fire testing it was 7 briquettes (pieces). A curve fit for the data is also shown in the plot.

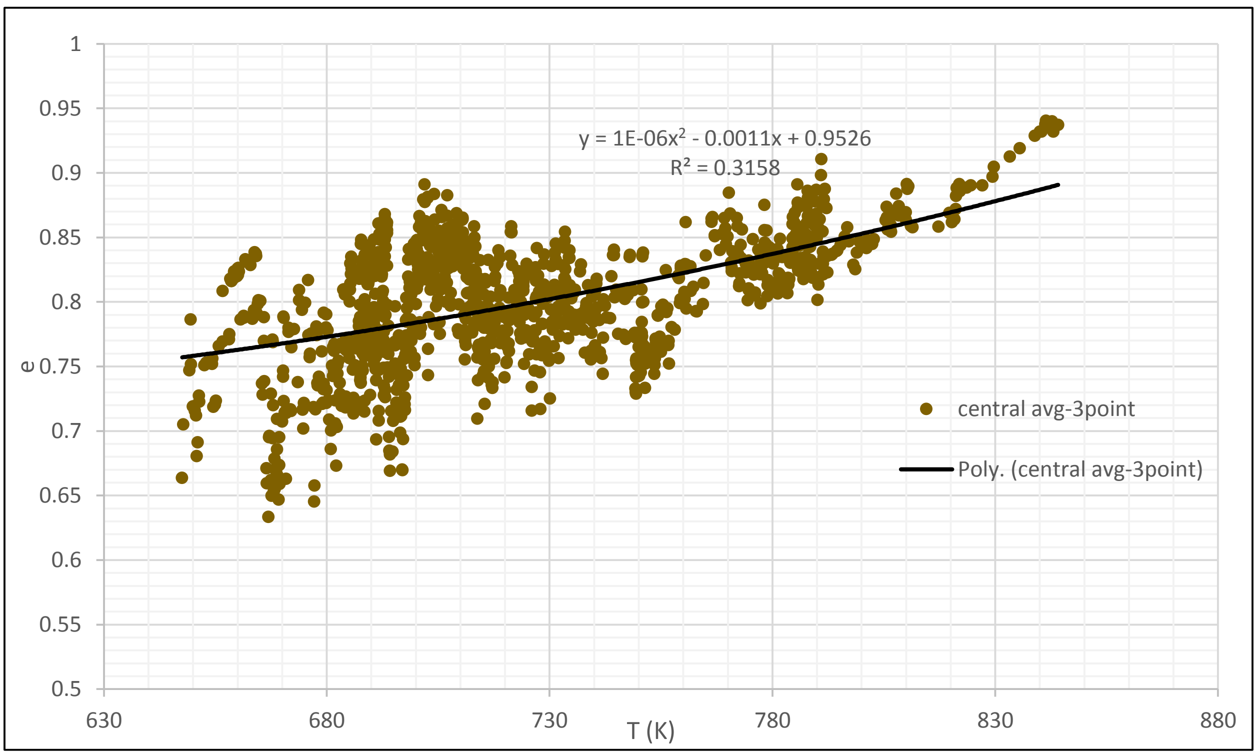

Figure 6. 10 Emissivity vs Temperature of Gray Surface Condition of Fuel 1 (Kingsford Matchlight Charcoal)

The curve fit is a second order polynomial with an R squared value of 0.3158. It can be deduced from the curve that the emissivity increases with the increase in temperature. The lowest emsissivity of the ash surface condition of this fuel is 0.76 (at 650K) and the highest is 0.89 (at 845K). Ususally, at the initial stages of ash formation, the temperature of the charcoal was around 820K and it dropped till the end of combustion, i.e. when the briquettes totally decompose into powdered ash.

In Figures. 6.11 and 6.12, both black and gray data of fuel 1 is presented. In Fig. 6.11, two separate curves are shown and in Fig. 6.12, both black and gray data is mixed and a single curve fit is demonstrated.

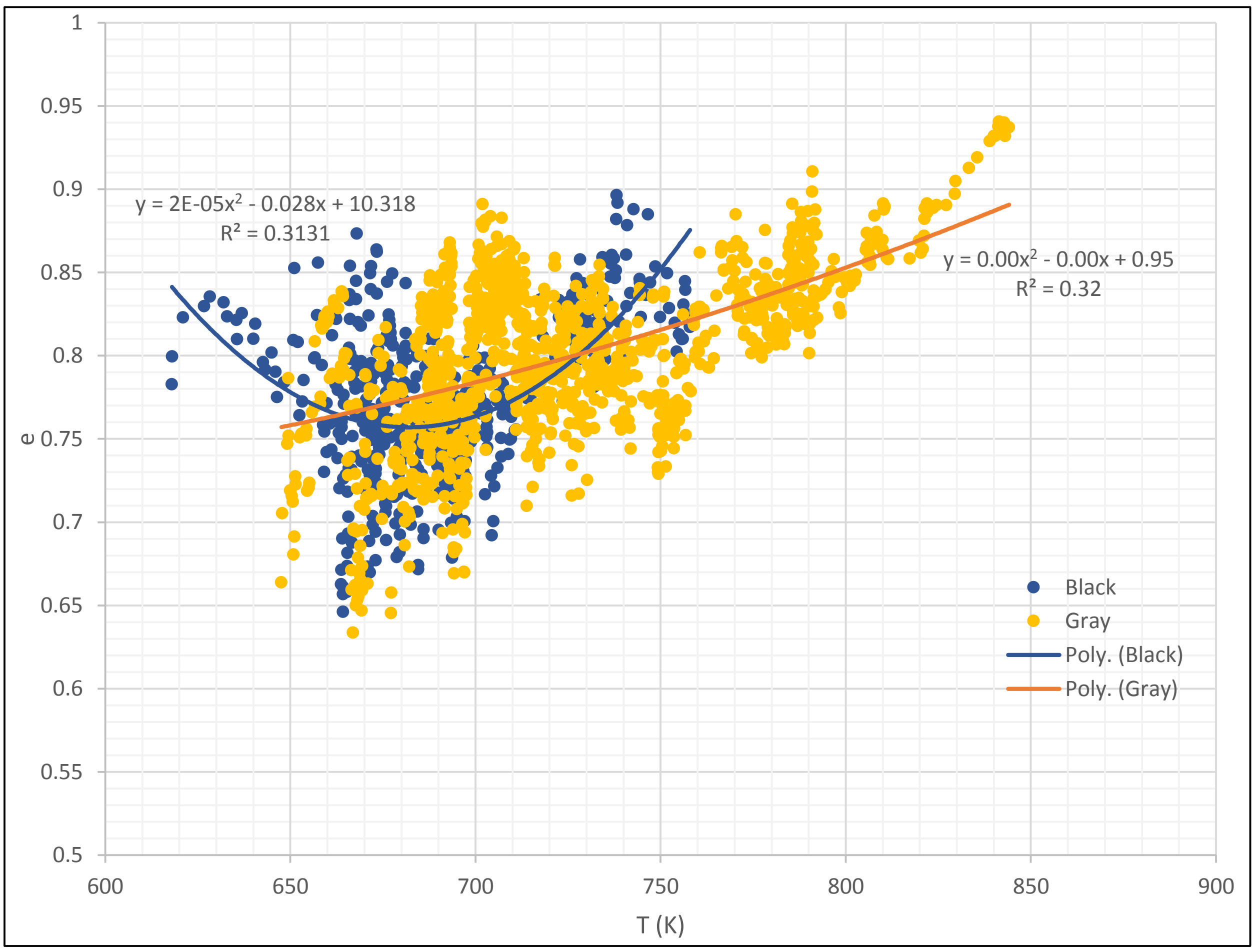

Figure 6. 11 Emissivity vs Temperature of Black and Gray Surface Conditions of Fuel 1 (Kingsford Matchlight Charcoal)

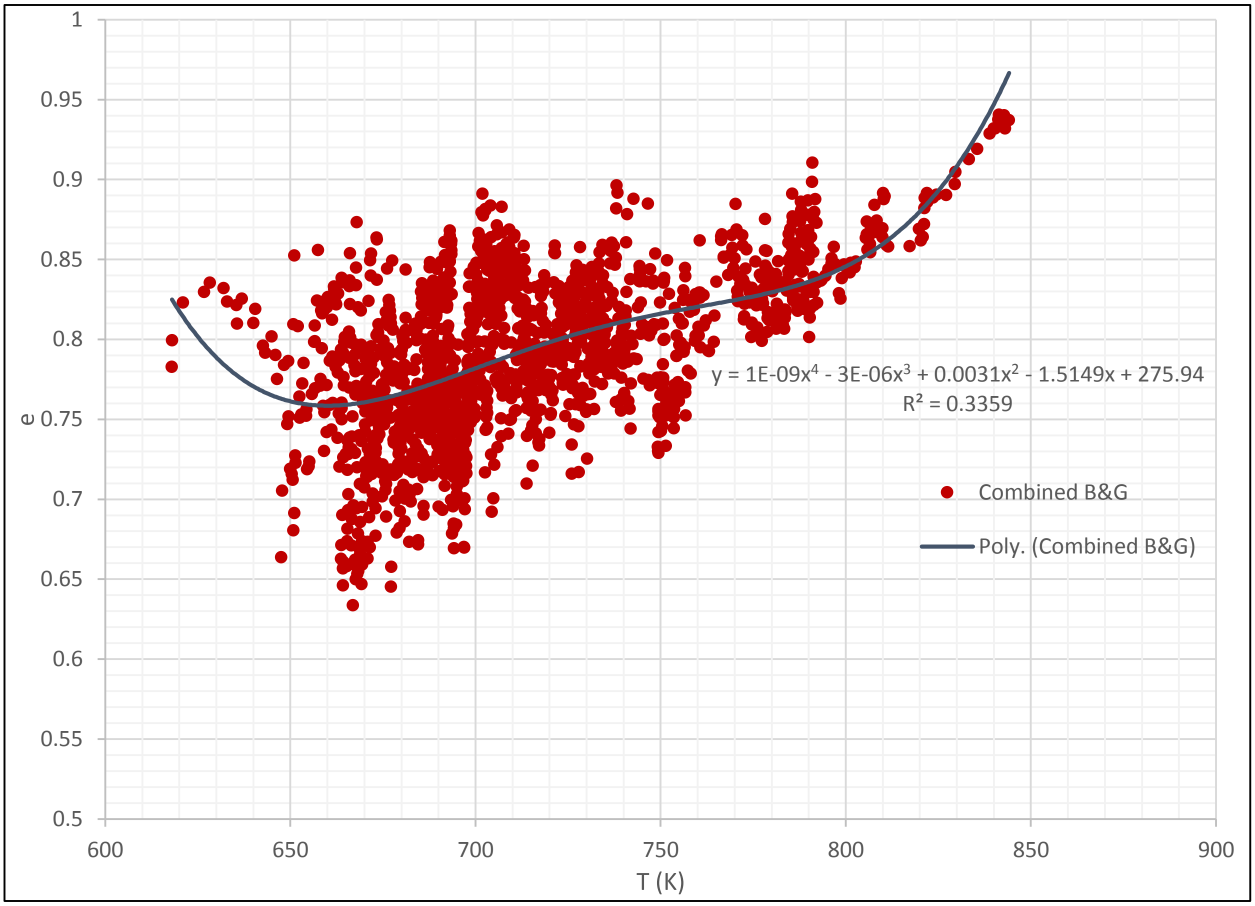

Figure 6. 12 Combined Emissivity vs Temperature Plot of Black and Gray Surface Conditions of Fuel 1 (Kingsford Matchlight Charcoal)

The margin of emissivity between black and gray surface conditions is less, and the point where the curves intersect can be assumed as the transition point. As it can be seen from Fig. 6.11, the curves intersect at 728.5K (second intersection) with an emissivity of 0.8. Fig. 6.12 demonstrates us that the emissivity decreases as temperature increases in the beginning and later, it increases with temperature.

Besides the variance of emissivity with temperature, the effect of fuel arrangement and air supply on the emissivity was also studied. Fig. 6.13 shows the e-T data retrieved from three experiments with Flat, Cone and Volcano types of fuel arrangement. The surface condition of the charcoal was gray in all the three experiments. Black zone has not been included in the plot as its temperature range is different from the gray surface condition.

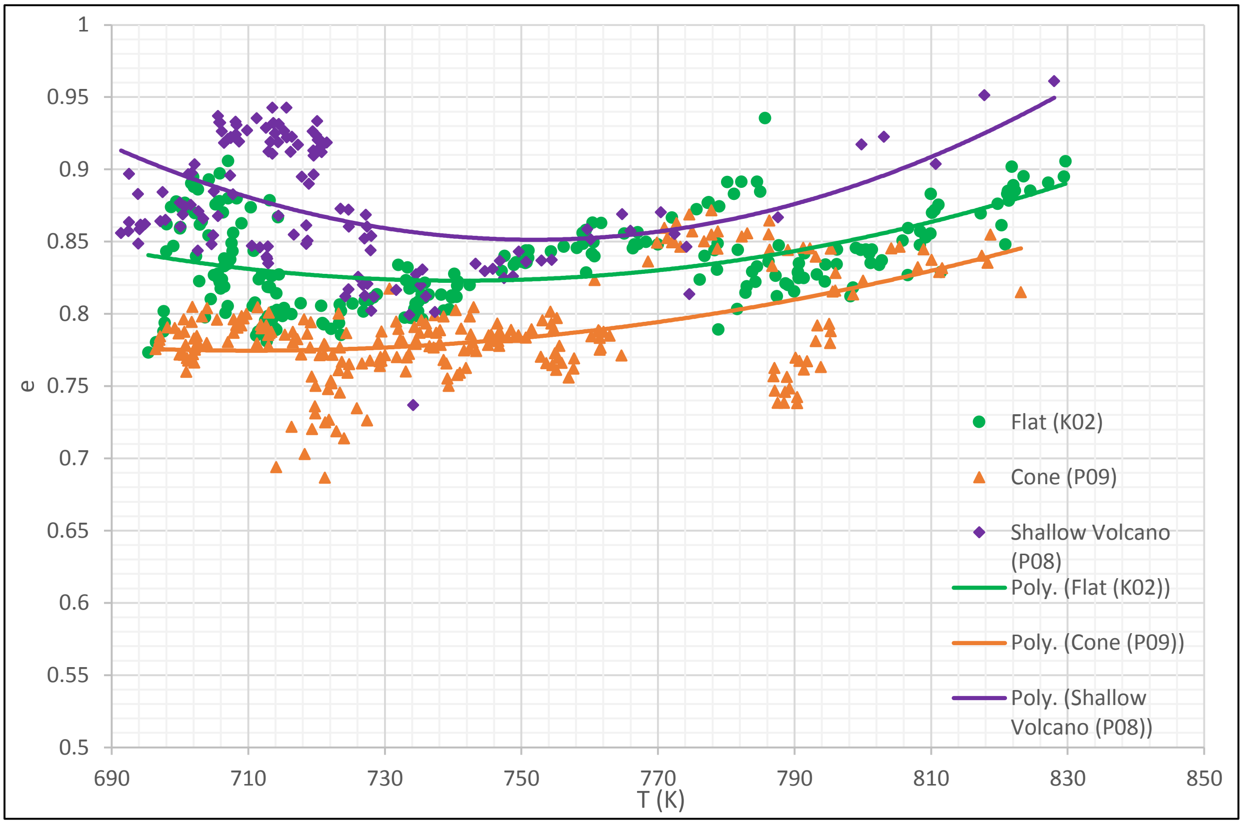

Figure 6. 13 Emissivity vs Temperature for different types of arrangement of Fuel 1

As it can be seen in the graph, the emissivity is much higher in the volcano set-up, followed by flat and cone arrangements. This is primarily because of the high amount of heat present in the heart of the charcoal pile. The briquettes are more exposed to air when the arrangement is flat, than the volcano set-up. In cone type of arrangement, the briquette-of-focus is almost totally exposed to the ambient air. Due to the air convection losses, the top most briquette experiences low emissivity conditions.

Volcano set up was an interesting aspect of studying the phenomenon happening in the deeper layers of the charcoal pile. The temperature and emissivity was observed to be the highest in the bottom layers of the charcoal pile. Several red and amber zones were observed on the hidden briquettes during combustion. Figs. 6.14, and 6.15 give us a clear idea of the three types of arrangement.

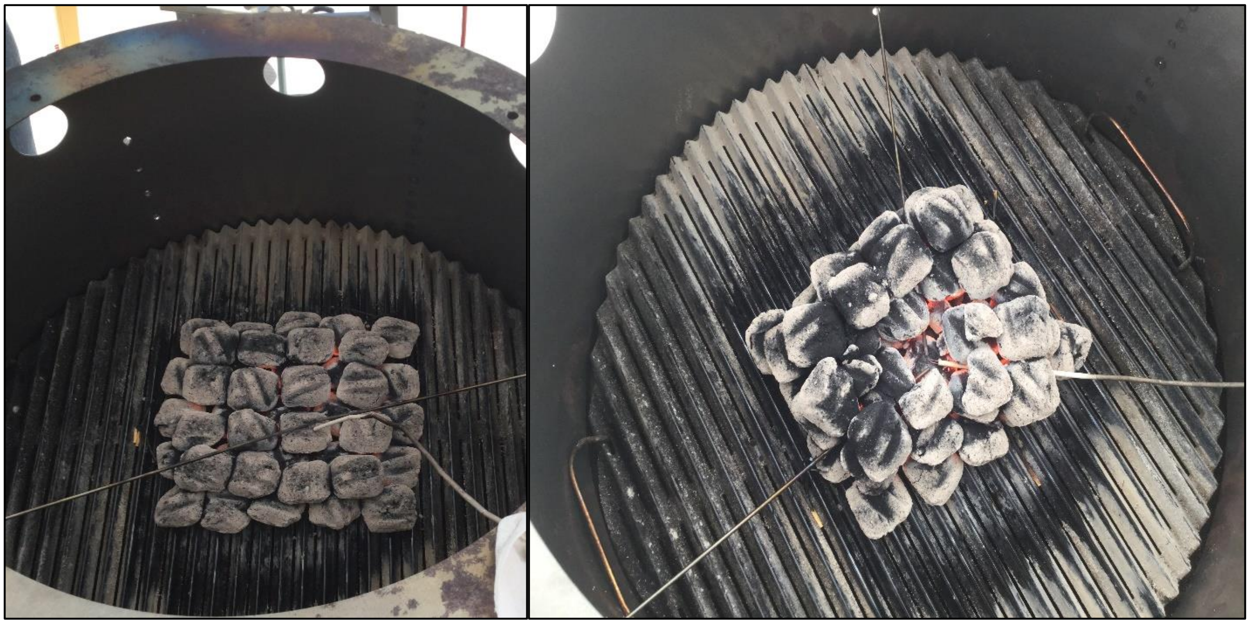

Figure 6. 14 Types of Fuel Arrangement: Flat (on the left) and Volcano (on the right)

Figure 6. 15 Types of Fuel Arrangement: Cone

6.2 Fuel 2 Testing

The third set of experiments were focussed on obtaining the black surface condition properties of Kingsford Original charcoal. This charcoal does not contain ignition oils in it, and has the property of burning at a slower rate than fuel 1 (Kingsford Matchlight). Five experiments (MC20-MC24) were carried out on the Mini-Chimney. The air set-up in all the experiments was Fireboxtop on Kettle. Holes were randomly sealed on the Mini-Chimney to regulate the supply of oxygen into the combustion chamber. Especially, holes which were close to the top-most briquette were sealed, to sustain the combustion for a longer time. On an average, 7 briquettes were used in all the experiments. The arrangement of briquettes, thermocouples and the Mini-Chimney is similar to the first set of experiments, explained in the previous sections. Fig. 6.16 shows the temperature-time plot of an experiment done on the Mini-Chimney (MC20). In this experiment, 7 briquettes were arranged in the Mini-Chimney with 1 oz lighter fluid on the bottom four briquettes. The ambient condition was less sunny, less humid and less windy with ambient temperature of 277.15K. The data acquisition started 35 minutes after firing up the briquettes, after all the flame had disappeared. In the graph, all the data has been presented including the readings with errors.

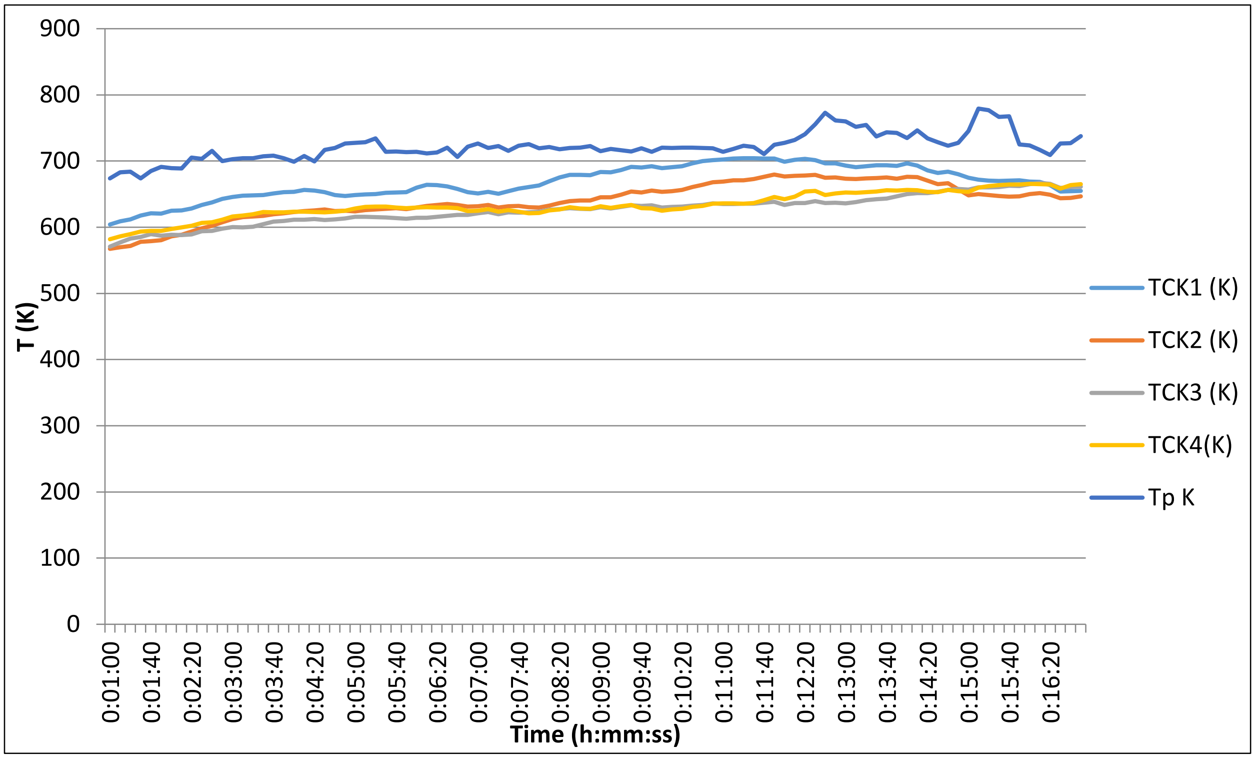

Figure 6. 16 Temperature-Time Plot of an Experiment on Black Using Kingsford Original Charcoal

It can be seen in the graph that the maximum temperature read by the thermocouples is 670K (considering the average of all thermocouples), while that of the pyrometer is 772K. The deviation of pyrometer readings at the end of experiment are due to improper positioning of the device. At 16:20, all the briquettes' surface condition was gray.

For the same experiment, the variation of emissivity with temperature is shown in Fig. 6.17. Fig. 18 is the e-T plot for another experiment (MC23) performed under the same conditions.

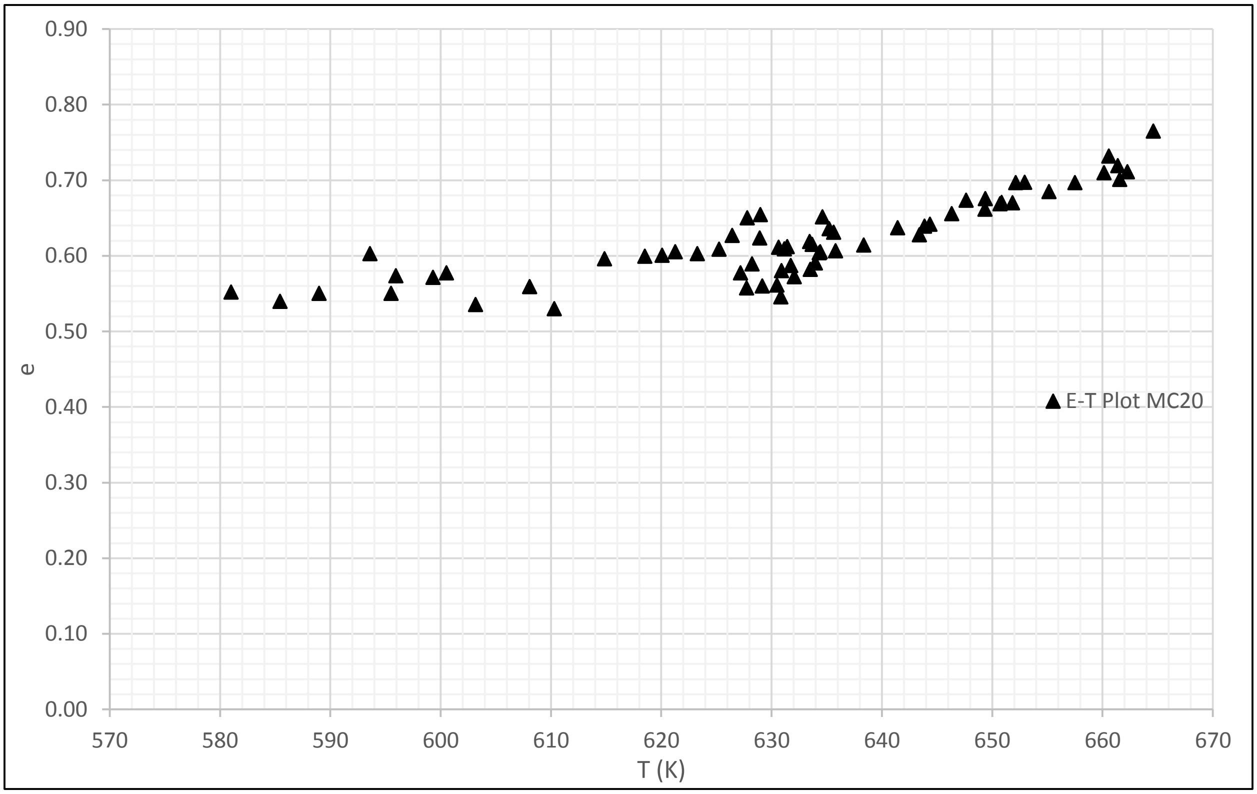

Figure 6. 17 Emissivity vs Temperature Plot of Black Surface Condition of Fuel 2- Experiment MC 20

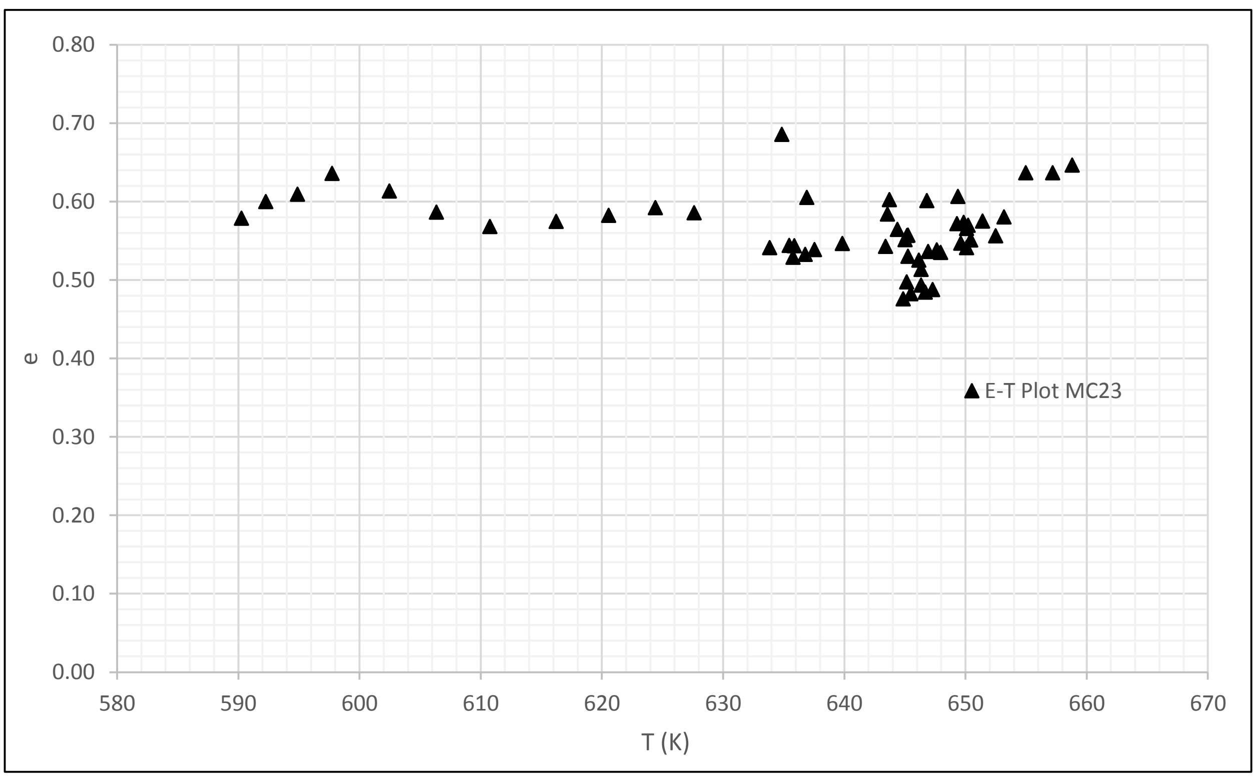

Figure 6. 18 Emissivity vs Temperature Plot of Black Surface Condition of Fuel 2- Experiment MC23

Considering all the experimental data, central averaging technique has been adopted and the resulting e-T plott is shown in Fig. 6.19 A curve fit is estalished for the same, which is included in the graph.

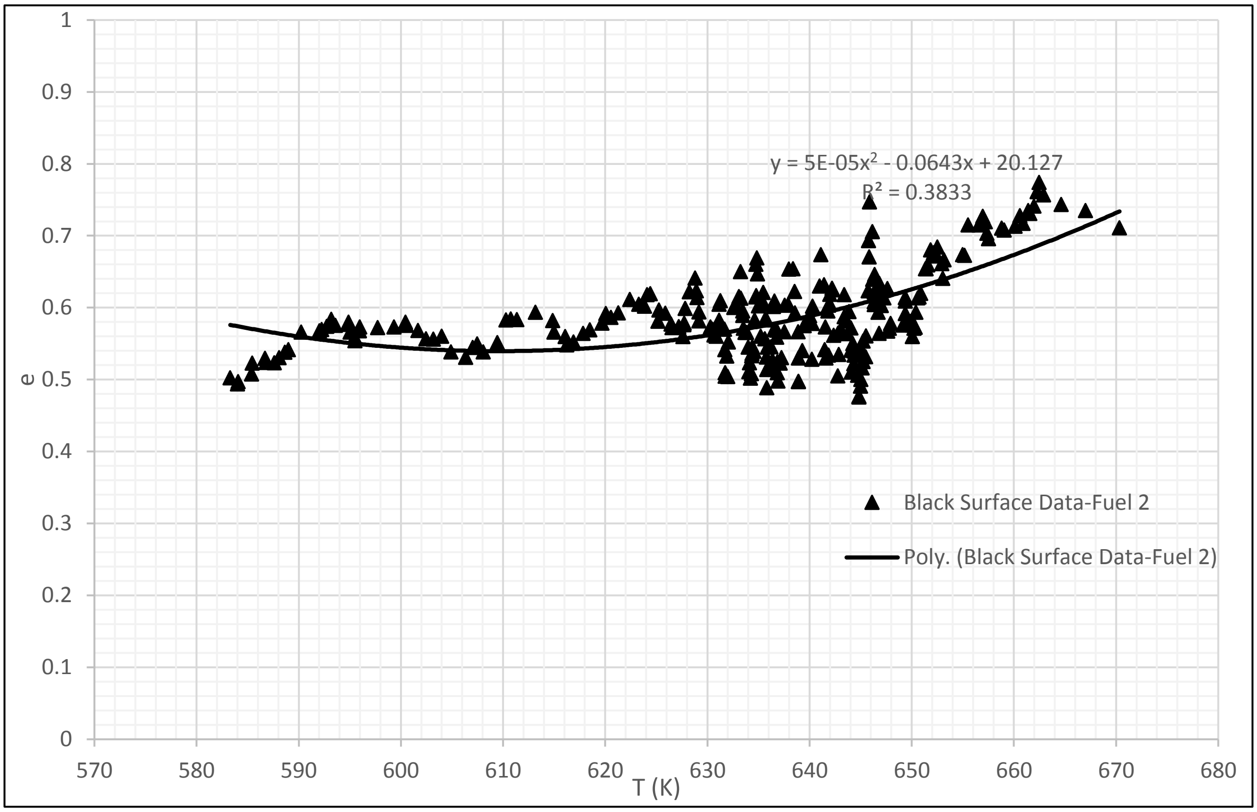

Figure 6. 19 Emissivity vs Temperature of Black Surface Condition of Fuel 2 (Kingsford Original Charcoal)

The data presented in the graph includes testing under different ambient conditions, hence the spread of emissivity is a bit higher.

It can be seen that the highest emissivity is 0.78 at 660K. The low emissivities at low temperatures is due to the low rate of reactivity of these charcoal briquettes. Moreover, the flame existed for a lesser time during the experiments, which lead to the development of more soot and fumes over the surface of charcoal. Generally the emissivity of charcoal is characterized collectively for the surface radiation and the emission spectra of the by products such as soot, fumes, and carbon monoxide. The latter being higher when compared to the Kingsford Matchlight charcoal resulted in low emissivities.

Experiments K05-K08 were performed to obtain the data on the gray surface condition. In the experiments, two regions of the combustion chamber were taken into consideration: Top briquette (one facing the air), and bottom briquette (core briquette). These can alternatively be considered as Flat and Volcano type of arrangements. The experiments on the bottom briquette resulted in high emissivity values at higher temperatures. Although experiments on the top briquette did not result in temperatures higher than 815K, their emissivity values were higher. Figs. 6.20 and 6.21 show the e-T plots for the top and bottom briquette experiments respectively.

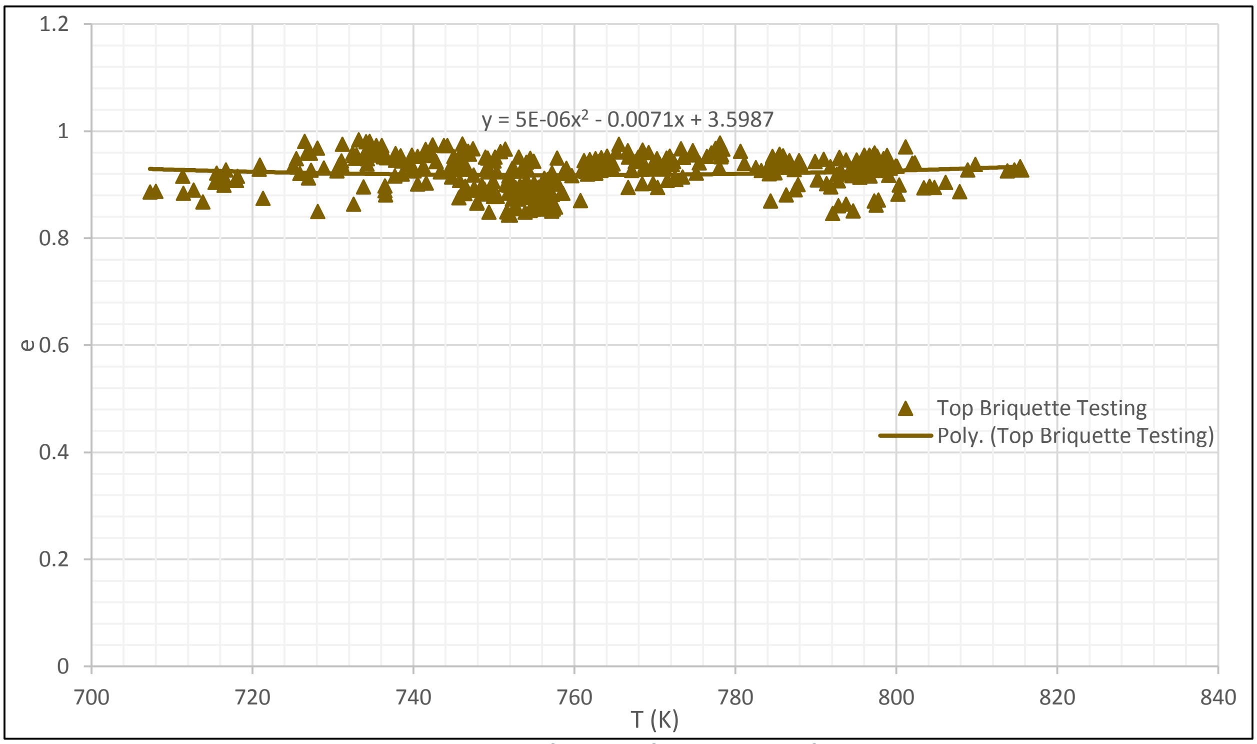

Figure 6. 20 Emissivity vs Temperature of Gray Surface Condition of Fuel 2 - Top Briquette Testing

In all the experiments, the thermocouples were fixed in such a way that they pass through the ash layer and read the surface temperature of the briquette throughout the experiment. The maximum emissivity is observed to be higher for the experiments with bottom briquette because of the flame and additive heat generated from the surrounding briquettes.

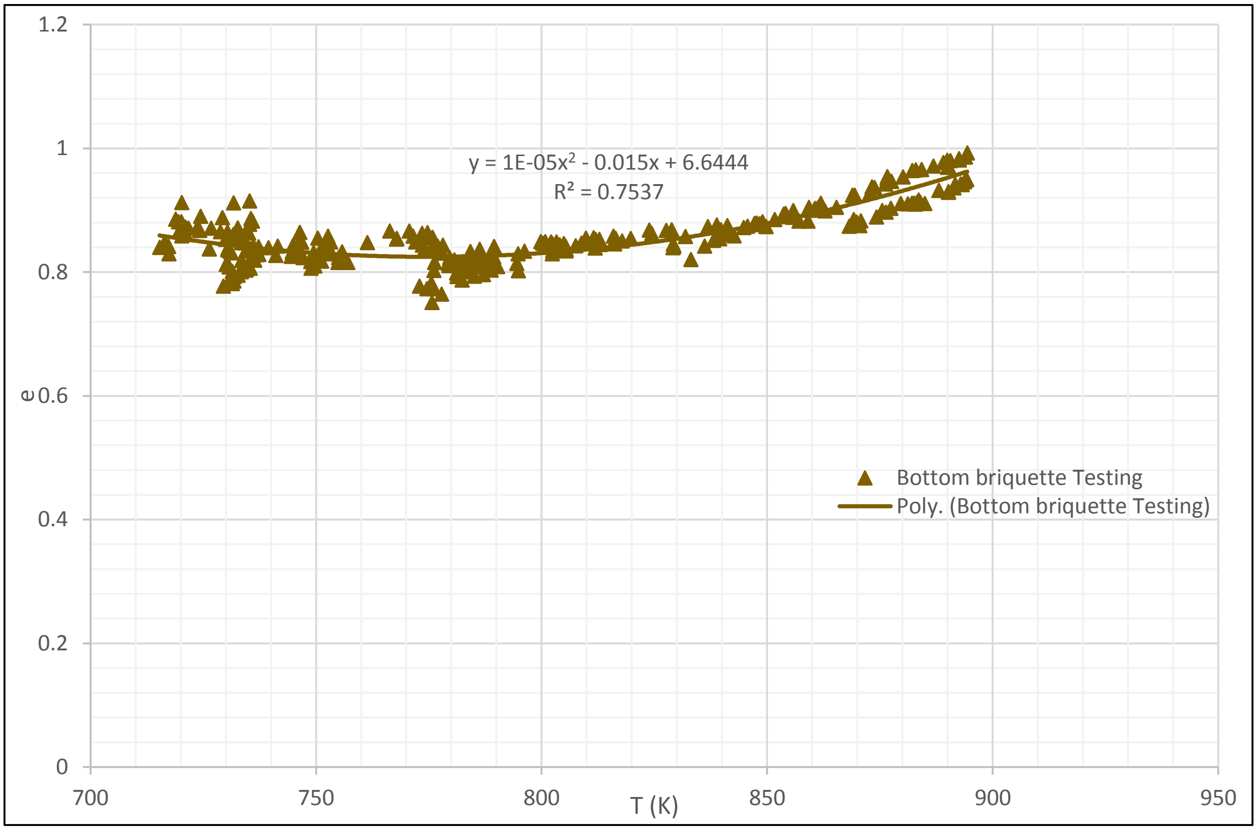

Figure 6. 21 Emissivity vs Temperature of Gray Surface Condition of Fuel 2 - Bottom Briquette Testing

Chapter 7
DISCUSSIONS

The variation of emissivity as a function of temperature is different for each fuel condition and each fuel type. The average emissivity is computed for all cases, indicated in the following Table 7.1

FUEL TYPE	SURFACE CONDITION	EMISSIVITY
Kingsford Matchlight Charcoal	Black	0.77339568584064
	Gray (Ash)	0.80016821997479
Kingsford Original Charcoal	Black	0.58913992988768
	Gray (Ash)	0.891936949

Table 7. 1 Summary of Average Emissivities of Different Charcoal types and Conditions

Due to the more available time of combustion in the Mini-Chimney, reliable data-sets on the black zone were achieved. The idea of seperating the black and ash conditions of charcoal is due to the fact that they have different emissivites. This is because emissivity is also dependent on the wavelength of the emitting media (which has not been the scope of study of this research). Moreover, the curve trend happens to be different for the emissivities of both conditions.

The thermocouple readings are generally affected by various sources such as convection due to air, radiation due to sun, and errors in positioning of them. A correction factor to account for the losses was formulated and shown in Appendix 2.

According to Planck's law of radiation, emissivity generally decreases with the increase in temperature. From the experimental results, it can be seen that this behavior is somewhat different.

For the gray conditions of charcoal, the emissivity is observed to increase with the increase in temperature. There are some interesting reasons to address this behavior. Due to the high heat gradients prevailing at the core of the combustion chamber, the emissivity behavior is deviating due to two reasons:

1. The thermocouples read higher when inserted inside a charcoal pile, than they would do for a single burning briquette. This is primarily because of the fact that there happens to be flame surviving on the briquettes which is almost not visible to the naked eye, especially during the daytime. To understand why the emissivities are so high at the heart of the combustion chamber, experiments were conducted after sunset, that is when the flame and flares are clearly visible. For sometime from the start of ignition of charcoal, flame exists on the briquettes. The visible flame apparently lasts for a lesser time than the real flame. This flame is complemented by the radiative heat from the surrounding briquettes, hence the briquette-of-focus has additive heat flux in its boundary layer. In a study by Smith [25], the rate of combustion of carbon per unit external surface area of the particle increases with temperature. This means that at high temperatures, there is immense chemical reactivity happening in the thermal boundary layer of charcoal. In addition to this, the flame zone is blue at the immediate proximity of the briquettes' surface, which is the highest temperature zone in a flame. Fig. 7.1 shows the test rig performed after sun set.

Figure 7.1 Experiment on KTG after sunset

2. The temperature of the briquette gradually drops right after the initial stage of combustion. This means that higher temperatures are experienced in the first half of combustion process than the second half. During the second half of the experiment, things are quite opposite to what is mentioned in point 1. The briquette-of-focus is greatly exposed to air instead of how it used to be during the first half of the experiment. Since the surface condition is ash, and the ash layer acts as an insulation for the rigid surface of the briquettes, the heat dissipation from the briquettes is reduced. As an impact of this, the emissivities are low at lower temperatures.

7.1 Uncertainty Analysis

When researchers make a measurement or calculate some quantity from raw data. It is generally assumed that some exact or true value exists based on how the measured (or calculated) variable is defined. Researchers reporting results usually specify a range of values that this true value is expected to fall within. The most common way to show the range of values is:

measurement = best estimate ± uncertainty

Uncertainty is defined as the quantification of the doubt about the measurement results. The uncertainty value specified for thermocouples is ± 2.2°C or ± 0.75% of reading and the same for the pyrometer is ± 2°C or ± 0.25%. The expression for emissivity from Eqn. 5.9 is

$$\varepsilon_{eff} = \left(\frac{T_C}{T_P}\right)^4$$

Uncertainty of any variable with degree > 1 is expressed as:

$$\delta a^n = n.\left(\frac{\partial a}{a}\right) \tag{7.1.1}$$

Applying Eqn. for T_c and T_p, we have

$$\delta T_C = 4\left(\frac{\partial T_C}{T_C}\right) \tag{7.1.2}$$

$$\delta T_P = 4\left(\frac{\partial T_P}{T_P}\right) \tag{7.1.3}$$

Where $\left(\frac{\partial T_C}{T_C}\right) = 0.75$ and $\left(\frac{\partial T_P}{T_P}\right) = 0.25$

The uncertainty in the given expression is expressed as

$$\Delta\in = \sqrt{(\delta T_c)^2 + (\delta T_P)^2} \tag{7.1.4}$$

From Eqns. 2 and 3, we have

$$\Delta\in = \sqrt{\left(4\frac{\partial T_C}{T_C}\right)^2 + \left(4\frac{\partial T_P}{T_P}\right)^2} \tag{7.1.5}$$

Substituting the uncertainty values in the equation, we get:

$$\Delta\epsilon = \pm 3.16\% \tag{7.1.6}$$

Considering the Figs. 6.9, 6.10, and 6.19 shown in Chapter 6, Figs. 7.2, 7.3, and 7.4 shown below are the same e-T plots including uncertainty bars calculated from Eqn. 7.1.6.

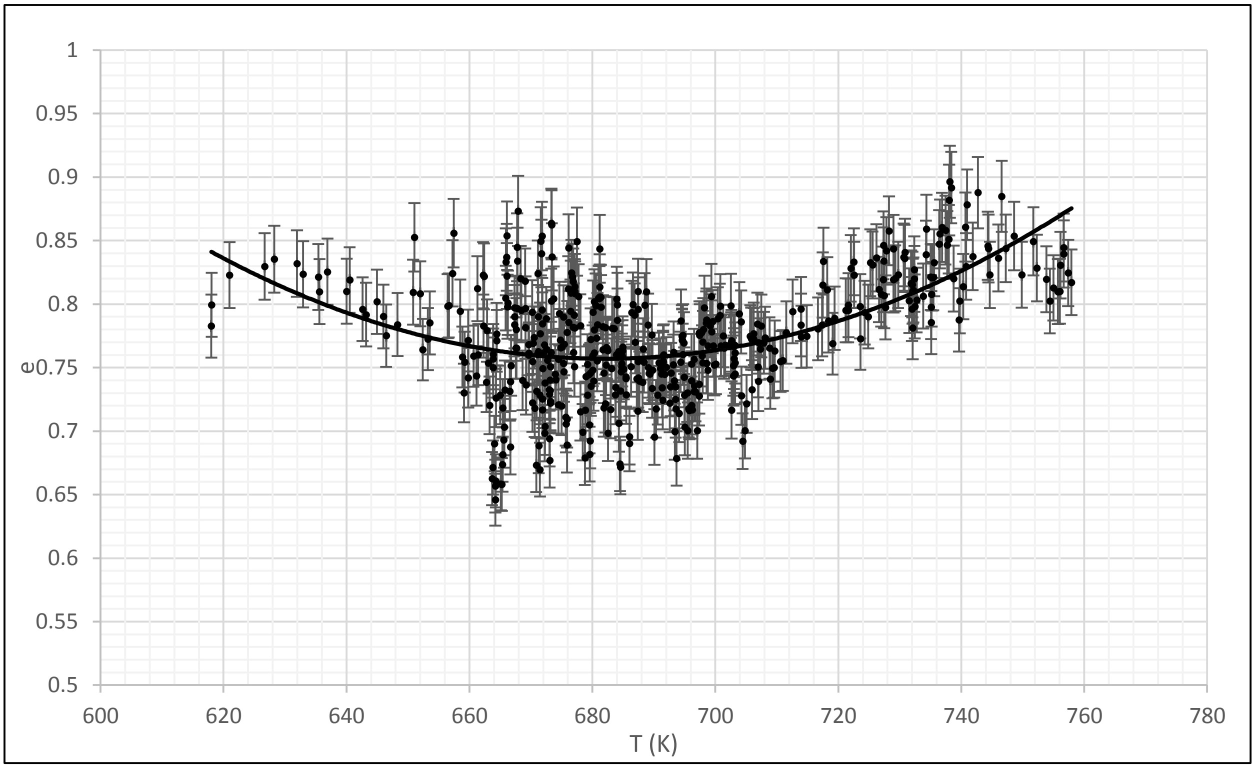

Figure 7. 1 Uncertainty Bars-Emissivity vs Temperature of Black Surface Condition of Fuel 1 (Kingsford Matchlight Charcoal)

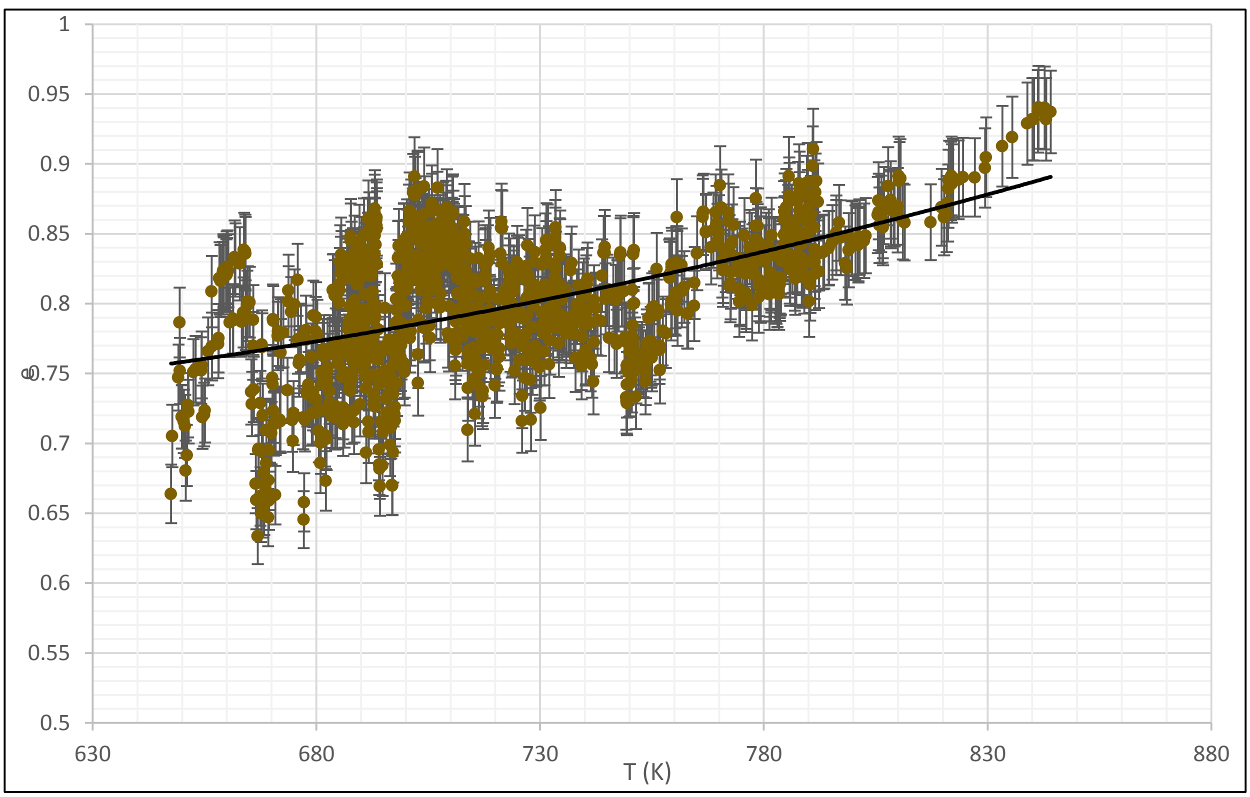

Figure 7. 2 Uncertainty Bars-Emissivity vs Temperature of Gray Surface Condition of Fuel 1 (Kingsford Matchlight Charcoal)

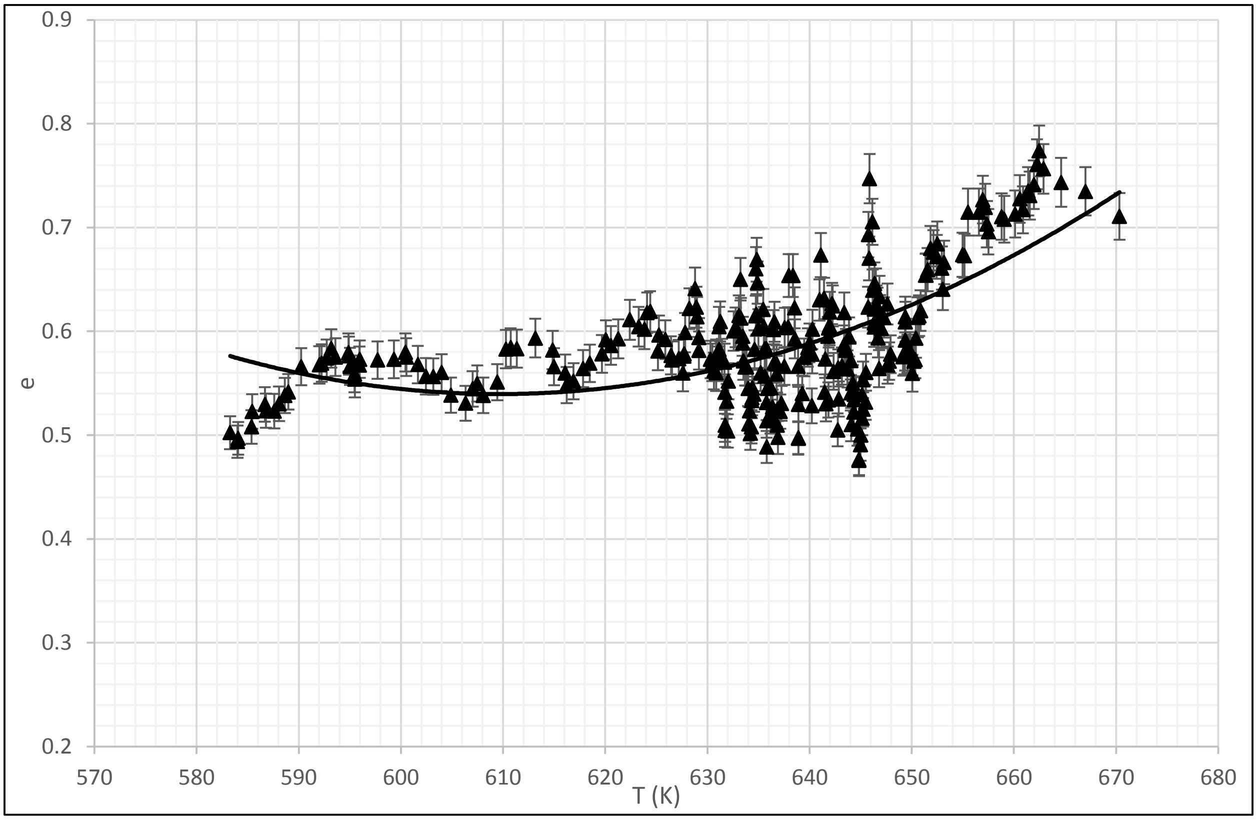

Figure 7. 3 Uncertainty Bars-Emissivity vs Temperature of Black Surface Condition of Fuel 2 (Kingsford Original Charcoal)

7.2 Challenges Faced

There were a couple of challenges faced while performing the experiments. They are discussed in detail below:

- Positioning of thermocouples – The positioning of thermocouples had to be tricky to obtain the measurements with least possible errors. The angle at which it is placed and the location on the briquette impacted the readings by a great amount. They had to be re-positioned whenever there was an ash collapse, or when they penetrated into the surface of the briquette, etc. The system of manually holding the thermocouples for the experiments on Mini-Chimney helped us a lot to overcome errors.

- Sorting out how to obtain the black zone data – Performing experiments on the KTG and LCG did not prove successful for achieving data on the black surface condition of the charcoal. This was due to the less time of combustion available during the black zone and also due to the fact that the flame existed for the most part, leading to erroneous temperatures. To overcome this problem, a Mini-Chimney was built at the sponsor's facility and we were able to achieve reliable data on the black surface condition.
- Controlling sun's radiation and sometimes wind – On a sunny day where the radiation from sun is pretty high, the emissivity of charcoal gets influenced because the pyrometer reads higher temperatures. This is primarily because the laser spot casted by the pyrometer is sensitive in reading temperatures collectively on that area of the briquette.
- Understanding the chemical reactions in the boundary layer of the briquette – The temperatures were observed to vary from one briquette to the other, from one day to another, and from one fuel to another. The chemical reactions happening in the boundary layer were not steady during the course of combustion. The nature of combustion is quite unsteady to relate the trends observed from one experiment and the other. The reasons as to why some of the deviations occur are discussed in the previous section of this chapter. The noise and irregularities in data was reduced by reproducing the results with central averaging technique.
- Difference in temperature gradients over the surface of the briquette as well as the height at which the thermocouples are placed – For a minute displacement of the tip of the thermocouples, we were able to observe a great difference in the temperature. This is due to the additive heat from the neighboring briquettes, and the change of surface condition on moving from one point to the other on a briquette. As the height of thermocouples

increased, the temperatures reduced. The temperatures were observed to be the highest at the layer immediate to the surface of the briquette, in other words, the boundary layer. To understand this, the heat flux values for all the surface conditions was calculated and its temperature variance was studied. The Radiative Heat Flux calculated for the different fuel conditions is shown in Figs. 7.4 – 7.6.

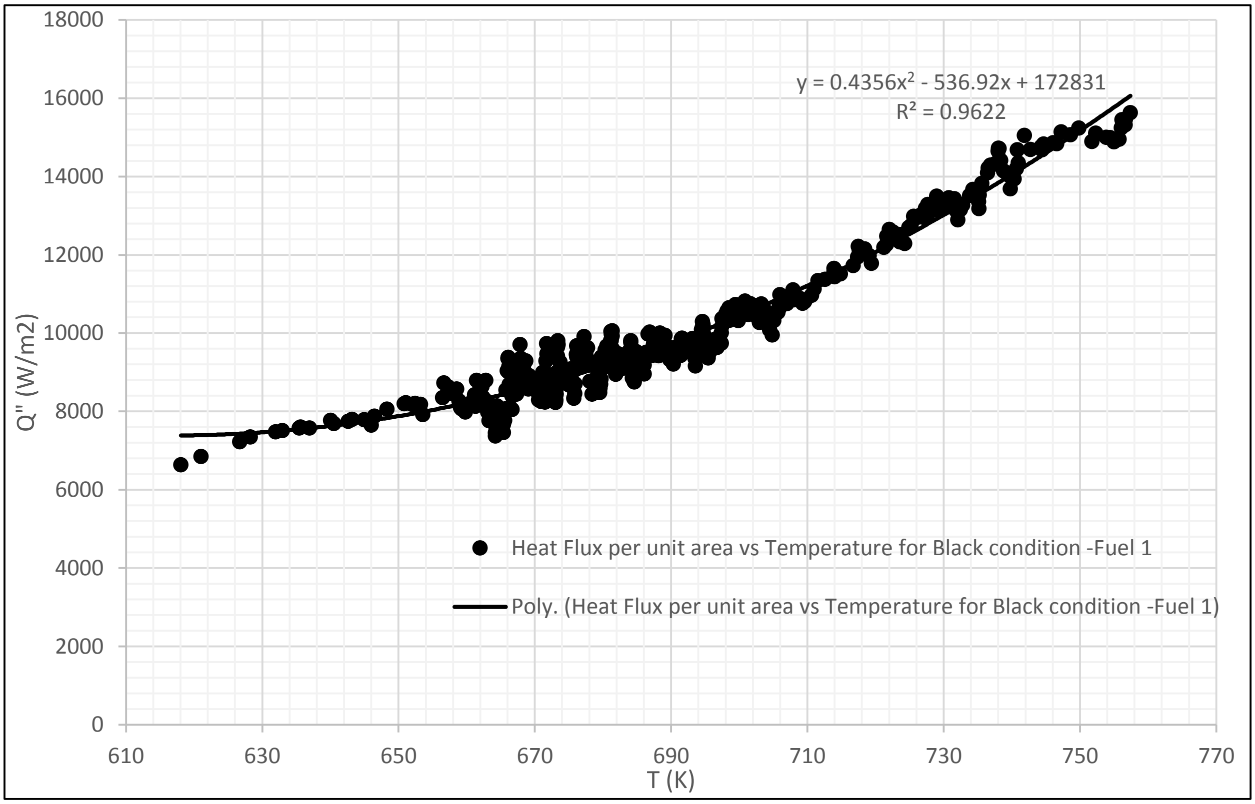

Figure 7. 4 Heat Flux per Unit Area vs Temperature for Black condition -Fuel 1

As we can see, the generated heat flux per unit area increases considerably with temperature. The slope is observed to be steeper in Fig. 7.5, which is for the gray surface condition. This indicates that the emissivity increases with the increase in temperature, as it is directly proportional to heat flux of the emitting media.

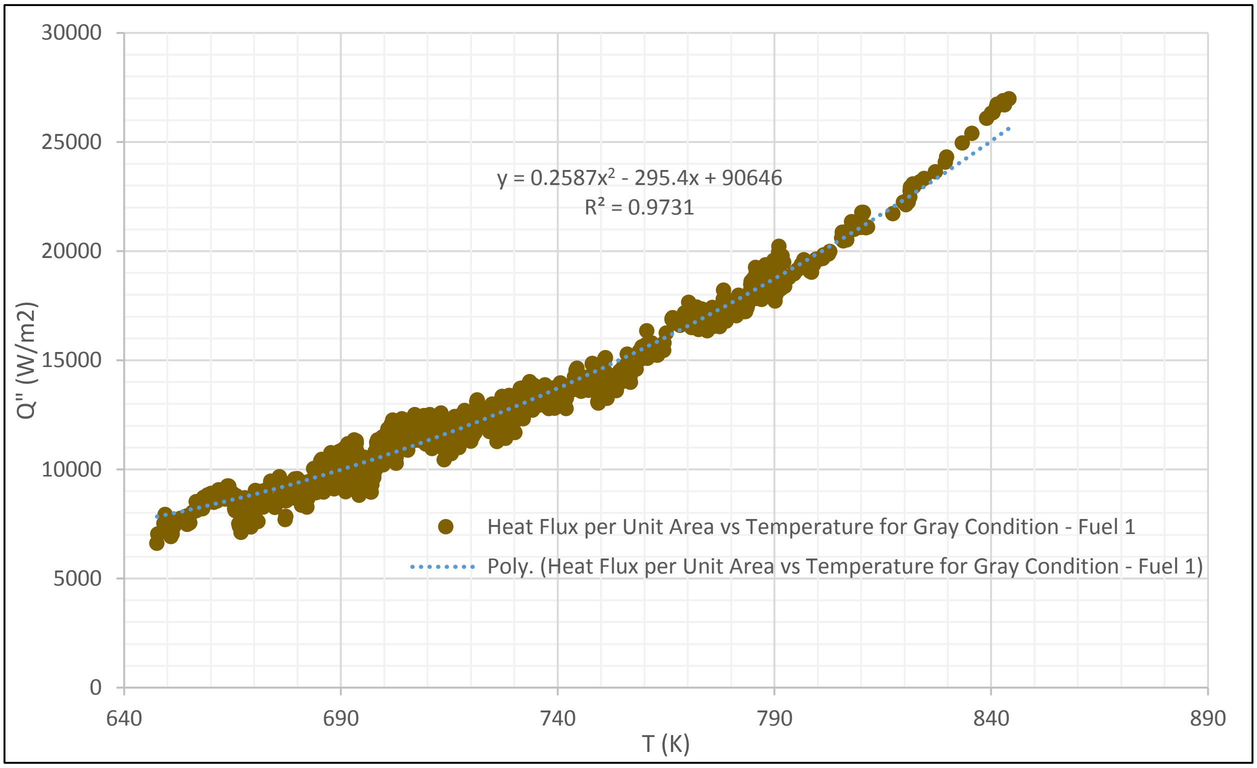

Figure 7. 5 Heat Flux per Unit Area vs Temperature for Gray Condition -Fuel 1

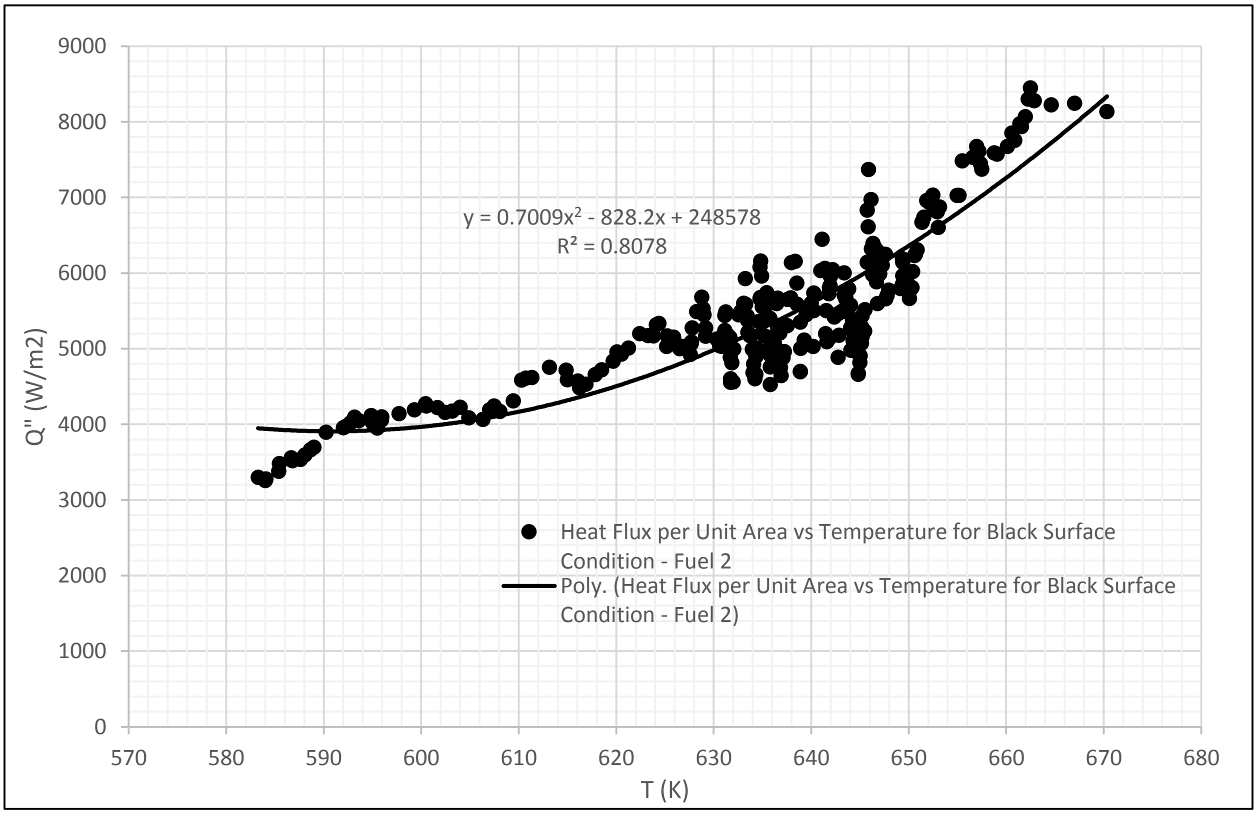

Figure 7. 6 Heat Flux per Unit Area vs Temperature for Black condition -Fuel 2

Chapter 8
CONCLUSIONS AND FUTURE WORK

The black and gray surface properties for Kingsford Matchlight, Kingsford Original and hardwood lump charcoal have been investigated. After obtaining the temperatures, emissivity has been determined by fitting a calculation curve to transient experimental data. The emissivity results are obtained with an uncertainty of 3.16%. These results can be used in the design of charcoal grills or any heat transfer application involving these fuels.

While obtaining the data for red surface conditions of charcoal, the emissivity values are high and erroneous because the core briquettes pick up enormous radiation from the surroundings. Whilst the pyrometer reads only the spotted temperature (black body power), the thermocouples read all the heat in the immediate proximity of their region of focus.

The same can be applied to any surface condition of the briquette. The emissivity values for ash-zone would be higher if we are looking at deeper layers of the combustion chamber. On the other hand, Emissivity values would be less on a briquette exposed to air. This can also be due to heat losses due to convection.

This study has been focused at examining the variation of emissivity with temperature for various conditions and types of fuels. The experiments were conducted in a natural draft uncontrolled ventilation set-up. Importance should also be given to the impact of wavelength of the emitting surface combined with temperature and the impact of convection on the radiative properties of charcoal.

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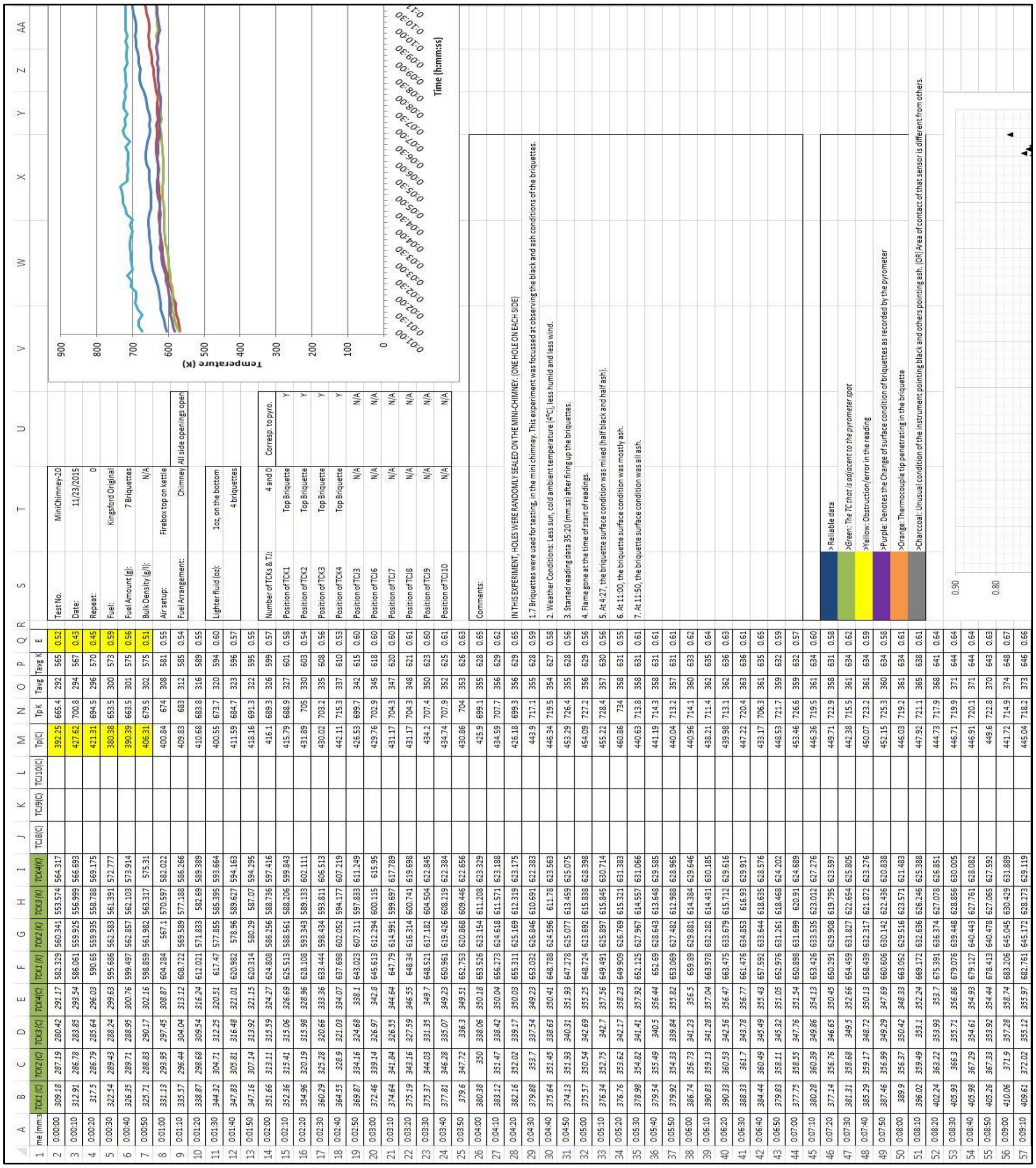
APPENDIX 1

Table A 1 below shows a sample test matrix for an experiment on MiniChimney.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	me (mm:s	TCK1 (C)	TCK2 (C)	TCK3 (C)	TCK4(C)	TCK1 (K)	TCK2 (K)	TCK3 (K)	TCK4(K)	TCJ8(C)	TCJ9(C)	TCJ10(C)	Tp(C)	Tp K	Tavg	Tavg K	E
2	0:00:00	309.18	287.19	280.42	291.17	582.329	560.341	553.574	564.317				392.25	665.4	292	565	0.52
3	0:00:10	312.91	286.78	283.85	293.54	586.061	559.925	556.999	566.693				427.62	700.8	294	567	0.43
4	0:00:20	317.5	286.79	285.64	296.03	590.65	559.935	558.788	569.175				421.31	694.5	296	570	0.45
5	0:00:30	322.54	289.43	288.24	299.63	595.686	562.583	561.391	572.777				380.38	653.5	300	573	0.59
6	0:00:40	326.35	289.71	288.95	300.76	599.497	562.857	562.103	573.914				390.39	663.5	301	575	0.56
7	0:00:50	325.71	288.83	290.17	302.16	598.859	561.982	563.317	575.31				406.31	679.5	302	575	0.51
8	0:01:00	331.13	293.95	297.45	308.87	604.284	567.1	570.597	582.022				400.84	674	308	581	0.55
9	0:01:10	335.57	296.44	304.04	313.12	608.722	569.589	577.188	586.266				409.83	683	312	585	0.54
10	0:01:20	338.87	298.68	309.54	316.24	612.021	571.833	582.69	589.389				410.68	683.8	316	589	0.55
11	0:01:30	344.32	304.71	312.25	320.51	617.47	577.855	585.395	593.664				400.55	673.7	320	594	0.60
12	0:01:40	347.83	305.81	316.48	321.01	620.982	578.96	589.627	594.163				411.59	684.7	323	596	0.57
13	0:01:50	347.16	307.14	313.92	321.15	620.314	580.29	587.07	594.295				418.16	691.3	322	595	0.55
14	0:02:00	351.66	313.11	315.59	324.27	624.808	586.256	588.736	597.416				416.1	689.3	326	599	0.57
15	0:02:10	352.36	315.41	315.06	326.69	625.513	588.561	588.206	599.843				415.79	688.9	327	601	0.58
16	0:02:20	354.96	320.19	315.98	328.96	628.108	593.343	589.133	602.111				431.89	705	330	603	0.54
17	0:02:30	360.29	325.28	320.66	333.36	633.444	598.434	593.811	606.513				430.02	703.2	335	608	0.56
18	0:02:40	364.55	328.9	321.03	334.07	637.698	602.052	594.177	607.219				442.11	715.3	337	610	0.53
19	0:02:50	369.87	334.16	324.68	338.1	643.023	607.311	597.833	611.249				426.53	699.7	342	615	0.60
20	0:03:00	372.46	339.14	326.97	342.8	645.613	612.294	600.115	615.95				429.76	702.9	345	618	0.60
21	0:03:10	374.64	341.84	326.55	344.64	647.79	614.991	599.697	617.789				431.17	704.3	347	620	0.60
22	0:03:20	375.19	343.16	327.59	346.55	648.34	616.314	600.741	619.698				431.17	704.3	348	621	0.61
23	0:03:30	375.37	344.03	331.35	349.7	648.521	617.182	604.504	622.845				434.2	707.4	350	623	0.60
24	0:03:40	377.81	346.28	335.07	349.23	650.961	619.426	608.219	622.384				434.74	707.9	352	625	0.61
25	0:03:50	379.6	347.72	336.3	349.51	652.753	620.868	609.446	622.656				430.86	704	353	626	0.63
26	0:04:00	380.38	350	338.06	350.18	653.526	623.154	611.208	623.329				425.9	699.1	355	628	0.65
27	0:04:10	383.12	351.47	338.42	350.04	656.273	624.618	611.571	623.188				434.59	707.7	356	629	0.62
28	0:04:20	382.16	352.02	339.17	350.03	655.311	625.169	612.319	623.175				426.18	699.3	356	629	0.65
29	0:04:30	379.88	353.7	337.54	349.23	653.032	626.846	610.691	622.383				443.9	717.1	355	628	0.59
30	0:04:40	375.64	351.45	338.63	350.41	648.788	624.596	611.78	623.563				446.34	719.5	354	627	0.58
31	0:04:50	374.13	351.93	340.31	351.93	647.278	625.077	613.459	625.075				453.29	726.4	355	628	0.56
32	0:05:00	375.57	350.54	342.69	355.25	648.724	623.692	615.838	628.398				454.09	727.2	356	629	0.56
33	0:05:10	376.34	352.75	342.7	357.56	649.491	625.897	615.845	630.714				455.22	728.4	357	630	0.56
34	0:05:20	376.76	353.62	342.17	358.23	649.909	626.769	615.321	631.383				460.86	734	358	631	0.55
35	0:05:30	378.98	354.82	341.41	357.92	652.125	627.967	614.557	631.066				440.63	713.8	358	631	0.61
36	0:05:40	379.54	355.49	340.5	356.44	652.69	628.643	613.648	629.585				441.19	714.3	358	631	0.61
37	0:05:50	379.92	354.33	339.84	355.82	653.069	627.482	612.988	628.965				440.04	713.2	357	631	0.61
38	0:06:00	386.74	356.73	341.23	356.5	659.89	629.881	614.384	629.646				440.96	714.1	360	633	0.62
39	0:06:10	390.83	359.13	341.28	357.04	663.978	632.282	614.431	630.185				438.21	711.4	362	635	0.64
40	0:06:20	390.33	360.53	342.56	356.47	663.475	633.679	615.712	629.616				439.98	713.1	362	636	0.63
41	0:06:30	388.33	361.7	343.78	356.77	661.476	634.853	616.93	629.917				447.22	720.4	363	636	0.61
42	0:06:40	384.44	360.49	345.49	355.43	657.592	633.644	618.635	628.576				433.17	706.3	361	635	0.65
43	0:06:50	379.83	358.11	345.32	351.05	652.976	631.261	618.468	624.202				448.53	721.7	359	632	0.59
44	0:07:00	377.75	358.55	347.76	351.54	650.898	631.699	620.91	624.689				453.46	726.6	359	632	0.57
45	0:07:10	380.28	360.39	349.86	354.13	653.426	633.535	623.012	627.276				446.36	719.5	361	634	0.60
46	0:07:20	377.14	356.76	346.65	350.45	650.291	629.908	619.795	623.597				449.71	722.9	358	631	0.58
47	0:07:30	381.31	358.68	349.5	352.66	654.459	631.827	622.654	625.805				442.38	715.5	361	634	0.62
48	0:07:40	385.29	359.17	348.72	350.13	658.439	632.317	621.872	623.276				450.07	723.2	361	634	0.59
49	0:07:50	387.46	356.99	349.29	347.69	660.606	630.142	622.436	620.838				452.15	725.3	360	634	0.58
50	0:08:00	389.9	356.37	350.42	348.33	663.052	629.516	623.571	621.483				446.03	719.2	361	634	0.61
51	0:08:10	396.02	359.49	353.1	352.24	669.172	632.636	626.246	625.388				447.92	721.1	365	638	0.61
52	0:08:20	402.24	363.22	353.93	353.7	675.391	636.374	627.078	626.851				444.73	717.9	368	641	0.64
53	0:08:30	405.93	366.3	355.71	356.86	679.076	639.448	628.856	630.005				446.71	719.9	371	644	0.64
54	0:08:40	405.98	367.29	354.61	354.93	679.127	640.443	627.761	628.082				446.91	720.1	371	644	0.64
55	0:08:50	405.26	367.33	353.92	354.44	678.413	640.478	627.065	627.592				449.6	722.8	370	643	0.63
56	0:09:00	410.06	371.9	357.28	358.74	683.206	645.045	630.429	631.889				441.72	714.9	374	648	0.67
57	0:09:10	409.61	372.02	355.12	355.97	682.761	645.172	628.273	629.119				445.04	718.2	373	646	0.66

S	T	U
Test No.	MiniChimney-20	
Date:	11/23/2015	
Repeat:	0	
Fuel:	Kingsford Original	
Fuel Amount (g):	7 Briquettes	
Bulk Density (g/l):	N/A	
Air setup:	Firebox top on kettle	
Fuel Arrangement:	Chimney	All side openings open
Lighter fluid (oz):	1oz, on the bottom	
	4 briquettes	
Number of TCKs & TJs	4 and 0	Corresp. to pyro.
Position of TCK1	Top Briquette	Y
Position of TCK2	Top Briquette	Y
Position of TCK3	Top Briquette	Y
Position of TCK4	Top Briquette	Y
Position of TCJ3	N/A	N/A
Position of TCJ6	N/A	N/A
Position of TCJ7	N/A	N/A
Position of TCJ8	N/A	N/A
Position of TCJ9	N/A	N/A
Position of TCJ10	N/A	N/A

Comments:

IN THIS EXPERIMENT, HOLES WERE RANDOMLY SEALED ON THE MINI-CHIMNEY. (ONE HOLE ON EACH SIDE)

1.7 Briquettes were used for testing, in the mini chimney. This experiment was focussed at observing the black and ash conditions of the briquettes.

2. Weather Conditions: Less sun, cold ambient temperature (4°C), less humid and less wind.

3. Started reading data 35:20 (mm:ss) after firing up the briquettes.

4. Flame gone at the time of start of readings.

5. At 4:27, the briquette surface condition was mixed (half black and half ash).

6. At 11:00, the briquette surface condition was mostly ash.

7. At 11:50, the briquette surface condition was all ash.

>Reliable data

>Green: The TC that is adjacent to the pyrometer spot

>Yellow: Obstruction/error in the reading

>Purple: Denotes the Change of surface condition of briquettes as recorded by the pyrometer

>Orange: Thermocouple tip penetrating in the briquette

>Charccoal: Unusual condition of the instrument pointing black and others pointing ash. (OR) Area of contact of that sensor is different from others.

Table A 1 Sample Test Matrix, showing all the data acquisition

APPENDIX 2

In order to account for the temperature losses due to convection, a correction for the thermocouple readings was formulated. The equation for the correction factor is given below:

$$Tcorr = 1.1562 * Tmeas + 183.4$$

Where, T_{corr} = Corrected temperature and T_{meas}= Measured temperature (Thermocouple readings in K). Fig. A2 1 below shows the measured and corrected temperature readings for an experiment on black surface condition.

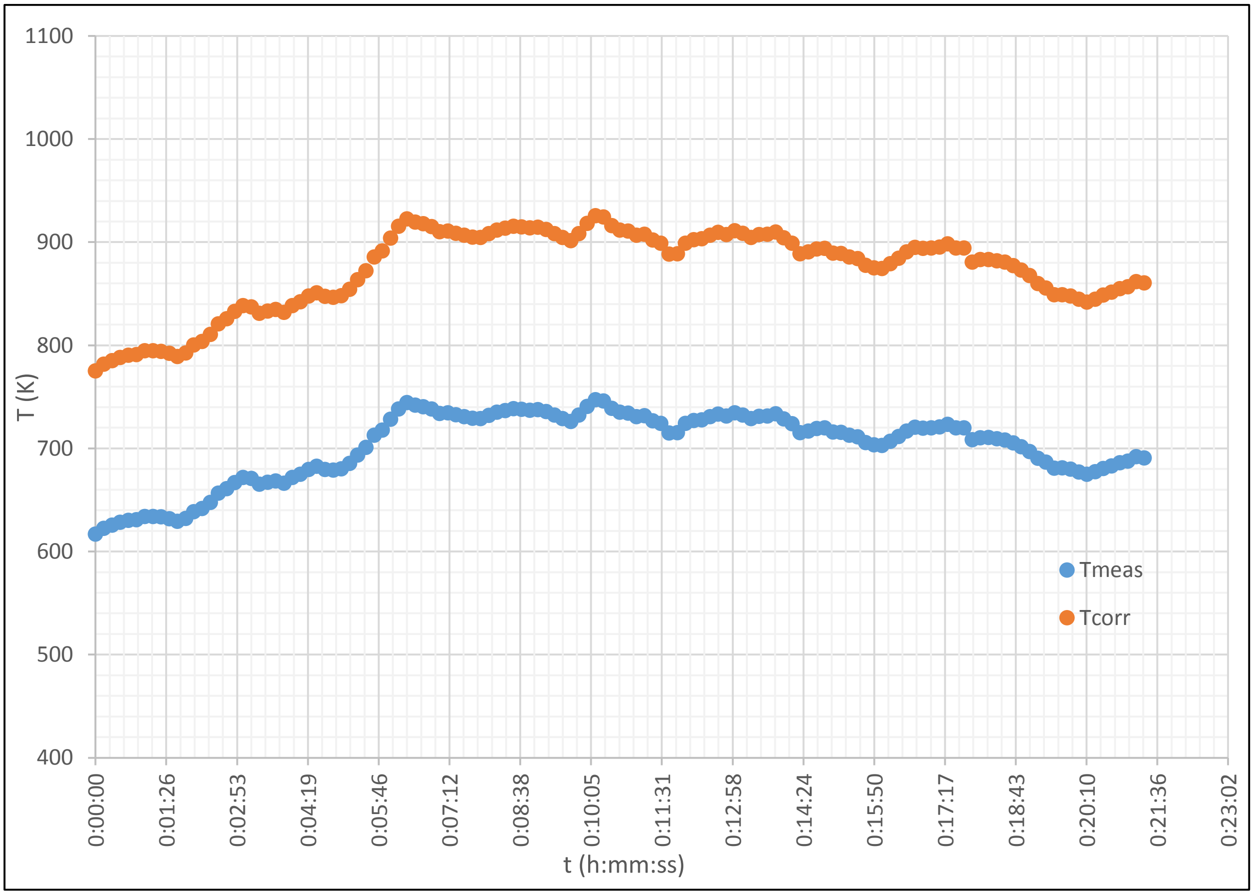


Figure A2 1. Comparison between the measured and corrected readings of the thermocouples