IDENTIFICATION OF THE OPTIMAL OPERATING PARAMETERS OF LOCALLY AVAILABLE COAL FOR USE IN PAKISTANI INDUSTRIES

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ABSTRACT

A parametric study intended to determine optimum burning parameters of locally available coal from mines in Darra Adam Khel is being reported. The coal samples were tested in a cyclone combustor using the pulverized coal combustion technique. Effect of mesh size, primary and secondary air velocity at various air fuel ratios was investigated to quantify the combustion performance by measuring the furnace temperature. Mesh size 200 was found to be readily combustible within the operating ranges, while tight control of the operating parameters was required to combust coal at mesh size 150. Optimum ranges of primary air and Air-Fuel Ratio are suggested for effective combustion. The study will help in effective utilization of indigenous coal reserves of Pakistan.

KEYWORDS: *Pulverized coal combustion, mesh size, air to fuel ratio, primary air*

INTRODUCTION

Energy shortage is the leading crisis of the world. Traditionally this energy has been obtained by consumption of fossil fuels. In 2012, the primary sources of energy consisted of 33.4% petroleum, 27.9% Coal, 22.6%, Natural gas, amounting to an 83.9% share for fossil fuels in primary energy consumption in the world (International energy Outlook, 2016). The World Energy demand is predicted to increase at an average rate of 1.4% per year (International energy Outlook, 2016), resulting in diminishing of the available reserves. In Pakistan, energy mix is highly dependent on two fuels i.e. Natural gas (approx. 47%) and Gasoline, while coal's share is only 7% (Pakistan Energy Year Book, 2012). Due to the depleting gas resources, gas shortages and rising energy prices, other options are now being explored by the consumers. Industries relying on gas as energy resource are the worst hit with reduced number of production days. To overcome the fuel shortages, some industries (e.g. plywood, cement etc.) have even tried to run their furnaces on non-sustainable options such as wood waste, tires and other hazardous materials.

Other resources of energy must be explored to overcome this crisis, and effective utilization of the available coal reserves is a plausible solution. Although coal has been extensively used in the world for energy production, little importance has been given to this resource in Pakistan despite having an estimated reserves of more than 186 billion tones, with 94% of the reserves identified at Thar coalfields. Pakistan's coal generally ranks from lignite (97%) to sub-bituminous (3%) and is not readily combustible, therefore, to cater domestic demand almost 4 million tons of coal is imported (Economic Survey of Pakistan, 2012-13). Coal fired power plants under construction will also be heavily relying on the imported coal, further adding to the import bills. Due to the acute shortage of Energy in Pakistan, the available reserves cannot be wasted anymore, and the need to devise methods for efficient usage of the reserves is imperative.

Recently, government and power generation sector have shown keen interest in the indigenous coal resources for its utilization in the electric power generation, cement and other related industries. Innovative methods are being devised to mine the coal reserves at Thar coalfields in parallel to pilot projects being undertaken on coal gasification. There is clearly a need to identify the right burning parameters for maximum utilization of the available reserves. Additionally, Pakistan cannot afford to continue relying on import of furnaces designed for the high quality coal, and efforts must be made towards developing indigenous methods for utilization of this energy resource.

Various methods for coal-fired power generation are well established; pulverized coal combustion (PCC) the most commonly used method. In PCC, the coal is

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ground (pulverized) to a fine powder, and is blown into the furnace through a series of burner nozzles, similar to fuel oil. Since coal is a low quality fuel compared to oil, its ignition and subsequent combustion is more complicated e.g. the particles must be 'small' enough for complete burnout to take place (bituminous coal requires 70-75% of the particles to be below 75 μm (Dong, 2010)). PCC is not appropriate for coal having high ash content. Traditional PCC systems require higher power, besides environmental issues such as escape of fly ash into the atmosphere as well as generation of the environmentally hazardous NOx and SOx. To overcome these issues, cyclone combustors have been proposed where in addition to primary air carrying the coal particles to the furnace, secondary air flow is provided in the tangential direction to induce swirls, and enhance the burning properties. Cyclone furnaces have been documented to handle a wide range of fuels including the low quality sub bituminous and lignite coal as well as the mineral rich anthracite. In general, Coal quality has an impact on the combustion characteristics, and selection of the most appropriate method of combustion (Central boiler plants, 1989). Composition of coal is determined by conducting Proximity and ultimate analysis (Gunn & Horton, 1995), which helps in calculating the theoretical stoichiometric A/F ratios, but since other parameters such as the mesh size, particle residence time etc. also control the combustion efficiency, and coal being a low quality fuel in terms of combustibility, the only approach towards identification of the right burning parameters is through practical testing of coal in a test rig. This will help towards identification of the most suitable technique and parameters for a particular grade of coal for maximization of the retrievable energy in an environment friendly manner.

The work reported here is an effort towards identification of the right burning parameters for coal mined from Darra Adam Khel. Specifically, effect of different mesh sizes at various A/F ratios was investigated to quantify the combustion performance. Details of the experimental investigation and the test rig are discussed next.

METHODOLOGY

The experimental investigation was conducted using a cyclone coal combustor. The furnace is a cylindrical compartment having a length of 40″ with an L/D ratio of 2. Coal is fed to the furnace using a hopper placed at a height of 10′ to avoid any coal dust. A screw conveyor operated by a 3hp, variable speed motor carries the coal particles towards the furnace. The coal feed rate can be varied between 1kg/min to 3kg/min. Primary air carrying the ground coal particles is supplied using a reciprocating compressor. To maintain the temperatures within the furnace within controllable limits to avoid bursting of the combustion chamber and minimize the formation of NOx, both air and water cooling systems were incorporated in the furnace. Water cooling pipes were arranged symmetrically around the circumference of cylinder, while air cooling pipes were arranged on the outer periphery of cylinder. Supply of the secondary air was controlled using a blower. As the air cools the furnace, it itself gets preheated and is fed back into the furnace as secondary air. In order to reduce the heat losses from the furnace to the surroundings, the pipes were studded to hold the refractory lining.

The objective of the current study was to identify the right burning parameters for effective utilization of the available coal. For this purpose, the mesh size, primary air and secondary air mass flow rates were varied for a particular grade of coal from a site in Darra Adam Khel. Proximate and ultimate analyses of coal under investigation provided in Tables 1 and 2 respectively showed that the coal was of the bituminous type, which shows that the coal of this site is better than coal available at other sites in Pakistan.

Table 1: Proximate Analysis of the Coal Sample.

Fixed Carbon	Moisture Content	Volatile Matter	Ash Content
71.6%	3.18%	16.75%	8.47%

Coal is not readily combustible at room temperatures; the ignition temperature varies from 315˚C to 450˚C depending on the coal type (Gupta, 2000). Therefore, the furnace was heated to a temperature of 450˚C using wooden stakes before feeding coal. Mesh sizes of 6, 16, 150 and 200 were investigated in the study reported here.

Table 2: Ultimate Analysis of the Coal Sample.

Carbon	Nitrogen	Hydrogen	Oxygen	Sulphur
79.2%	1.75%	4.42%	4.90%	1.20%

The corresponding particle sizes are given in Table 3.

Table 3: Mesh Number and their respective Sieve Sizes.

Mesh No	Sieve size (Inches)
6	0.1310
16	0.0460
150	0.0040
200	0.0029

Primary and secondary air supplies to the combustor were controlled by valves. Density of air was assumed to remain constant during all tests, and mass flow rates were calculated from the velocities measured using anemometers. A picture of the test rig is shown in Fig. 1.

Figure 1: The cyclone combustor test rig.

Statistical Experimental Design

Design of experiments (DOE) is a technique used to plan experiments, by conducting statistical analysis of relevant data (Ullah et al., 2016, Davies, 1979, Montgomery, 2008). This method is particularly helpful for large set of independent variables, and is capable of identifying the interaction of multiple factors on the dependant variable. The experimental runs in the current investigation were planned using fractional factorial design. In this technique, an orthogonal experimental plane is arranged to independently evaluate the main effect as well as interaction amongst the factors (Montgomery, 2008). Any presence of interaction is indicated by a change in the effect of a factor, while changing the levels of another factor. A fractional factorial experiment was carried out to evaluate the effects of the main factors involved in effective combustion of coal. A similar methodology for identification of manufacturing of coal briquettes has been reported in (Ullah et al., 2016). The factors and their relative levels are listed in Table 4.

Table 4: Factors Considered for Planning Experiments.

Factors	Min. Level	Max. Level	Levels Tested
Mesh Size(A)	6	200	6, 16, 150, 200
Primary Air (m/s) (B)	18	24	18, 20, 22, 24
Secondary Air (m/s) (C)	14	18	14, 15.5, 17, 16

Since there are 3 factors with 4 levels: Mesh Size (A) and Primary Air (B), and Secondary Air (C), the full factorial design required 64 experimental runs for all combinations of the levels of the factors investigated. However, variation of primary and secondary air independently resulted in variation of air to fuel ratio, whose effect has also been reported in the next section.

RESULTS AND DISCUSSION

The investigation reported here was directed towards determining the right burning parameters for locally available coal. For this purpose different mesh sizes, air to fuel ratio (AFR), % primary air and %secondary air were experimentally tested in a cyclone combustor, and effect of the changing parameters on furnace temperature was observed. The effect of coal particle size is discussed first.

Effect of Particle size

In order to 'prepare' coal for combustion, grinding of coal into small particles is required, such that the surface area in contact with air is increased to a level where coal is readily combustible. The selection of particle size represents a trade-off between the cost of power required for grinding coal and the resulting value added to the performance of the coal fired furnace. To examine the effect of particle size, four different mesh sizes i.e. 6, 16, 150 and 200 were tested in the furnace at various AFRs. A cursory look at Fig. 2 shows that larger particle sizes (Mesh 6 and 16) did not combust properly. Although furnace temperatures of up to 740°C were measured, these were due to the combustion of volatile matter, and show incomplete combustion. However, as the particle size of coal fed to the furnace was further reduced, combustion of carbon elements started, and much higher furnace temperatures were noted. Maximum furnace temperatures of 1165°C and 1220°C were measured for mesh 150 and 200 respectively, signifying lesser amount of un-burnt carbon compared to larger particle sizes. Since particle size is just one of the controlling variables, effect of primary and secondary air on coal combustion is discussed next.

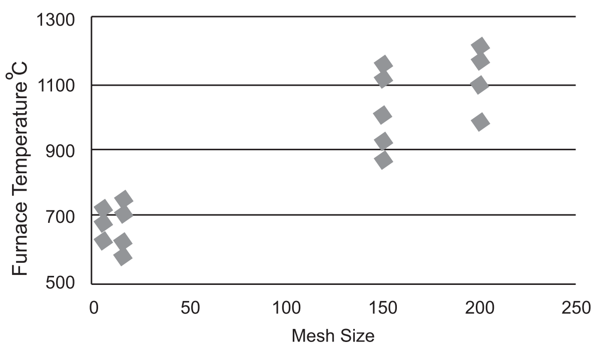

Figure 2: Effect of Mesh Size on Furnace Temperature.

Effect of Primary Air

Air that carries pulverized coal from the hopper to the cyclone combustor is termed as the primary air. The primary air supply to the combustor controlled by a regulatory valve was preheated to enable evaporation of surface and characteristic moisture in the coal. Tests were conducted at 4 different primary air velocities of 18, 20, 22 and 24m/s at four different values of secondary air velocities. Fig. 3 shows the effect of varying primary air supply on the furnace temperature for mesh size 150. It can be clearly observed that primary air fraction of the total air supply significantly affects the combustion characteristics of coal particles for this mesh size. The furnace temperature crossed the 1100°C boundary over a very narrow range of 8-9%.

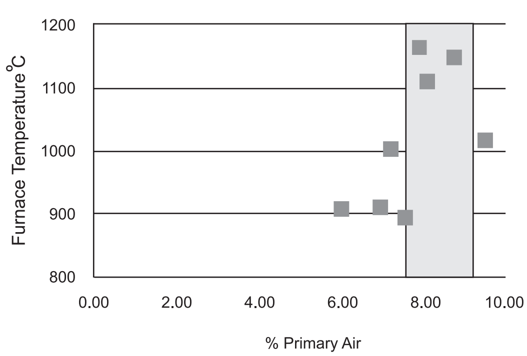

Figure 3: Effect of Primary Air on Furnace Temperature (Mesh Size 150).

However, as the particle size was further reduced (Mesh Size 200), the effect of varying primary air on combustion became less significant over the range tested, and temperatures higher than 1100°C were obtained in all tests conducted. A quick look at Fig. 4 elucidates that the increase of primary air had a positive impact on the combustion of coal. Temperatures close to 1200°C are clearly visible for primary air constituent higher than 7.1%. The furnace temperature shows a third order correlation with the primary air of the form

$$y = 24.912x^3 - 595.82x^2 + 4751.4x - 11435$$

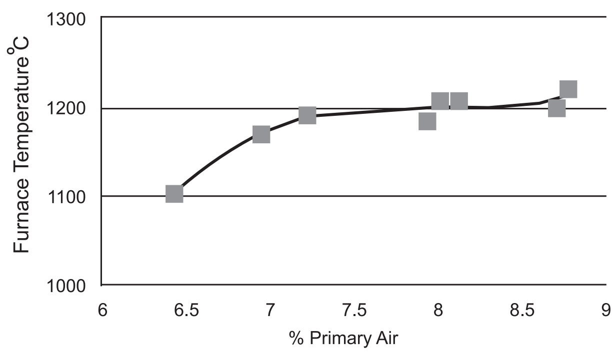

Figure 4: Effect of %Primary Air on Furnace Temperature (Mesh Size 200).

The results highlight that reduction of particle size was advantageous in two ways; In addition to easing out of the burning parameters for coal, the combustion efficiency measured in terms of furnace temperature also increased for the smaller particles tested.

Effect of Secondary Air

For efficient combustion, a swirling effect within the furnace is desirable, which is provided by the secondary air. This secondary air is generally the larger constituent of the total air supplied for combustion. Exact pattern of the swirl is dependent both on the physical arrangement of the combustor as well as the velocity at which air is injected into the furnace. Since the tests were conducted for a particular arrangement, the effect of secondary air velocity (and thus the mass flow rate) variations on combustion was investigated. The tests were conducted at 4 different secondary air velocity values of 14, 15.5, 17 and 18m/s. For mesh size 150, the plot of furnace temperature at different % secondary air is shown in Fig. 5. Since the primary air results were also presented as

% values, the results do not reveal further insight into coal combustion (Fig. 5 is the complement of Fig. 3). However, the experiments were designed such that variation of secondary air caused changes in the air fuel ratio.

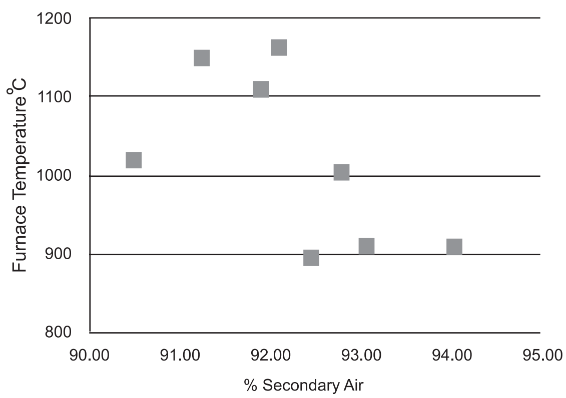

Figure 5: Effect of %Secondary Air on Furnace Temperature (Mesh Size 150).

Effect of Air to Fuel Ratio

The theoretical amount of air required for complete combustion termed as stoichiometric air to fuel ratio (A/F) is generally not sufficient for complete combustion. Absence of excess air to the combustion process will increase emissions consisting of unburned fuel, soot, smoke, and carbon monoxide. All combustion processes are therefore provided with excess air to ensure complete combustion. However, too much excess air also results in reduced combustion efficiency. Hence, both, determination of the optimal amount of air supply as well as the division of this air into primary and secondary air are important variables controlling coal combustion. The stoichiometric amount of air can be calculated by considering the products of combustion obtained on complete combustion using balanced chemical equations. For the sub bituminous coal under investigation, 9 kg of air was needed for every kg of coal supplied to the combustor.

Since the AFR varied due to the variation of either of primary and secondary velocity, the tests were therefore conducted at 16 different AFR. However, only the repeatable tests are reported in this paper. Fig. 6 shows the effect of AFR on furnace temperature. For a mesh size of 150, and at an AFR of approx. 20, furnace temperatures vary from 1000°C to 1150°C. This variation is due to the changes in the primary/secondary air component of the AFR. A similar observation can be made for an AFR of approx. 24, where temperatures of 1165°C and 910°C were noted for only slight variation of AFR. Hence, as discussed above, at a mesh size of 150, very tight control of the burning parameters is needed for proper coal combustion, and only slight variation of operating conditions can result in improper combustion of coal. An important finding of this work is that AFRs beyond 24 are harmful for coal combustion. It is important to mention here that all tests were conducted for more than 200% excess air. This value of excess air is significantly higher than the generally employed values available in literature. However, it must be recalled that the main function of secondary air, which forms a major component of the total air supplied is to generate swirls within the cyclone combustor, and all the supplied air is not involved in combustion. Mesh size 200, however lends itself for combustion much more easily and AFR within the range of 20-22 (222-244% excess air) as the optimal working range for coal combustion are clearly visible in Fig. 6. Provision of excess air beyond this range resulted in a decrease in combustion efficiency indicated by the furnace temperatures.

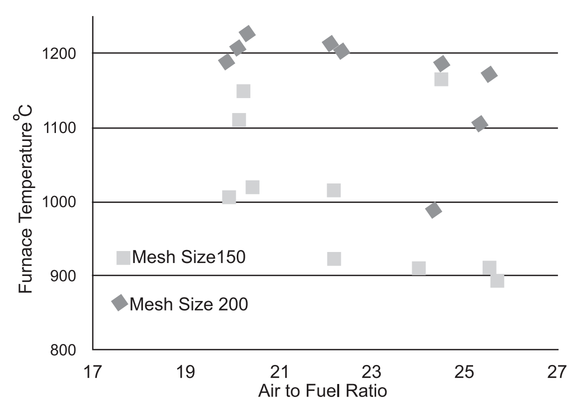

Figure 6: Effect of Air to Fuel Ratio on Furnace Temperature (Mesh Size 150 and 200).

CONCLUSION

Effective utilization of the available coal reserves of Pakistan is imperative due to the worsening energy crisis. However, this can only be achieved once the right burning parameters of the relatively low grade coal have been identified. The work reported in this paper was an effort towards this, where experimental investigation of coal from Darra Adam Khel mines in a pulverized combustor was carried out. Effect of mesh size, primary and secondary air velocity at various air fuel ratios was on the furnace temperature was investigated. Mesh size 200 was found to be readily combustible within the operating ranges, while tight control of the operating parameters was required to combust coal at mesh size 150. Maximum furnace temperatures of 1165°C and 1220°C were measured for mesh 150 and 200 respectively, while larger particle sizes were found to be little practical usage. An AFR range of 20-22 was noted to be the optimal working range for mesh size 200. A larger fraction of the primary air component had a positive impact on the combustion process for this mesh size as long as the AFR lied within the optimal range. The results highlight that reduction of particle size was advantageous in two ways; In addition to easing out of the burning parameters for coal, the combustion efficiency measured in terms of furnace temperature also increased for the smaller particles tested.

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