THERMO ECONOMIC ANALYSIS OF CO-FIRING BASED THERMAL POWER PLANT

THESIS

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In

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Submitted by

SANJEEV KUMAR

(ROLL NO. 801583022)

UNDER THE GUIDANCE OF
Prof. S.K. MOHAPATRA
Senior Professor & Head

DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR UNIVERSITY, PATIALA – 147004
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CERTIFICATION

I hereby certify that this thesis entitled, **"Thermo economic analysis of co-firing based power plant"** in fulfillment for the requirements for the award of Degree of Master of Engineering in Thermal Engineering submitted to Mechanical Engineering Department, Thapar University, Patiala, is an authentic record of my own work and is carried under the supervision of Dr. S.K. Mohapatra. The matter submitted via this thesis report has not been submitted for the award of any other degree to the best of our knowledge.

Date: 12/06/17

Place: Patiala

Sanjeev Kumar

(801583022)

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Supervisor:

Dr. S.K.MOHAPATRA

Head and Senior Professor

Thapar University, Patiala

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Sanjeev Kumar

M.E. – Thermal Engineering

801583022

Abstract

Co-firing option for utilizing biomass fuels is gaining popularity in developing countries like India. Fluidized bed combustion (FBC) system is widely used to effectively utilize co-firing option. In the present study, combustion and kinetic characteristics of a coal, biomass co-fired thermal power plant is studied. The biomass used is rice husk and blends of rice husk with coal varying in proportions of 20%, 30%, and 40% by weight of rice husk were prepared. TG and DTG analysis was then carried out on both samples and their combustion and kinetic parameters were analyzed. It was found that co-combustion of coal and rice husk blends consisted of mainly three stages i.e. moisture evaporation, volatile release and char combustion. Further, the kinetic parameters obtained by using Coats-Redferns method provided the best suitable solid state mechanism that could be used for kinetic analysis. The results obtained are in agreement with TG and DTG data.

Further exergy analysis of co-fired boiler is carried out and results show 55.46 MW of exergy destruction in boiler along with 35.1% of exergy efficiency. Co-firing with biomass fuel is not an easy task; there are some issues of slagging, fouling and bed agglomeration. These problems greatly affect the economics of plant. In this present study, bed agglomeration and economic analysis is also done of 20MW FBC boiler based thermal power plant. Bed agglomeration is also depicted from free swelling index (FSI). FSI provides the measure of sticky nature of particles in FBC boilers. Along with samples collected from plant (Rice husk and coal (S-III)), one bagasse sample and two Indian coal samples (S-I from Bathinda thermal power plant, S-II from Yamuna nagar thermal power plant) were used and their blends with each biomass fuel were prepared.

Experimental results have shown no signs of bed agglomeration for all the samples. Bagasse and

S-I, S-II shows sticky nature when tested for FSI and can form large agglomerates. Economic analysis shows the huge effect of sale rate on the profit share of plant. Break-even point in terms of operating hours has been calculated and various means of enhancing the profit has been suggested.

Key words: Agglomeration; Break-even; Co-firing; Exergy; Thermo-gravimetric.

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Nomenclature

CO_2	Carbon dioxide
Kt/yr	Kilo ton per year
CH_4	Methane
SiO_2	Silicon oxide
kWh	Kilowatt hour
Mt	Metric ton
T_v	Volatile release onset temperature
T_o	Ignition temperature
T_m	Temperature at maximum weight loss rate
$T_{burnout}$	Burnout temperature
m_o	Initial mass of sample
m_f	Final mass of sample
m_t	Mass of sample at time t
k	Reaction constant
E_a	Activation energy
R	Universal gas constant
T_o	Initial temperature
B	Heating rate
R^2	Correlation factor
a_o	Area of orifice (cm^2)
A1, A2	Area of section 1 and 2 in model (cm^2)
A_T	Total area of fluidized bed (cm^2)

d_o	Actual diameter of orifice (cm)
e_{mf}	Bed voidage at minimum fluidization
e_B	Average bubble voidage in section 1 of model
g	Acceleration due to gravity
h_g	Height of jet (cm)
H	Bed height at minimum fluidization (cm)
N	Total number of orifices
N_1/N	Fraction of active number of holes
U	Total superficial gas velocity (cm/sec)
P_{av}	Average pressure in distributor
P_B	Pressure drop across fluidized bed
P_D	Pressure drop across the distributor
T_b	Absolute bed temperature (K)
U_1, U_2	Superficial gas velocities across section 1 and 2
U_{mf}	Minimum fluidization velocity (cm/sec)

Greek symbols

α	Mass loss ratio
g(α)	Integral function of conversion
ρ_g	Density of fluidized gas (g/cm^3)
ρ_s	Density of solids in bed (g/cm^3)
∅	Orifice density

Acronyms

MW	Mega Watt

FBC	Fluidized bed combustor
TGA	Thermo-gravimetric analysis
SEM	Scanning Electron Microscopy
EDS	Energy Dispersive Spectroscopy
VM	Volatile matter
FC	Fixed carbon
HHV	Higher heating value
DTG	Differential thermo gravimetric
CHP	Combined heat and power
CV	Control volume
TPH	Tons per hour
AFT	Ash fusion temperature
FSI	Free swelling index

CHAPTER 1

INTRODUCTION

The combustion of fossil fuels results in combustion products which causes pollution and are major threat to our atmosphere and hence dangerous to mankind. Also, fossil fuel reserves are depleting day by day. The main pollutant from fossil fuels is carbon dioxide which is released mostly from fuels used for electricity generation. There are numerous emission reduction options available for industries. Some methods are applicable on site while some are still in initial stage of evolution. CO_2 sequestration technology represents the future dream of CO_2 emissions-free power generation sector, but sequestration technology will take lot of time to come to the power sector market. Also, cost of CO_2 sequestration is very high ranging from 40-60 US$/ton of CO_2 that too hanging on the kind of plant (Byrer et al. 2009, IEA 2009). This is a huge economic load on the particular industry, and may be potentially increase the cost of electricity generated by as much as 60%.

Today developing countries are demanding more electricity which results in more use of fossil fuels and hence results in more threat to our atmosphere until some alternatives are made available. To eliminate the use of these highly pollution causing fuels one should go for clean energy and less pollutant emitting fuels which will help to conserve our environment. There are many fuels which can be used to substitute fossil fuels like biomass fuels. The main advantage of using biomass as fuel is that it is carbon neutral fuel as it only emits carbon dioxide which it takes at the time of its growth for respiration. Also, biomass has a large potential all over the world which makes it affordable and easily available for use as a fuel. In last few years biomass is one of the most used and promising fuel for developing and under develop countries.

The main source of biomass fuel is crops. The residue part left obtained before and after processing of crops has a potential to be used as a fuel. Countries where large amount of crops are produced are using residues for power generation. In the Asia- Pacific region, 56% of world population gets food from number of crops produced there and hence more residues are available for power generation (Natrajan et al. 1998). Biomass based power generation is carried out in India, where states like Punjab, Uttar Pradesh and Maharashtra are known for high crop production. Punjab has massive biomass resources from different crops production system and agro industries. Energy consumption from biomass is carried out in India from ancient times when people use cow dung cakes and woods for preparing food. Recently, according to Ministry of new and renewable energy of India, as on 28th Feb, 2017 renewable energy contributes to 15.86% of total power generation. Out of 15.86% only 16% is contribute by biomass fuels. Table 1.1 shows India has biomass residue of 511041.39 kilo ton per year from various types of crops. From this huge amount of biomass residue power of high potential around 50,000 MW can be generated per year. These biomass fuels are renewable and as discussed above are less pollution causing than fossil fuels. Also, they are easily available in nature. The areas where there is a huge demand of electricity and there is a presence of these types of fuels, it proves to be promising to use these fuels. Its utilization depends upon availability, transportation and storage. Utilization of biomass fuel for power generation can be done in many ways like direct burning, gasification and co-firing with coal. Out of above mentioned ways, co-firing is considered to be most effective and efficient process.

Table 1.1: Biomass potential for power generation in India. (Kumar et al. 2015)

Crop	Residues	Biomass potential (Kt/yr)	Crop	Residues	Biomass potential (Kt/yr)
Arecanut	Fronds, husk	1,000.80	Meshta	Stalks, leaves	1,645.50
Arhar	Stalks, husk	5,734.60	Moong	Stalks, husk	762.5
Bajra	Stalks, cobs, husk	15,831.80	Moth	Stalks	17.8
Banana	Residue	11,936.50	Mustard	Stalks, husk	8,657.10
Barley	Stalks	563.2	Niger seed	Stalks	94
Barseem	Stalks	71.6	Oilseeds	Stalks	1,143.10
Black pepper	Stalks	29.1	Onion	Stalks	66.5
Cardamom	Stalks	43.6	Others	Others	0.34
Cashew nut	Stalks, shell	189.4	Paddy	Straw, husk, Stalks	169,965.10
Castor seed	Stalks, husk	1,698.60	Peas and beans	Stalks	27.4
Casuarina	Wood	211.8	Potato	Leaves, stalks	887.3
Coconut	Fronds, husk, pith, shell	10,463.60	Pulses	Stalks	1,390.40
Coffee	Husk, pruning and wastes	1,591	Ragi	Straw	2,630.20
Coriander	Stalks	188.3	Rubber	Primary and secondary wood	2,492.20
Cotton	Stalk, husk, bollshell	52,936.50	Safflower	Stalks	539.3
Cow gram	Stalks	48.5	Sunnhemp	Stalks	14.1
Cumin seed	Stalks	182.6	Sawan	Stalks	0.22
Dry chilly	Stalks	268.6	Small millets	Stalks	600.1
Dry ginger	Residue	5.3	Soyabean	Stalks	9,940.20
Eucalyptus	Stalks	162.8	Sugarcane	Tops and leaves	12,143.90
Gram	Stalks	5,440.60	Sunflower	Stalks	1,407.60
Groundnut	Shell, stalks	15,120.40	Sweet potato	Stalks	12.8
Guar	Stalks	233.3	Tapioca	Stalks	3,959
Horse gram	Stalks	191.3	Tea	Sticks	909.8
Jowar	Cobs, stalks, husk	24,207.80	Til	Stalks	1,207.70
Kesar	Stalks	9.4	Tobacco	Stalks	204.8
Kodo millets	Stalks	3.13	Turmeric	Stalks	32.3
Linseed	Stalks	86.3	Urad	Stalks, husk	924.9
Maize	Stalks, cobs	26,957.70	Wheat	Stalks, panicle	112,034
Masoor	Stalks	600.3	**Total**		**511,041.39**

1.1 Co-Firing

Co-firing is the co-combustion of two or more types of fuels with coal in the same boiler or in different boilers in some cases. For this co-combustion many type of biomass fuels are used usually with coal. Co-firing should not be confused with the combustion of multiple fuels in boilers designed especially for burning of multiple fuels. The basic difference between such a type of combustion and co-firing is that co-firing is achieved in a boiler originally designed to burn only a specific kind of fuel. In common words, co-firing with biomass can be thought of as the process of partial replacement of biomass fuel with coal in coal-fired power plant boilers. Co-firing is likely-looking technology and it is gaining popularity around the world (Loo et al. 2002). It offers many advantages in the energy sector; some of which are discussed here:

1.2 Advantages of Co-firing

- Co-firing can be implemented in ongoing coal fired boilers. It causes les investment and less time to switch on the co-firing mode on existing coal fired boiler. Also no extra investment is required to dispose the ash generated from burning of biomass. Therefore, it is a quicker method of expanding the use of biomass based renewable energy in the energy sector.
- As discussed earlier, biomass is carbon neutral fuel so it emits on combustion the same quantity of CO_2 as is it takes during its breathing. Therefore, co-firing biomass fuel with coal does not contribute to the increasing global warming effects. Hence, biomass co-firing can help reduce overall CO_2 emissions.
- Due to low sulphur and nitrogen content in most biomass fuels than coal, they emit less NO_x and SO_x emissions and this is the main advantage keeping atmosphere in mind.
- A study conducted by (Sami et al. 2001) and (Demirbas 2003) reveals that co-firing biomass fuel lower the risk of greenhouse effects by minimizing CH_4 release from otherwise landfilled biomass. Because biomass residue is a major source of methane (CH_4) which is considered as 21 times more productive than CO_2 in terms of greenhouse gas impact.
- Today, a number of methods and processes are there for reducing global warming effects. However, co-firing is the least costly option to mitigate these harmful gases

(Basu et al. 2011).

- Generally, the output (efficiency) of power plants that uses only biomass fuels is in the range of 18 to 22% which is nothing in front of large coal units. Moreover, it was found that co-firing biomass fuel at 3-5% could causes a slight decrease in boiler efficiency (less than 1%) (Loo et al. 2008).
- Co-firing option is very flexible for using different types of fuels. If there is no biomass supply then also plant can work at 100% coal firing. This is more feasible in areas where the biomass supply can be seasonal.

1.3 Technical issues with co-firing:

- Biomass fuels have different properties than coal and these properties vary from fuel to fuel thus each of these properties needs to be considered while co-firing.
- Availability of biomass fuels is very crucial. It should not affect food production or tropical rain forest. Transportation costs play a large role in economics of co-firing.
- Some biomass fuels needs to be handled and stored properly which can increase the cost co-firing for those fuels.
- Moisture content is generally very high in biomass fuels than coal which can affect the fuel conversion rate.
- Slagging and fouling problems can largely affect the boiler performance resulting in lowering the overall efficiency.
- Ash related problems like bed agglomeration can result in de-fluidization.

1.4 Global status of co-firing:

World electricity demand is increasing day by day and which results in more consumption of fossil fuels. This results in depleting fossil fuel reserves and at the same time increasing severe environmental problems. Renewable energy generations options to be employed to cater these problems. According to world energy council report renewable based power generation is only 23% of worldwide power generation (world energy council). Out of 23% share of renewable power, less than 9% is from biomass fuels. Countries having huge biomass reserves are focusing on using biomass as a fuel for power generation.

Biomass co-firing began in the 1980s in Europe and USA and interest in co-firing has grown rapidly in last decade. At present, out of all renewable energy technologies, co-firing is considered as widely used and growing technology. Fig. 1.1 shows the countries using biomass as a partial replacement of coal.

At present over 230 power and combined heat and power (CHP) plants are working on co-firing technology. Most of these plants are situated in Europe and United States of America with capacity varying from 50-600 MW (Baxter et al. 2004).

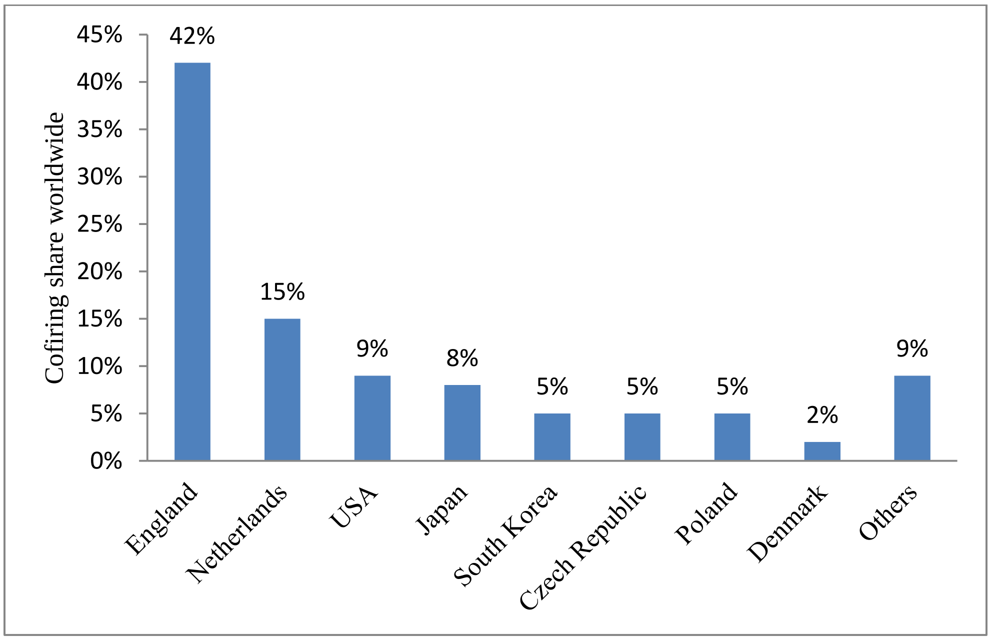


Figure 1.1: World co-firing fleet using biomass as a secondary fuel (Baruya 2015)

1.5 Technology options for co-firing

Biomass co-firing is gaining popularity with more than 150 installations worldwide. The biomass fuel used in these installations may vary depending on the location. To employ co-firing technology these units may be broadly classified under following three types:

1. Direct co-firing
2. Parallel co-firing
3. Indirect co-firing

In all above options, the used biomass fuel replaces same amount of coal (on energy basis or weight basis), and provides the straight reduction of CO_2 and NO_x emissions (Armesto et al. 2002, Sims et al. 2003, Ninimiya et al. 2004, Theis et al. 2006, Bernds et al. 2007). The selection of the type of co-firing option to be used relies on a number of biomass and coal fuels to be used and site specific factors. Brief descriptions of the above mentioned co-firing options are presented here.

1.5.1 Direct co-firing

Direct co-firing is widely used and is very economical co-firing configuration. It consist the combustion of biomass fuel and coal at same time and in the same furnace. Also, for burning same or separate burners and mills can be used for biomass fuel depending on the type and properties of biomass fuel. (Basu et al. 2011) proposed following four methods are presented by which direct co-firing can achieved in pulverized coal boilers.

- In the first method, the biomass fuel and coal are mixed together in the fuel management systems and then this blended mixture is transferred into the furnace directly. This is the utmost common and cheapest option; however, there is a limit on the use of biomass fuel, very low percentages can be used usually <5%, depending on the pulverize type (Tillman 2000). This low percentage of biomass fuel can be used only in conservative wall or corner-fired boilers (Maceijewska et al. 2006). Also this first option is used for selected number of biomass fuels. Some other biomass fuels like Olive or palm kernels, sawdust and cocoa shells can also be co-fired with coal but these fuels grounds some difficulties during feeding and sizing. (Maceijewska et al. 2006).

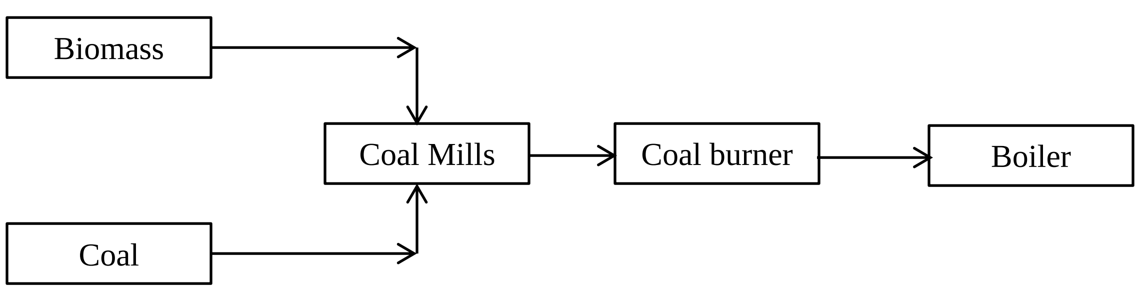


Figure 1.2: Layout of Direct co-firing first method.

- In the second method, as shown in Fig. 1.3, injection of both fuels is done together after their individual milling. The injection of biomass fuel and coal can be whichever upstream of the flame or at the burners. The advantage of this type is that higher co-firing ratios can be used. At the same time cost of its implementation is higher than first option.

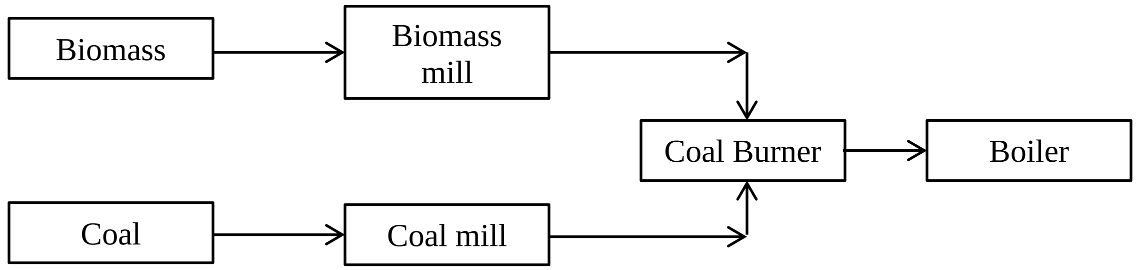


Figure 1.3: Layout of Direct co-firing second method.

- The third method also involves separate milling of fuels but there are two separate feeding lines one for coal and other for biomass fuel. Main or original injection line is taken by coal, while biomass fuel is inoculated separately into the special devoted burners located at the minor of furnace. This methodology is the costliest among all direct co-firing options.

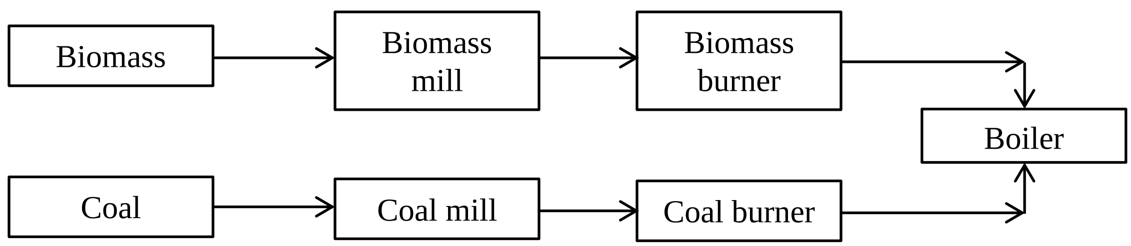


Figure 1.4: Layout of Direct co-firing third method.

- In the final method, biomass fuel is used as a re-burn fuel to limit the NO_x emissions. Distinct milling schemes and distinct biomass-fired burners at the exodus of the furnaces are used in this method.

1.5.2 Parallel co-firing

In this option, low grade steam is produced by combusting biomass fuel in a separate boiler as shown in Fig. 1.5. This low grade steam is then transferred to main stream of coal fired system. The investment in this type of co-firing installations is greater than direct co-firing; however, it has the subsequent benefits:

- Main unit does not affected by co-firing.
- Very high alkali and chlorine contents fuels can be handy to use.
- This option produces distinct tributaries of biomass and coal ashes.

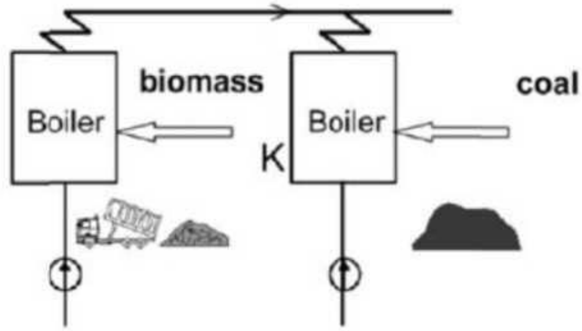


Figure 1.5: Layout of parallel co-firing technology (Mansour et al. 2010).

1.5.3 Indirect co-firing

In this kind of co-firing, the hard biomass fuel is burned distinctly leading to formation of producer gas, and then this producer gas is burned in the furnace of prevailing coal fired boiler, as shown in Fig. 1.6. Though this selection has significantly high capital costs, it compromises the subsequent benefits:

- Since there is no physical blending of biomass fuel and coal, a extensive variety of biomass fuels can be used. Moreover, biomass fuel ashes are kept separated from coal ashes.
- Any impurities or traces of chlorine, alkali etc if present in produce gas then it can be cleared before its burning in the furnace. So, the dangers of oxidization and fouling are short in this method.
- The producer gas is burnt beyond the burner, letting for a reduction of NO_x emissions.

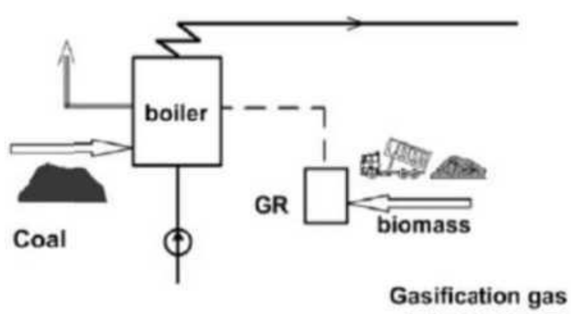


Figure 1.6: Layout of indirect co-firing technology (Mansour et al. 2010).

CHAPTER 2

LITERATURE REVIEW

In this chapter literature survey on ash agglomeration, co-firing techniques, economic analysis, exergy analysis and thermo-gravimetric analysis has been discussed. The objective of this chapter is to review all the literature related to the subject extensively.

2.1 Co-firing techniques:

Eddings et al. (2015) examined a 1.5 MW pulverized-coal test facility in which pulverized coal was co-fired with wood culled from pinion–juniper (P–J) forests in Utah (USA). The woody material was categorized in three practices: raw, untreated material; torrefied material, and bio-char from the pyrolysis of the P–J material. Tests were conducted using 5%, 10% and 20% biomass thermal input basis of above mention samples. The samples were pyrolyzed and torrefied to increase high heating value. Results shows that When the raw wood percentage was 10% of the firing rate, there was a significant variability in feed rate due to temporary blockages in the transport line and when torrefied wood at 10% was used, there were some feeding problems but they were notably less than when using raw wood at 10%. When operating with bio-char at 10%, no problems were observed at all, Subsequent testing with 20% co-firing indicated that the bio-char continued to operate and feed very well, while there were still problems with the torrefied material at 20%.The O_2 and NO_x concentration increases when raw wood percentage increased from 0 to 5 to 10% co-firing. A similar behavior was seen for the torrefied wood but with reduced severity. The bio-char, however, produced emission traces that were similar to baseline coal operation, at co-firing percentages up to 20%.

Kumar et al. (2015) studied a 30 MW captive power plant located in district Ropar, Punjab (India). Rice husk is used as biomass fuel and contributes to 30% of energy input. The cost of generating 4.2 MJ energy from rice husk was found to be rupees 1.30 approximately. Problems like ash evacuation from ash hoppers and sticky nature of ash causes, fouling and hard soot deposits. Bed temperatures observed were lower in case of co-firing as compared to coal firing boilers. Also, due to less Also due to low bed temperatures NO_x formation is also in permissible limits.

Kebede et al. (2013) investigated the case of co-firing wood pellets in Alabama. Using wood pellets reduction in coal import and creation of economic activities has increased in Alabama. 10% co-firing of wood pellets reduces coal import and carbon emission. It was observed that one ton of wood pellet generates 400 KW of electricity. So using wood pellets as a fuel will have a long term financial influence on economy.

Basu et al. (2011) presented his study seeing three different co-firing choices (direct, In-direct and Gasification) in a 150 MW powdered coal fired power plant located in Canada. Biomass fuel only contributes to 10% on energy basis in all three options. It was concluded that direct co-firing can be twice as efficient as that of indirect co-firing. Also, with co-firing cost of sequestration of CO_2 is very much lower than without co-firing. Problems like fouling and oxidization of super heater tubes, and failure of the grinders while treating biomass can be faced in direct co-firing. However external (In-direct co-firing) co-firing option includes higher capital asset, but there are no problems as in direct co-firing.

Tan et al. (2011) examined the co-firing of mold biomass pellets with coal in a 300 MW powdered coal-fired furnace in China. Biomass use is limited to 16.1% by energy input. A roller mill is used to pulverize mold biomass pellets. It was observed that furnace gas temperature decreases with increase in biomass feed and unburned carbon increases in fly ash. Also, furnace output is slightly reduced. It was observed that with rise in biomass feed proportion the NO_x emissions decreases.

Xiao et al. (2010) presented his study on low temperature pyrolysis of sawdust, rice hull, and peanut shell and their co-firing with coal. It was observed that low temperature pyrolysis improves the bulk density of biomass and results in lower volatile matter and high heating value of the biomass which improves the efficiency of the co-firing unit. Co-firing results shows that the problems like fouling, slagging and roughness can be evaded by giving a balanced mixing relation. Further, high ash and SiO_2 in pyrolyzed rice hull would result in slagging issues, which will lower the mixing fraction. Due to high alkali metal oxide proportion in pyrolyzed peanut shell ash, fouling problem is significant, which will also bind the mixing ratio.

Narayanan et al. (2007) conducted his study on an 18.68 MW travelling grate boiler. Bituminous coal is co-fired with bagasse, wood chips (Julia flora), sugarcane trash and coconut shell in proportions of 20%, 40% and 60% by mass. From the cost point of view coal and sugarcane blend in 40:60 is cheapest.

Turn et al. (2006) conducted experiment on co-fired coal with fuel oil (coal contributing 83% energy input), blend of fuel oil and bagasse (coal contributing 38 % energy input) and blend of bagasse and fiber cane (coal contributing 50% energy input) in a spreader stoker-type boiler. It was observed that boiler efficiencies were 82%, 54%, and 50%, respectively. Lower boiler performance is generally due to high moisture content in biomass fuel. Also emissions were found to be low when biomass fuels are used.

Tharakan et al. (2005) determined the economics of power generation in a plant co-firing willow biomass with coal. Like coal, willow biomass has low sulfur content and contains low traces of metals in ash. It was found that co-firing Willow does not cause any major problems. Apart from that willow biomass co-firing involves high costs of harvesting, transport etc.

2.2 Thermo-gravimetric analysis:

Kumar et al. (2016) presented his analysis of co-firing coal with biomass with oxygen augmented circumstances in a 20 kW bubbling fluidized bed. Biomass fuels blended with coal are rice husk, Prosopis juliflora, pine needles and plant litter. When different proportion of each of biomass fuels was blended, it was found that best combustion efficiency is obtained with 75% coal 25% Prosopis juliflora. Also all fuel blends burned effectively under oxygen rich conditions and there performance increases with increase in oxygen concentration.

Yaman et al. (2015) suggested that firing biomass with coal result in high thermal reactivity of biomass. To lower the reactivity of biomass during co-firing process, carbonization of biomass is done at 600^0C to obtain bio-char. It was concluded that when bio-char is co-fired with lignite separation propensity in the mass damage features mostly eliminates. Carbonization of woody biomass at 600°C depressed the volatile content and shifts burning to higher burning temperatures.

Jiang et al. (2013) performed experiment using blends of coal and bio-ferment residue (BR, hazardous waste) for performing thermo gravimetric and kinetic analysis to understand their co-combustion characteristics at different proportions. It was observed that BR which does not has combustion properties as good as coal has composition that favors combustion. Results also shows with growing BR co-firing ratio, ignition temperature, and burning rate decreases which results in decrease in total energy output. The calorific value of coal would be condensed suggestively by mixing wet BR. Blending BR decrease the burnout, flammable and burning enactment of coal.

Muthuraman et al. (2010) presented an investigation using municipal solid waste co-combustion with different ranks of coal, i.e. Indian, Australian and Indonesian coals. Biomass fuel was blended by weight in proportions from 10% to 50% with 10% gap. It was found that blending of biomass improves de-volatization properties of coal. Also, for low quality Indian coal the adding of biomass helps and chains the detonation of the coal.

2.3 Exergy analysis:

Sharma et al. (2016) presented his study on a comprehensive energy, exergy and thermo-economic analysis of a 7.5 MW (at Muktsar, Punjab, India) biomass-fired bubbling fluidized bed sub-critical thermal power plant has been done. A break-even economic analysis to enhance the profit of the plant also been performed. Mixture of three different biomass fuels is used in selected thermal power plant at the time of the observations. Results from energy analysis shows the need to enhance the performance of the water cooled condenser, whereas exergy analysis suggests that improving the performance of the boiler will lead to increase in the output of the plant. The plant efficiency can be improved by reducing the condenser pressure as this can give higher range of expansion of steam in the turbine section. Also lowering the temperature of cooling water entering condenser below ambient can increase the performance of the plant. Here the generation cost per kWh is rupees 2.91, whereas the generation cost per kWh for coal-fired thermal power plants in India is rupees 3.05. The maximum exergy destruction taking place at the boiler and improving boiler’s performance will result an improvement in the power plant performance.

Khoodaruth et al. (2015) analyzed the main culprit for exergy destruction in a coal fired boiler. Also overall exegetic efficiency of plant was calculated. It was found that 77% of exergy destruction takes place in boiler section followed by turbine (14.5%). Further, author analyzed that with upsurge in turbine inlet temperature the cycle efficiency can be increased by 42% and an extra electricity of 52 GWH would be formed.

Zhao et al. (2011) performed detailed exergy analysis of oxy-combustion pulverize coal 600 MW power plant was compared with simple pulverize coal fired boiler. Exergy of major boiler parts was evaluated. Result shows in oxy-combustion system, exergy output is 37.13%, which is

4.08% lesser than that of the simple system. Furnace output in the oxy-combustion system is about 4 % greater than that in the simple incineration system, which should be the main aim for 0.8 % higher exergy output of the oxy-combustion boiler.

Naterer et al. (2010) presented comprehensive exergy and energy examination of a sub-critical boiler–turbine generator is executed on a 32 MW coal-fired power plant. In order to maximize the plant efficiency various operating parameters like pressure, temperature and flow rates are varied. According to results the maximum destruction is found to be in boiler (nearly 87%). Further, the power plant's energy efficiency is found to be 30.12% for the gross generator output. The plant exergy efficiency for the arrangement is 25.38% for the gross generator output.

Saidur et al. (2010) performed exergy and energy analysis of a boiler. From results exergy and energy analysis corresponding efficiencies were found to be 24.89% and 72.46%. Maximum destruction of exergy was found to be in combustion chamber of boiler section which is 75%. To increase energy efficiency of plant numerous energy convertible actions were proposed such as heat recovery from flue gases and use of adjustable speed drive in operating fan.

Aljundi et al. (2009) presented study on energy and exergy study of a sub critical coal fired 66 MW power plant in Jordan. The main objective is to find the culprits having major energy and exergy losses and their variation by varying the reference environment state. Results show the exergy output of the power cycle to be 25%. The given exergy efficiency is very low and the main sources of its destruction are found to be boiler (77%), turbine (13%) and forced draft fan (9%). In boiler there are various reactions happening and this chemical reaction is responsible for major exergy destruction. This destruction can be lowered by heating the burning air and falling the air–fuel ratio.

2.4 Bed agglomeration:

Armesto et al. (2009) performed an experiment work on 30 kW pilot scale plant having atmospheric bubbling fluidized bed combustor in Spain. The fuel used is rice husk. Rice husk burned with combustion efficiency of above 97%. It was bring into being that as the operating hours upsurges the potassium content in ash increases which leads to formation of large agglomerates. Potassium content in ash needs to be controlled to avoid bed agglomeration.

Vamvuka et al. (2009) addressed the thermal effects of ash and bed agglomeration during incineration in a FBC boiler. The fuel used was blends of lignite, olive kernel and olive tree wood. Each type of biomass was mixed with coal in the ratio of 5%, 10% and 20%. It was found that blending up to 20% of biomass fuel with coal improves slagging and fouling tendency as it was when each of these fuels were fired alone. There was no sign of bed agglomeration.

Llorente et al. (2006) worked on bubbling fluidized bed combustion plant having 1 MW output. The bed material is silica and the biomass fuel used is woody biomass, poplar and herbaceous biomass. It was found that alkaline compounds in biomass fuel are main reason for bed agglomeration. Bed agglomeration is due to high content of potassium, sodium and sulphur in biomass fuel.

Wey et al. (2004) added sodium, magnesium and calcium to artificial waste and predicted the bed agglomeration. He found that with increase in sodium content the agglomeration rate increases. After 3% by weight of sodium content it was observed that adding magnesium and calcium decreases rate of agglomeration.

2.5 Economic analysis:

Madlener et al. (2013) investigated the economic analysis by replacing 10% of coal by biomass fuel in an 800 MW hard coal dust fired power plant. Biomass fuel used is wood pellets which are imported from other regions. Results show that the use of wood pellets is technically realistic. Also results shows that use of biomass fuel has upper limit which is limited to 20% on energy basis.

O'Mahoney et al. (2013) conducted a study in EU where four kinds of biomass fuels were co-fired with peat coal. Fuels co-fired with peat are willow, miscanthus, wood resources and meat and bone meal in the proportions of 15%, 30%, and 45%. There will be 30% reduction in emissions if these fuels work smoothly in four stations. Apart from emissions the cost involved is very high and cost of biomass fuels is very high as likened to coal.

Wiley et al. (2013) investigated the effect of co-firing biomass with coal at a typical 500 MW Australian black coal-fired plant with and without post-combustion capture. In Australia renewable are more expensive than fossil fuels and hence, they are not economically competitive in the current energy market. In the present study a typical existing coal plant (as the base plant), the base plant retrofitted for 10% biomass co-firing (on an energy basis), and, the base plant retrofitted for 10% biomass co-firing and 90% post-combustion capture with mono-ethanolamine solvent are considered. This plant uses wood waste as the biomass feed stock which is based on previous trials for co-firing in Australia. The results show that co-firing 10% wood waste with coal would result in 0.33 Mt CO_2 avoided per year for a 500 MW plant at an almost negligible efficiency loss. For the co-firing plant with CO_2 capture, 2.96 Mt CO_2 would be captured each year resulting in 0.02 Mt per year of negative CO_2 emissions at an efficiency loss of about 8% as a result of the energy required to power the CO_2 capture plant. The cost of electricity for co-firing with CO_2 capture is higher than the COE for co-firing alone by 10 - 16 $/MW h, The results show that retro-fitting an existing coal plant with 10% biomass co-firing would slightly change the plant performance and efficiency while reducing the plant emission intensity by about 9%.

Hoffmann et al. (2012) estimated the technical limits of using woody biomass with low ranked Brazilian coal in south of Brazil. Woody biomass is transported from nearby regions; maximum distance for transportation of biomass is also discussed in this paper. Temperature of fluidized bed is around 900°C and from analysis lower heating value of coal and biomass is found to be 94% of that of coal. Also due to higher moisture content in biomass fuel it generates more water vapors in flue gases as compared to coal. Maximum distance allowed for transportation of biomass was found to be 123 km. Total cost of biomass incudes transportation and generation is very high as compared to that to coal.

2.6 Tabular summary:

S NO.	REFERENCE	INVESTIGATION	APPRATUS AND MATERIAL USED	KEY RESULTS
1	Eddings et al. (2015)	Co-firing of pulverized coal with Pinion Pine/Juniper wood in raw, torrefied and pyrolyzed forms.	1.5 MW pulverized coal fired	The O_2 and NO_x concentration increases when raw wood percentage increased from 0 to 5 to 10% co-firing. A similar behavior was seen for the torrefied wood but with reduced severity.
2	Kumar et al. (2015)	Study of a 30 MW bubbling fluidized bed combustor based on co-firing biomass and coal.	30 MW AFBC type thermal power plant	A strong rise in the bed temperatures of coal fired boilers is witnessed as likened to co-firing boilers. Also due to insignificant sulphur proportion in biomass and very low sulphur proportion in coal used at CPP, the SO_2 creation remains within allowable limits.
3	Kebede et al. (2013)	Economic impact of wood pellet co-firing in South and West Alabama.	1220 MW thermal power plant	Given the present 10% co-firing which is considered as effective, the usage of wood pellet will lower coal import and carbon emission and

				produce economic movement in the area.
4	Basu et al. (2011)	Biomass co-firing options on the emission reduction and electricity generation costs in coal-fired power plants.	150 MW pulverized coal (PC) fired power plant	The study designates that direct co-firing can propose an internal rate of return of higher than twice that of indirect co-firing. The cost of sequestration of 40e60$/ton of CO_2 was much greater than the 33$/ton CO_2 decline cost through co-firing.
5	Wang et al. (2011)	Experimental investigation on biomass co-firing in a 300 MW pulverized coal-fired utility furnace in China.	300 MW pulverized coal-fired furnace	It is detected that the start and incineration of the mold straw pellets should be much further steady, and the self-ignition of the biomass should be prohibited during the procedures of biomass pulverization. The flame on the biomass injector is stable.
6	Xiao et al. (2010)	Studies on co-firing of low-temperature pyrolyzed biomass with coal	Muffle Furnace for pyrolysis	It shows the questions of fouling, slagging and roughness can be evaded, providing a balanced blending ratio.
7	Narayanan et. al (2007)	Experimental studies on co-firing of coal and	18.68 MW power plant	Results shows that lowermost cost necessities

		biomass blends in India.		for the fuels, have been establish to be for coal and sugarcane trash mixture and for a 40:60 ratio, which is Rs. 25,800/h, a discount of around 40% in contrast to coal only firing, which is Rs. 42,000/h. Also it can be gotten that the amount of fuel required, generating 70 ton/h of steam, surges as the biomass share is improved in the fuel mix.
8	Turn et al. (2006)	Test results from sugar cane bagasse and high fiber cane co-fired with fossil fuels.	Spreader Stoker-Type Boiler	Boiler efficiency for Tests 1, 2, and 3 were 82%, 54%, and 50%, correspondingly, and the condensed boiler enactment is usually due to high content of moisture (around 50%) in the biomass. A 61% drop in NO_x emission was attained by firing 100% biomass likened to 100% coal.
9	Tharakan et al. (2005)	Evaluating the impact of three incentive programs on the	Willow biomass	Comparative to coal, willow biomass has nearly no sulfur,

		economics of co-firing willow biomass with coal in New York State.		comprises lesser quantities of ash and trace metals (e.g. mercury), and can result in lower NO_x emissions. This study validates that the claim of small quantities of inducements that exactly mark both the fuel cultivator and the power plant, and aid to suitable value for the optimistic externalities from the use of willow biomass feedstock, can help safeguard a gainful co-firing process for all parties worried.
10	Kumar et al. 2016	An investigation in 20 kW oxygen enriched bubbling fluidized bed combustor using coal and biomass.	20 kW bubbling fluidized bed	The results showed that the coal-biomass mixture burned positively inside the combustor and finest incineration efficiency is 97.09% with 75% coal and 25% PJ under oxygen enhanced bubbling fluidized bed.
11	Yaman et al. 2015	Does carbonization avoid segregation of biomass and lignite during co-firing?	Thermo-gravimetric analyzer	It was determined that carbonization built co-firing of biomass with lignite typically

		Thermal analysis study.		eliminated the separation propensity in the mass damage features.
12	Jiang et al. 2013	Evaluation of co-firing bio ferment residue with coal at different proportions: combustion characteristics and kinetics.	Mettler Toledo TGA/SDTA851 thermo analyzer	The results showed that with increasing BR residue co-firing ratio, ignition temperature, and combustion rate decreased resulting in a decrease in total energy output.
13	Muthuraman et al. 2010	Characteristics of co-combustion and kinetic study on hydrothermally treated municipal solid waste with different rank coals: a thermo-gravimetric analysis.	Thermo-gravimetric analyzer	The blending of biomass improved the de-volatilization properties of coal.
14	Sharma et al. 2016	Thermo-economic analysis of a biomass fired bubbling fluidized bed thermal power plant.	7.5 MW biomass fired bubbling fluidized bed power plant	The results showed that refining the presentation of the boiler can advance the output of the plant. Also, by lowering the temperature of cooling water entering the condenser below ambient can increase the performance of the plant.
15	Khoodaruth et al. 2015	Performance analysis of a grate stoker coal fired power plant based on the second law of	30 MW grate stoker coal fired power plant	The boiler (77%) and steam turbine (14.5%) were observed to have the uppermost exergy

		thermodynamics.		destruction.
16	Zhao et al. 2011	Exergy analysis of a 600MW Oxy-combustion pulverized coal fired power plant.	600 MW power plant	It was observed that around 60% exergy destruction was in the boiler section. Also, for turbine and FWH, it was found to be around 9%.
17	Saidur et al. 2010	Energy and exergy of economic analysis of industrial boilers.	-	The boiler energy and exergy efficiencies were found to be 72.46% and 24.89% respectively. Here, the exergy destruction in boiler was found to be 75%, in which major contributor was the combustion chamber followed by heat exchanger.
18	Naterer et al. 2010	Exergy analysis of a thermal power plant with measured boiler and turbine losses.	32 MW coal fired power plant	The maximum exergy destruction was found to be in boiler (87%). The plant's energy efficiency was determined to be 30.12% whereas plant's exergy efficiency was found to be 25.38%.
19	Aljundi et al. 2009	Energy and exergy analysis of a steam power plant in Jordan.	56 MW power plant	The exergy efficiency of the power cycle was found to be 25%. The main sources of exergy destruction were found to

				be boiler (77%), turbine (13%), and FD fan (9%).
20	Armesto et al. (2009)	Combustion behavior of rice husk in a bubbling fluidized bed.	30 KW pilot scale plant ABFBC	It was found that as the operating hours increases the potassium content in ash increases which leads to formation of large agglomerates. Potassium content in ash needs to be controlled to avoid bed agglomeration.
21	Vamvuka et al. (2009)	Ash effects during combustion of lignite/biomass blends in fluidized bed.	Experimental fluidized bed	It was found that blending up to 20% of biomass fuel with coal improves slagging and fouling tendency as it was when each of these fuels were fired alone. There was no sign of bed agglomeration.
22	Llorente et al. (2006)	Behavior of lignocellulose biomass in bubbling fluidized bed combustion.	1 MW bubbling FBC boiler	It was found that alkaline compounds in biomass fuel are main reason for bed agglomeration. Bed agglomeration is due to high content of potassium, sodium and sulphur in biomass fuel.
23	Wey et al. (2004)	The effects of mineral composition of waste and operating	Bubbling fluidized bed reactor	It was found that with increase in sodium content the agglomeration

		conditions on particle agglomeration/de-fluidization during incineration.		rate increases. After 3% by weight of sodium content it was observed that adding magnesium and calcium decreases rate of agglomeration.
24	Madlener et al. (2013)	Economic viability of biomass co-firing in new hard-coal power plants in Germany.	800 MW hard coal dust fired power plant	Results show that the use of wood pellets is technically realistic. Also results shows that use of biomass fuel has upper limit which is limited to 20% on energy basis.
25	O'Mahoney et (al. 2013)	A cost-benefit analysis of generating electricity from biomass.	-	Results show that there will be 30% reduction in emissions if these fuels work smoothly in all working stations. Apart from emissions the cost involved is very high and cost of biomass fuels is very high as compared to coal.
26	Wiley et al. (2013)	Techno-economic study of biomass co-firing with and without CO_2 capture in an Australian black coal-fired power plant.	500 MW coal fired FBC boiler	In Australia renewable are more expensive than fossil fuels. The results show that co-firing 10 % wood waste with coal would result in 0.33 Mt CO_2 avoided per year for

				a 500 MW plant at an almost negligible efficiency loss. The cost of electricity for co-firing with CO_2 capture is higher than the COE for co-firing alone by 10 - 16 $/MW h.
27	Hoffmann et al. (2012)	An evaluation of the techno-economic potential of co-firing coal with woody biomass in thermal power plants in the south of Brazil.	-	Due to higher moisture content in biomass fuel it generates more water vapors in flue gases as compared to coal. Maximum distance allowed for transportation of biomass was found to be 123 km. Total cost of biomass incudes transportation and generation is very high as compared to that to coal.

2.7 Gaps in literature:

An extensive literature survey has been discussed in previous chapter. It is clear from the survey that lot of work has been done to investigate the effects of co-firing on emission control from different prospective. Various factors that affect co-firing have been investigated by researchers. However, a gap in study reveals that there is still a lot of work to be done in determining the economic feasibility of co-firing biomass in power plants. Also, problems like slagging and fouling has been explained by researchers but content on ash behavior leading to formation of large agglomerates is very less. The properties of biomass fuels vary significantly from place to place and a definite pattern of decomposition cannot be assumed for these fuels. Asian countries like India are rich in biomass fuels and impact of co-firing these fuels with coal on plant efficiencies has not been found in literature.

2.8 Problem formulation:

A 20 MW FBC boiler, co-fired thermal power plant is selected for analysis in this study. Indian coal is co-fired with rice husk in this plant. Fuel samples and their blends were analyzed for physical and chemical properties along with TG, co-combustion and kinetic analysis. In addition to this, exergy analysis is done for co-fired boiler. A very common problem of bed agglomeration, which can lead to de-fluidization in FBC boiler, is also predicted in co-fired boiler. Plant is also analyzed on economic point of view and a complete economic analysis along with break-even analysis is done for selected plant.

CHAPTER 3

PLANT DETAILS AND MATERIAL ANALYSIS

3.1 Plant configuration:

Basic information of selected plant and its physical parameters are to be discussed here. As discussed earlier the plant selected is Trident Ltd., Barnala, Punjab. Trident group is a dynamic and continuously growing group having textile division, Terry Tower Division, world largest agro based paper manufacturing unit and one of the largest producer of yarn color Textile Limited in India. For this purpose they incorporated three thermal power plants. Plant layout of 20 MW capacity is shown in Fig. 3.1.

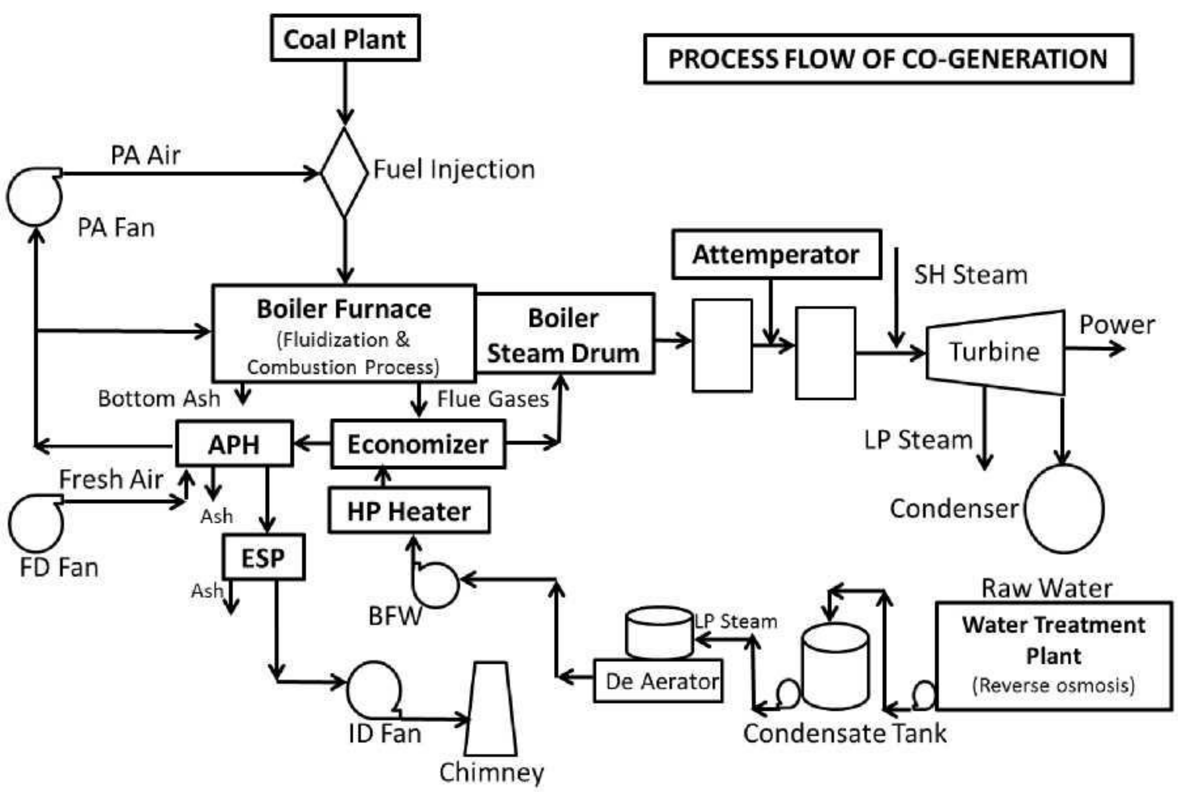


Figure 3.1: Process flow diagram of Trident plant.

Three power plants are fired with coal and biomass; one has capacity of 9.4 MW and other two of 20 MW each. Rice husk is used as biomass fuel and replaces 30% by weight of coal. Physical parameters of 20 MW plant are shown in Table 3.1.

Table 3.1: Physical parameters of co-fired plant.

Total power	20MW
No. of units	2
Main steam pressure	105 ata
Main steam temperature	505 °C
Main Stream flow rate	130 TPH
Flue gas temperature	350 °C
Fuel type	coal and rice husk
% of co-firing	30%
Average heating value	3200 kcal/kg

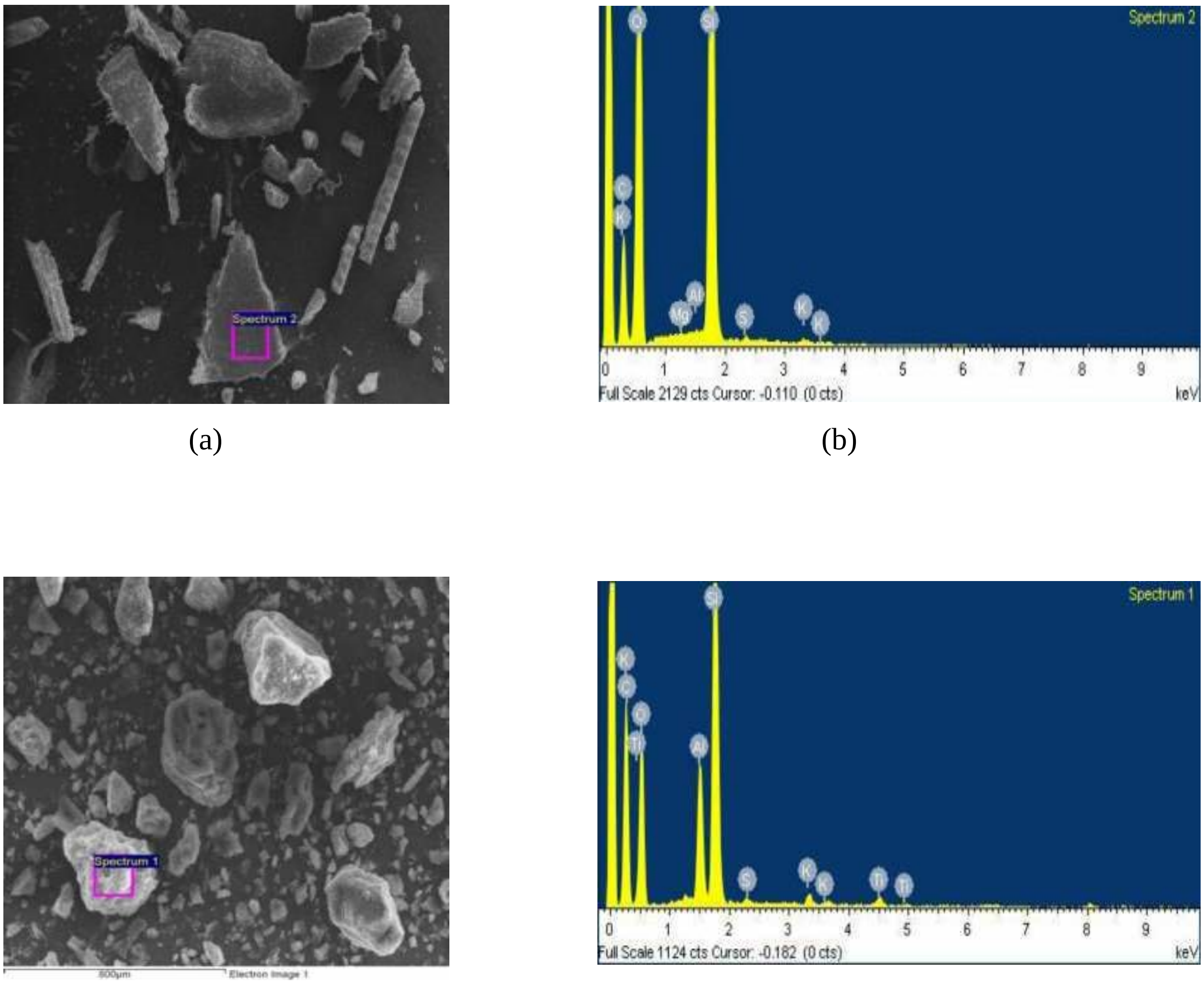
3.2 Material analysis:

In this present study samples of coal and biomass fuels were collected from Trident Ltd. Barnala, Punjab. Biomass fuel used in this study is rice husk, which is collected from nearby areas. The co-firing is done by replacing 30% by weight of coal with rice husk. Direct co-firing option is used for co-combustion of fuels. Properties of coal may be different from rice husk which are discussed here.

3.2.1 Proximate and chemical analysis:

Characterization of samples of coal and rice husk for obtaining the chemical composition and proximate analysis was done. Proximate analysis was done by the method prescribed in IS-1350; part I, on air dried basis. The results of proximate and chemical analysis are shown in Table 3.2.

The morphological characteristics and the chemical composition of the coal samples were obtained by SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy) techniques respectively. In SEM micrographs the field depth obtained is very large which helps in yielding a useful three dimensional appearance useful for studying the surface of coal and biomass fuel samples (Roy et al. 2015). For SEM imaging, the coal samples must be electrically grounded in order to prevent scanning faults caused due to electrostatic charge at the surface, therefore the coal samples gets coated with an ultrathin coating, usually gold (Au). This process is known as sputter coating. The SEM micrographs obtained for the rice husk and coal samples are shown in Fig. 3.2 (a), and 3.2 (c) respectively.



(a) (b)

(c) (d)

Figure 3.2: (a) SEM micrograph for rice husk, (b) EDS peaks for rice husk, (c) SEM micrograph for coal and (d) EDS peaks for coal.

Figures 3.2 (b), and 3.2 (d) depicts the EDS output of the rice husk and coal samples. EDS is a logical method used for fundamental study or chemical composition of a sample (Roy et al. 2015). The chemical composition of the three coal samples as obtained by the EDS output peaks are listed in Table 3.2.

Table 3.2: Proximate and chemical analysis of coal and rice husk samples.

Composition	Coal	Rice Husk
Moisture (%)	6.33	9
VM (%)	29	62
FC (%)	28.33	18.5
Ash (%)	36.34	10.5
HHV (kcal/kg)	3500	2800
Carbon (%)	74.19	42.54
Oxygen (%)	24.2	38.82
Aluminum (%)	0.03	4.13
Silicon (%)	15.37	13.17
Sulphur (%)	0.16	0.14
Potassium (%)	0.14	0.59
Tin (%)	Nil	0.62
Iron (%)	0.52	Nil

Most of biomass fuels have high alkali content in them as compared to coal. As shown in Table 3.2, rice husk has less ash content, high volatile content, fewer fixed carbon content and almost similar moisture content as likened to that of coal. The high volatile content of rice husk is due to the formation of complex layers of organic matter. High volatile content of rice husk favors the oxidation and dominates the combustion process. The above discussions boost the chances of co-firing rice husk with coal in coal fired boilers. Also chemical composition shows coal and rice husk has almost same sulphur content which will not affect flue gases composition. Rice husk is rich in oxygen content as likened to coal which will led to high reactivity (Yaman et al. 2008) and easy ignition (Muthuraman et al. 2010).

3.3 Thermal decomposition analysis:

In this section decomposition of samples is analyzed to predict various reactions and temperatures. Various zones of decomposition and reactions were studied. An extensive thermo-gravimetric analysis of samples and their blends has been done along with kinetic analysis and are discussed here.

3.3.1 Thermo-gravimetric analysis:

When biomass fuels are co-fired with coal, their combustion behavior and various reactions play an important role in energy output. Biomass fuels vary in properties than coal. Thermal decomposition behavior of coal and biomass blends can be understood by thermo gravimetric analysis or thermo gravimetric analysis (TGA).

TGA is a technique of thermal examination in which variations in physical and chemical properties of materials are restrained as a purpose of growing temperature (with constant heating rate), or as a purpose of time (with constant temperature and/or constant mass loss). Thermo gravimetric analysis is an important tool for obtaining weight loss nature of the sample with admiration to temperature or time. Differential thermo gravimetric (DTG) analysis is also very important tool for thermal and kinetic analysis of a given sample. DTG curve is first derivative of TG curve. DTG results highlight the region of reaction where numerous reaction stages are taking place over the whole temperature scale.

In a DTG scan at a constant heating rate where a solid sample fuses, the reference material increases in temperature at the designated heating rate, while the sample temperature remains at the melting temperature until the transformation is complete.

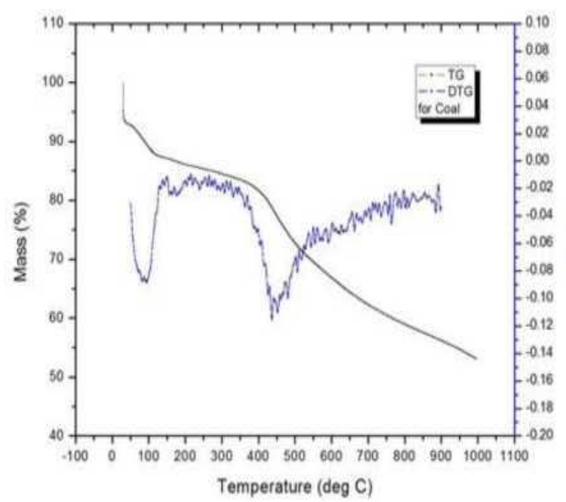
In this study, TG and DTG analysis was then carried out on the obtained samples. Further, blends of both samples with the rice husk varying in proportions of 20%, 30%, and 40% by weight were prepared.

Methods:

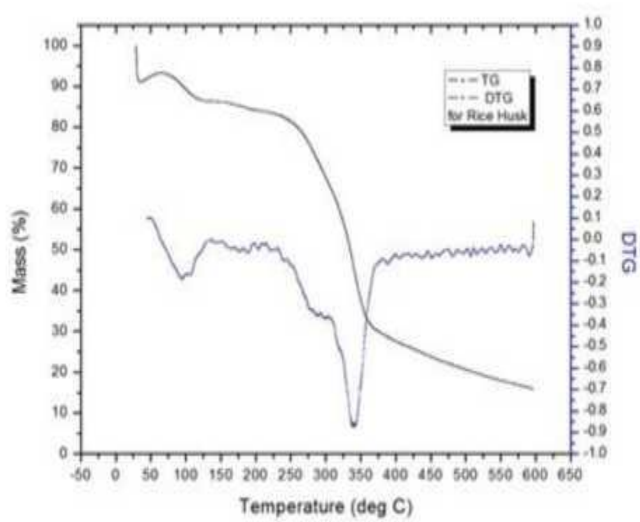
The equipment used for carrying out TG and DTG analysis was thermo-gravimetric analyzer. The analyzer consists of a sample pan supported by a precision balance. The pan is located inside an electrically heated furnace that is heated and cooled while carrying out the experiment. A sample gas (inert gas) controls the experimental environment. The heating rate maintained during the experiment process is 10 °C/min. The temperature range for coal and blends of rice husk and coal is up to 900°C and that for rice husk alone is up to 650°C.

Results:

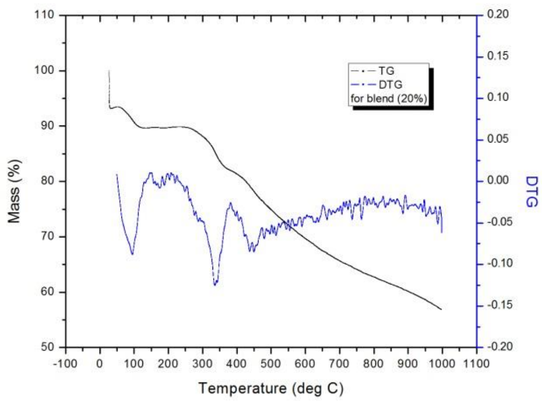
TGA was carried out on coal, rice husk, and a blend of both samples with the rice husk varying in proportions 20%, 30%, and 40% by weight. Figure 3.3 represents the TGA and DTG curves of coal, rice husk and their blends. During combustion weight loss of a sample is represented as percentage weight of original sample weight. Properties of coal, rice husk and their blends are compared in this section. The peaks of DTG curves represent the weight loss. In Fig. 3.3 (a) for coal, initial peak represents a weight loss which is due to evaporation of moisture. After that curves show different combustion nature of samples. Coal has a single peak ranging from 350^0C to 650^0C, represents loss of weight in a definite manner. Almost 50% of weight is burned out in this range. On the other hand for rice husk, scenario is something different. As seen from the Fig. 3.3 (b), there are multiple peaks one ranging from 140^0C to 310^0C and another major peak ranging from 310^0C to 425^0C, in between and after them there are some small spikes. In the first range weight loss is around 20% and in second range weight loss is 50% of the total weight of sample. Also, from the proximate analysis of coal total volatile content is 57.33% and for biomass is 80.5%, which can be justified from TG and DTG curves. The small variations in volatile loss for both coal and rice husk are due to different heating environment and different heating rate. As discussed above, there is a weight loss of around 70% for rice husk in two stages and for coal it is around 50% in a single state, this is due to the fact that rice husk is formed by different volatile fractions with dissimilar reactivity whereas coal is dense form of biomass and is less reactive having low volatile content (29%) and low carbon (28.33%) (Sami et al. 2007). The above results can vary if the rate of combustion is changed.



(a)



(b)



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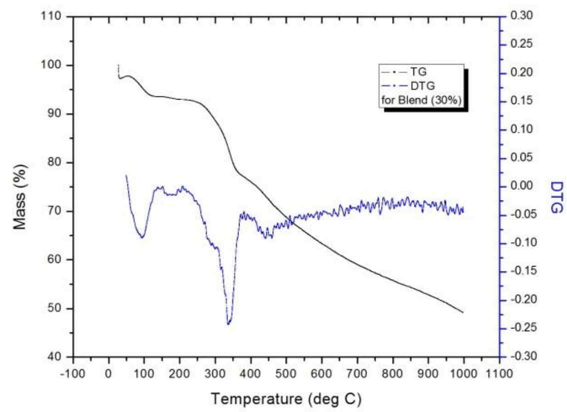
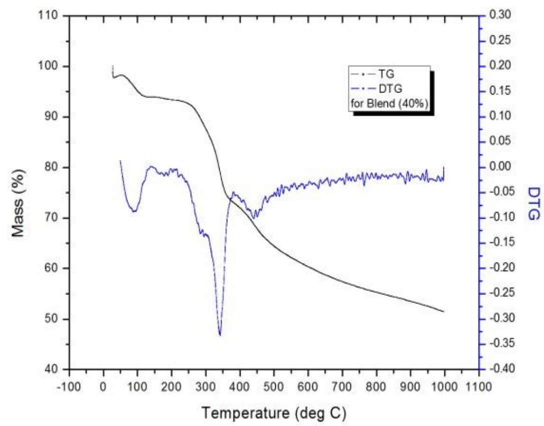
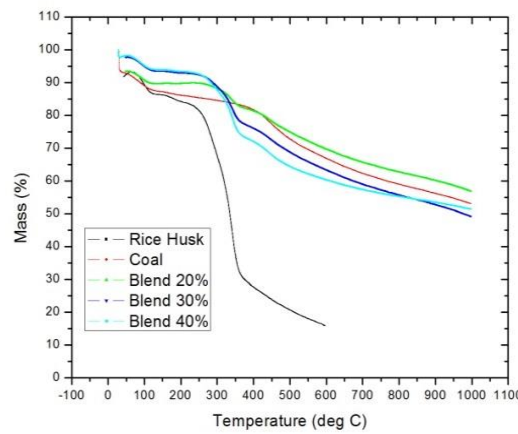


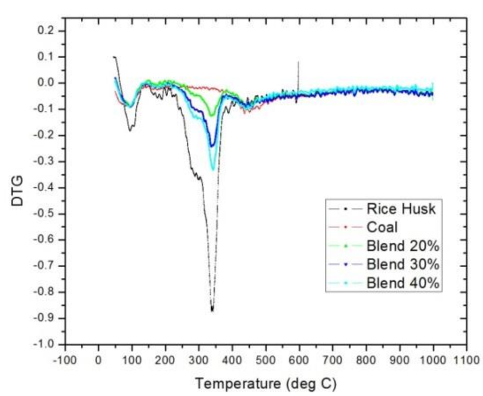
(d)



(e)



(f)



(g)

Figure 3.3: TG and DTG curves of (a) coal sample (b) rice husk sample (c) 20% blend of rice husk by wt., (d) 30% blend of rice husk by wt., (e) 40% of rice husk by wt., (f) combined TG curve and (g) combined DTG curve

To analyze the burning properties of rice husk and coal blends, the TGA and DTG plots obtained from burning of blends of coal and rice husk are shown in Fig. 3.3 (c),(d) and (e) with rice husk proportions of 20%, 30%, and 40% by weight. Also, Fig. 3.3 (f) and (g) shows the combined TGA and DTG curves of individual and blends at all mentioned ratios.

From TGA and DTG curves of blends, it is detected that they lie between curves of pure coal and rice husk. From Fig. 3.3 (g), it is observed that combustion consists of several stages. First stage represents the evaporation of moisture below 140^0C for all blends. In the second stage from 140^0C to 340^0C the burning of thermally less stable volatiles in rice husk is carried. In the third stage from 340^0C to 600^0C the burning of more thermally stable volatiles of coal and rice husk blends is carried. After these stages there is burning of char content of blends. With the increase in blending ratio the peak of less stable volatile from 140^0C to 340^0C increases due to increase in more volatile component in the sample. Also, the peak of thermally stable volatile combustion is decreases as blending in coal increases which shows the presence of highly stable volatiles in the coal.

3.3.2 Co-combustion characteristics and kinetic parameters of coal and rice husk blends:

A row of combustion parameters were examined from TG and DTG curves which characterizes the burning of coal, rice husk and their blends. Table 3.3 shows the characteristic parameters for pure coal, pure rice husk and their blends.

The volatile release onset temperature (T_v), represents the weight loss of a sample after its moisture evaporation (Muthuraman et al. 2010). The moisture content in coal and rice husk is 6.33% and 9% and its evaporation is clear on the DTG curve. After moisture evaporation it is volatiles that start to evaporate, for coal volatile release temperature is 305°C and for rice husk it is 140°C. Hence volatile release for rice husk is at relative low temperature than coal.

Table 3.3: Combustion parameters of coal, rice husk and their blends.

Sample	T_v(°C)	T_o(°C)	T_m(°C)	$T_{burnout}$(°C)
Coal	305	350	460	600
Rice husk	140	265	330	400
20% rice husk 80% coal	200	310	350	590
30% rice husk 70% coal	180	290	345	570
40% rice husk 60% coal	175	275	340	520

Difficulty in ignition of a sample is reflected by ignition temperature (T_o). The ignition temperature was determined using the method proposed by Li et al. 2006, Gani et al. 2005, Sorum et al. 2001, Vamvuka et al. 2009 and Wang et al. 2009. As shown in Table 3.3 the ignition temperature for coal is 350°C and that for rice husk is 265°C indicating that rice husk start to ignite at earlier temperatures than coal. Peak values on DTG curve represent the maximum weight loss rate of a sample and temperature corresponding to that maximum weight loss rate is T_m. As seen from Table 3.3, T_m for rice husk is very much below than coal. Maximum weight loss temperature for blends lie between those of coal (460°C) and rice husk (330°C). The burnout temperature ($T_{burnout}$) represents the temperature when weight loss rate stabilizes. At burnout temperature char content burned completely. Table 4.2 shows higher $T_{burnoout}$ for coal (600°C) as compared to rice husk (400°C), which indicates that coal, has more stable char content than rice husk.

3.3.3 Kinetic analysis:

There are various approaches used to model thermal devolatisation process. Biomass and coal blends generate additional complex reactions which includes gaseous reactions between volatiles at low temperatures (Skodras et al., 2007). In this present study correlation between rates of mass loss with temperature is done using Arrhenius equation and Coats-Redfern equation which is used by other researchers also (Munir et al. 2009, Shen et al. 2009, Wang et al. 2009, Yorulmaz and Atimtay et al. 2009). The decomposition of any sample can be described by the various reactions explained below.

$$\text{Sample} \rightarrow \text{Volatiles} + \text{Char} \qquad (3.1)$$

The Arrhenius equation for kinetics is given as:

$$\frac{d\alpha}{dt} = k \times f(\alpha) \qquad (3.2)$$

Where α represents the mass conversion or mass loss ratio which can be calculated as:

$$\alpha = \frac{m_o - m_t}{m_o - m_f} \qquad (3.3)$$

Where m_o is original mass of sample, m_f is closing mass of sample left after combustion and m_t is mass of sample at time t. k is reaction constant at particular temperature T and $f(\alpha)$ is function of mass conversion. The value of reaction constant (k) obeys Arrhenius equation as:

$$k = A \exp\left(\frac{-E_a}{RT}\right) \qquad (3.4)$$

In Eq. (3.4) A is the pre-exponential factor (min^{-1}). E_a Is the activation energy in (kJ mol^{-1}), R is the universal gas constant (JK^{-1} mol^{-1}), and T is the absolute temperature (K).

By substituting the Eq. (3.4) into Eq. (3.2) we get general expression for kinetic parameters:

$$\frac{d\alpha}{dt} = f(\alpha)\ A\ exp\left(\frac{-E_a}{RT}\right) \qquad (3.5)$$

Equation (3.5) represents kinetic equation for decomposition under isothermal processes. For non-isothermal conditions (samples being heated at constant rate), the actual temperature is given as:

$$T = T_o + Bt \qquad (3.6)$$

Where, T_o represents initial temperature (K), B represents heating rate (°C/min), and T represents temperature at any time t.

Kinetic equation for decomposition under non-isothermal processes is given as:

$$\frac{d\alpha}{dT} = \frac{A}{B} \exp\left(-\frac{E_a}{RT}\right) f(\alpha) \qquad (3.7)$$

The above Eq. (3.7) can be re written as:

$$\frac{d\alpha}{f(\alpha)} = \frac{A}{B} \exp\left(-\frac{E_a}{RT}\right) dT \qquad (3.8)$$

The integration of the Eq. (3.8) would result in a function g(α) (integral function of conversion) as:

$$g(\alpha) = \int_0^{\alpha} \frac{d\alpha}{f(\alpha)} = \frac{A}{B} \int_{T_o}^{T} \exp\left(-\frac{E_a}{RT}\right) dT \qquad (3.9)$$

The complete integration of Eq. (3.9) is achieved by Coats-Redfern method (Coats and Redfern et al. 1964) and is expressed as:

$$\ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{BE_a}\left(1 - \frac{2RT}{E_a}\right)\right) - (E_a/RT) \qquad (3.10)$$

The various values of $g(\alpha)$ to obtain kinetic parameters (activation energy) for solid state reactions are shown in Table 3.4:

Table 3.4: Expressions for g(α) for various solid state reactions. (Sun et al. 2006)

Mechanism and model	**g(α)**
A1	-ln (1-α)
A2	$(1-\alpha)^{-1}$
A3	$(1-\alpha)^{-2}$
A4	$1-(1-\alpha)^{1/2}$

Results:

The various mechanisms mentioned in table were tested in Coats-Redfern Eq. (3.10) in order to obtain the best mechanism for combustion of fuel. It is clear from DTG curves of coal and rice husk that when the fuels are fired alone for combustion, the maximum weight loss is in a lone stage i.e. a single temperature range. Whereas, when coal and rice husk samples were blended and co-combusted, the weight loss was found to exist in two or three different stages (temperature ranges- Table 3.5). Hence, Eq. (3.10) was used for each stage (temperature range) and a straight line was obtained when regression analysis was carried out (Fig. 3.4) and the mechanism which yielded the highest correlation factor (R^2) was found to be best suited.

Table 3.5: Kinetic parameters of coal, rice husk and their blends.

Sample	Temperature Range (°C)		R^2		Activation Energy (E_a) kJ/mol	
	Stage 1	**Stage 2**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
Coal	350-650	NA	0.99	NA	145.9	NA
Rice husk	310-425	NA	0.99	NA	130.33	NA
20% rice husk 80% coal	250-380	400-500	0.98	0.99	58.36	64.35
30% rice husk 70% coal	200-390	400-500	0.99	0.99	67.79	76.19
40% rice husk 60% coal	210-375	385-500	0.98	0.99	72.86	81.66

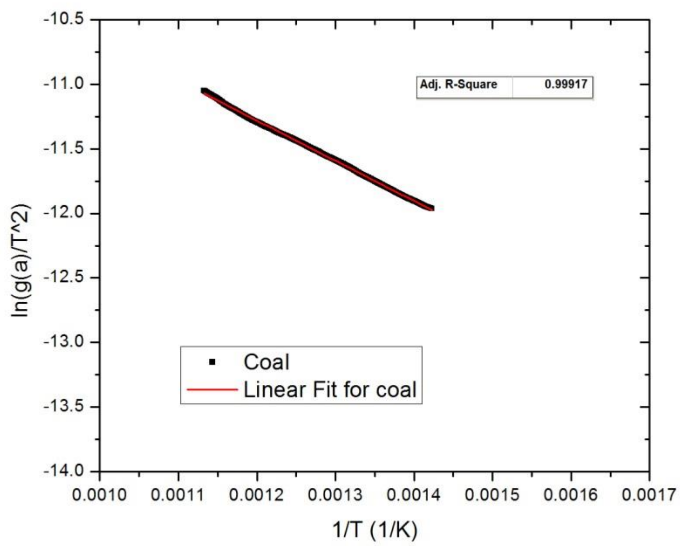


Figure 3.4: Regression analysis of sample containing 100% coal with R^2 value

For coal and rice husk, the models A1, A2, A3 and A4 shown in Table 3.5 had correlation coefficient ranging from 0.95 to 0.99. However, model A3 showed the maximum value of correlation coefficient, thus the best suited mechanism for coal and rice husk combustion is that mentioned as A3 in Table 3.5. On the other hand, the blends having 20%, 30% and 40% of rice husk had the highest correlation values at models A3, A1 and A2 respectively. Ghaly et al. 1999 also conducted their analysis on rice husk but obtained a dissimilar result due to varied variety of rice husk and the location of its procurement.

CHAPTER 4

EXERGY ANALYSIS

4.1 Introduction:

The augmented consciousness about the world's energy capitals are inadequate has caused scientists to take a serious look at the energy transformation maneuvers and to introduce new methods for improved utilization of current restricted capitals. The performance of engineering systems (power plants) is tainted by the occurrence of irreversibility's, and the entropy generation which is a portion of the magnitudes of the irreversibility's existing through the process. Greater the amount of irreversibility's, greater is the entropy generation. So, entropy can be used as a measurable amount of irreversibility's related with a process (Bejan 1988).

All of the main industrial energy operators used huge amount of fossil fuel to generate steam. The major use of steam is in food handling (57%), pulp and paper (81%), chemicals (42%), gasoline purifying (23%), and principal metals (10%). Since industrial schemes are very varied, but often have main steam schemes in common, it makes a valuable mark for energy efficiency procedures (Einstein et al. 2001). Assessment and optimization of energy related schemes can be done by exergy analysis. The energy analysis is based on the first law of thermodynamics, is the utmost usually used technique for the analysis of energy conversion procedures. Though, energy conversion does not justify for the internal losses in the process. On the other hand exergy analysis is grounded on the second law of thermodynamics and aids to classify the scale and positions of the irreversibility's in order to improve the performance of the system or process. Exergy analysis may be considered as secretarial of the use of energy and material possessions provide info on how real a process takes place towards conserving natural resources. Exergy is the valuable work probable of a system or stream as it continues to symmetry state with high opinion to a reference atmosphere. It is commonly not preserved and watched as excellence of the energy.

4.2 Approach and Methodology:

Evaluation of a thermodynamic system is a complex process and involves consideration of its components and their characteristics, chemical reactions and thermodynamic losses. The main focus of the current learning is to analyze the impacts of co-firing on the performance of system. To achieve this goal, a series of balance equations based on the exergy analysis are developed for selected component of the system. The balanced equations are presented in the study. Some specific assumptions are made to derive these balance equations, which are described in below sections. The system is analyzed based on the main assumption that the operating temperature and pressure of the constituents of the steam sequence are not changing while the feeding rate to the boiler is altered by changing fuel type and co-firing ratio. In order to investigate the effect of biomass adding in the mixture, the boiler is nourished with biomass and coal in a co-firing manner and system presentation is analyzed.

4.2.1 Exergy model analysis:

The performance of a power plant is the function of the performance of each of its individual component and sometimes the performance analysis of a component on the basis of the first law of thermodynamics may be misleading. The exergy analysis is important as it provides different insight that the energy analysis is unable to do. The exergy analysis indicates the points of irreversibility in the power plant and highlights the transformation potential of a component to extreme theoretic work under the given environmental circumstances. In this study, the exergy destruction and the exergy efficiencies of one major constituent of the thermal power plant have been analyzed and exergy losses per unit power production in the plant is calculated and used as another exergy performance analysis parameter. The exergy destruction rate resulting from the exergy equilibrium for a control volume of any plant constituent at steady-state condition is explained by Cengel and Boles (2008) and same has been used in the present work.

$$Ex_D = \left[\sum Ex_{in} + \sum Q\left(1 - \frac{T_0}{T}\right)_{in}\right] - \left[Ex_{out} + \sum Q\left(1 - \frac{T_0}{T}\right)_{out}\right] \pm W \tag{4.1}$$

Where the exergy rate of a stream is given as (Regulagadda et al., 2010):

$$E_x = E_x^{tm} + E_x^{ch} \tag{4.2}$$

In this analysis, the thermo-mechanical exergy due to mass flows crossing the control volume is calculated by using following expression (Hashem, 1991):

$$E_x^{ch} = m[(h - h_0) - T_o(s - s_o)] \quad (4.3)$$

Total exergy destruction will be the sum of exergy destruction of each component of the power plant. For the power plant, exergy efficiency will be given as:

$$\eta_{exergy} = \frac{W_{net}}{m_{fuel} \times Ex_{fuel}} \quad (4.4)$$

Where, Ex_{fuel} is the specific exergy of the biomass fuel used at the power plant. By the exergy and energy analysis, useful information required for performance improvement of the plant can be obtained.

4.3 Assumptions:

The subsequent basic conventions are made in the present work:

1. Every component is a control volume (CV) and works under steady state conditions.
2. All the gases are ideal gases.
3. Ambient temperature and pressure of the reference atmosphere are 27°C and pressure 1.013 bar respectively.
4. All the constituents of the steam cycle have adiabatic limits.
5. Kinetic and potential energy belongings are deserted.
6. Ambient air is 79% nitrogen and 21% oxygen on a volume basis. The excess air is 50% (Basu et al. 2000).
7. Radiation, bottom ash and convective heat sufferers through the boiler are neglected.
8. All carbon and sulphur in the fuel are rehabilitated to CO_2 and SO_2 respectively.

4.4 Exergy analysis of boiler:

In this section exergy analysis of boiler is carried out. Exergy efficiency of boiler and exergy destruction rate were evaluated using the above mentioned parameters. Exergy equations were formulated for boiler from methodology discussed in section 4.2.1. Layout of boiler section and exergy equations is mentioned below:

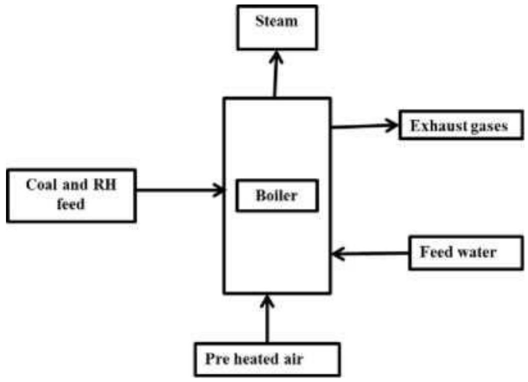


Figure 4.1: Layout of boiler.

The exergy efficiency of boiler is given by:

$$\eta_{Exb} = \frac{exergy\ of\ steam - exergy\ of\ feed\ water}{exergy\ of\ fuel + exergy\ of\ preheated\ air - exergy\ of\ exhaust\ gases} \qquad (4.5)$$

Also exergy destruction rate of boiler is given as:

$$Ex_{D\ boiler} = exergy\ of\ fuel + exergy\ of\ preheated\ air + exergy\ of\ feed\ water - exergy\ of\ steam - exergy\ of\ exhaust\ gases \qquad (4.6)$$

The exergy destruction rate of boiler is calculated to be 55.46 MW. Also, the exergy efficiency of boiler is found to be 35.1 %. There are many components in a steam power plant which causes exergy destruction but in this study only boiler part is analyzed. In the boiler, the main culprit for exergy destruction is flue gases (Naterer et al. 2010). Apart from the flue gases energy supplied to steam and to combustion reaction lead to irreversibility's, so enhancing these parameters will increase the efficiency of boiler and decrease irreversibility.

CHAPTER 5

AGGLOMERATION

5.1 Introduction:

In fluidized bed combustor (FBC) boilers, the combustion operation is adversely affected due to amount of issues related to the chemical composition of fuel ash. This composition of fuel ash and bed material has a tendency to sinter thereby forming larger agglomerates, process termed as bed agglomeration. The problem of bed agglomeration is caused due to high alkali content in fuel when fired in FBC. Generally, biomass fuels are more prone to agglomerate than coal due to high alkali content in them. Low melting temperature compounds and many other mixtures formed during combustion along with sulphur, chlorine, silica etc. causes the formation of several types of compounds known as eutectics which sticks along with ash particles and get glued to the bed. These compounds may form large agglomerates resulting in reduction of the mixing of the bed and may cause rupture of the fluidized bed, termed as de-fluidization.

5.2 Mechanism of bed agglomeration:

Composition of fuel ash related factors can adversely affect the performance of FBC boilers. Sinter formation of fuel ash leading to bed agglomeration is the common phenomena in most of the FBC boilers. Too much agglomeration can cause poor air distribution and ultimately lead to de-fluidization which needs to be avoided. The common mechanisms which tell about the formation of large agglomerates are discussed below (Loo et al. 2008):

- Formation of low viscosity liquid phase from low ash melting temperature components. This type of sintering occurs in fuel ashes having high alkali, phosphate and heavy metal content.
- At sintering temperature there are chances of solubility of solid bed particles with liquid phase. Particle-particle bonding can be stronger in this mechanism.
- There are chances of chemical reactions at the surface of bed particles which can strengthen inter-particle bonding.

In terms of ash composition biomass fuels are divided into three groups depending upon the content of calcium, potassium and silica.

- First group contains most of the woody fuels and are rich in calcium and potassium but poor in silica content.
- In second group the fuels having high silica content but low calcium and potassium content are kept. Rice husk, sugarcane bagasse, grass etc. are lies in this group.
- Sunflower seeds and rapeseed cakes belong to group three and are characterized by high calcium, potassium and phosphorus content. (Hiltunen et al. 2008).

When biomass fuels belong to group one are fired in FBC boiler, high potassium and calcium content can react with quartz particles present in bed and form a thick layer of calcium and potassium silicates. This layer gets thicker with time and became sticky leading to formation of large agglomerates. Agglomeration problem can be avoided by regularly discharging the ash and feeding fresh sand to the bed. Ash of these biomass fuels starts to sinter around 900°C to 1000°C. Coal ash does not have these difficulties in above mentioned range. The alkalis and silicates are not in free form to react as in biomass fuels. Hence co-firing these biomass fuels can cause difficulties in operation of FBC boiler.

In second group most of the fuels are herbaceous or biofuels. These fuels are very diverse in combustion and chemical properties. Some fuels like cereals and straws contains high calcium and potassium and can sinter around 700-900°C. The mechanism of agglomeration here is different from group one. Here instead of formation of layers, sticky and partially melting particles cause agglomeration. Straw ash contains potassium chloride and low melting point potassium silicates. Another fuel contains in this group is rice husk, it has high silica content and most of the ash contains SiO_2 particles making it completely different from straws and cereals. Due to high SiO_2 content its ash fusion temperature is around 1500°C. Problems like fouling and slagging are prevented by rice husk when co-fired with other fuels. Thus it is very safe to co-fire rice husk in FBC boilers.

Biomass fuels in group three covers big amount of calcium, potassium and phosphorus along with high chloride content. Ash sintering can start around 700°C and complete ash can melts around 1200°C. These fuels are not extensively used and can be co-fired with coal in low ratios. (Hiltunen et al. 2008).

5.3 Materials and methods:

5.3.1 Materials:

Trident Ltd. uses mixtures of coal (S-III) and rice husk for power generation. In this present study, bed agglomeration caused by ash of blended fuel is predicted. Additionally, to compare the results two coal samples one from Bathinda thermal power plant (S-I) and other from Yamuna Nagar thermal power plant (S-II) and one sample of bagasse fuel is taken. Three coal samples were blended with biomass samples and the behavior of their ashes were related to bed agglomeration. In each of prepared sample biomass fuel replaces 30% of coal by weight.

5.3.2 Proximate and chemical analysis:

Characterization of samples of coal and rice husk for obtaining the chemical composition and proximate analysis was done. Proximate analysis was done by the method prescribed in IS-1350; part I, on air dried basis. The results of proximate analysis are shown in Table 5.1.

Table 5.1: Proximate analysis of coal and biomass samples (air-dried basis)

Parameters	Coal S-I	Coal S-II	Coal S-III	Rice Husk	Bagasse
Total Moisture %	4	2.5	6.33	9	8.48
Volatile Matter %	22	21.5	29	62	76.58
Ash %	32.5	43	36.34	10.5	2.92
Fixed Carbon %	41.5	33	28.33	18.5	12.02

The morphological characteristics and the chemical composition of the coal samples were obtained by SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy) techniques respectively. In depth procedure was discussed in section 3.2.1. Table 5.2 shows the chemical composition of all the coal and biomass samples:

Table 5.2: Chemical composition of the coal and biomass samples as obtained by the EDS.

Samples	Chemical Composition								
	C	O	Al	Si	S	Ca	Cu	Fe	K	Na
Coal S-I	60.4	28.72	3.88	4.96	1.04	--	1.19	0.99	--	--
Coal S-II	57.9	3.58	2.68	4.83	0.23	0.38	1.29	0.94	0.14	--
Coal S-III	74.19	24.2	0.03	15.37	0.16	--	--	0.52	0.14	--
Rice Husk	42.54	38.82	4.13	13.17	0.14	--	--	--	0.59	--
Bagasse	55.49	34.58	--	9.54	--	--	--	--	0.17	0.21

5.3.3 Experiment details:

Researchers have used many methods to predict bed agglomeration like Yue and Kolaczkowski used an equation to learning the effect of minimum fluidization velocity on portion of number of lively holes. (Skrifvars et al. 1999) used three different methods for fusion test; compression based sintering test and lab scale FBC test to predict bed agglomeration.

However in this study practical approach is used in which artificial bed of stainless steel bowls having 2 mm diameter hole at the bottom is prepared (Fig. 5.1) for bed agglomeration. Two grams of blended fuel sample (70% coal sample+30% biomass fuel) were taken in these steel bowls and kept in a muffle furnace at 900°C for one hour. This process is done for individual samples of coal and rice husk. After taking out samples from muffle furnace their agglomeration with steel bowls is observed. Agglomeration begins when temperature of ash formed goes above the ash fusion temperature (AFT). Higher temperature than AFT causes ash to melt and causes adhesion of bed particles.

(a) (b)

Figure 5.1: Stainless steel bowls having holes at the bottom.

Another method is used in this study for predicting bed agglomeration. Free swelling index (FSI), a fuel property is correlated to bed agglomeration. FSI is measured experimentally by taking one gram sample of coal in a silica crucible. This silica crucible is kept covered from top and is heated to a temperature of 900°C keeping in mind the average bed temperature of 850°C. FSI test is conducted for both coal and rice husk samples. FSI provides a measure of sticky nature or binding propensity of particles (Reddy et al. 1999). The larger the FSI number more is the tendency of particles to swell leading to agglomeration.

5.3.4 Mathematical analysis:

Agglomeration can be related to minimum fluidization velocity. Nozzle holes in FBC become inactive once agglomeration starts results in high fluidization velocity. In this section the effect of minimum fluidization velocity on the portion of lively holes is analyzed and the approach given by Reddy et al. (1999) has been used. A partially operated distributor plate is shown in Fig. 5.2.

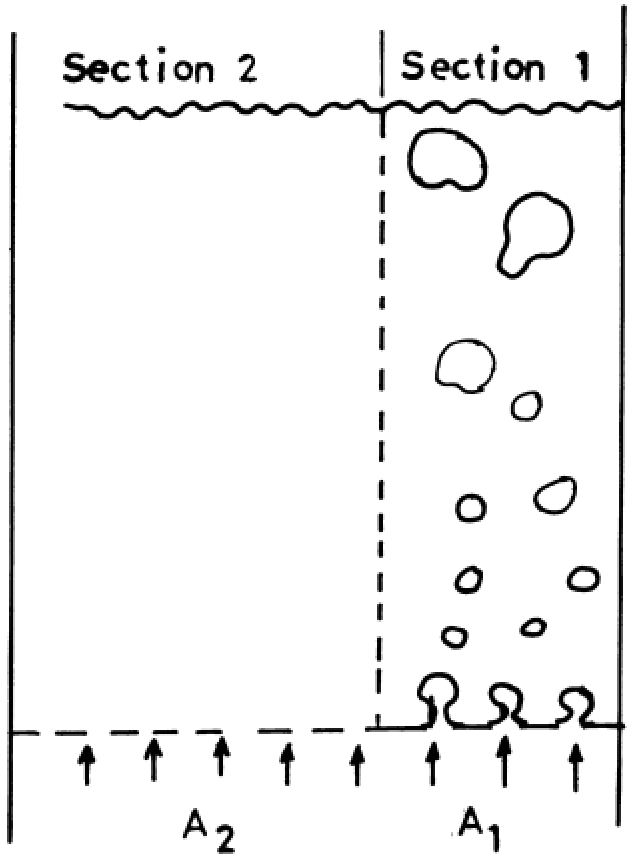


Figure 5.2: Gas distributor model showing partial operations.

Generally the flow of gas is through to the higher voidage part of bed. Therefore this section has lower pressure drop in bed. Hence, two sections of different voidage occur, as shown in Fig. 5.2. Section 1 has its voidage greater than e_{mf} and is freely bubbling. The values of superficial gas rates in these sections are U_1 andU_{mf}.

For the arrangement shown in Fig. 5.2 to be in symmetry, the pressure drip around distributor plate and bed in both units necessity is similar, i.e.

$$\Delta P_{D1} + \Delta P_{B1} = \Delta P_{D2} + \Delta P_{B2} \tag{5.1}$$

The pressure drop across a lone orifice in the distributor plate is given as

$$\Delta P_o = \frac{\rho_f}{2gC_D^2} U_o^2 \tag{5.2}$$

Hence, the difference between the distributor pressure drips of the two units is given by:

$$\Delta P_{D1} - \Delta P_{D2} = \left(\frac{A_1}{N_1 a_o}\right)^2 \frac{\rho_f U_1^2}{2gC_D^2} - \left(\frac{A_2}{N_2 a_o}\right)^2 \frac{\rho_f U_{mf}^2}{2gC_D^2} \quad (5.3)$$

For a multi-orifice distributor with a steady range of holes, each of the same dimensions, we have

$$\frac{A_1}{N_1} = \frac{A_2}{N_2} = \frac{A_T}{N_1} \quad (5.4)$$

Therefore,

$$\Delta P_{D1} - \Delta P_{D2} = \frac{\rho_f}{2gC_D^2 \emptyset^2}\left(U_1^2 - U_{mf}^2\right) \quad (5.5)$$

Where $\emptyset = N_{ao}/A_T$, which may be entitled orifice density.

The total gain in bed height can be calculated from a volumetric balance given below:

$$\Delta H = \frac{\bar{e}_B (N_1/N) H_{mf}}{1 - \bar{e}_B\, N_1/N} \quad (5.6)$$

The difference between the pressure drips around the two units due the pressure of bubbles in unit 1 is given by

$$\Delta P_b = \rho_s g\left(1 - e_{mf}\right)\left(H_{mf} + \Delta H\right)\bar{e}_B \quad (5.7)$$

Using ΔH from Eq. (5.6), Eq. (5.7) becomes

$$\Delta P_b = \bar{e}_B \Delta P_{Bmf} + \frac{\bar{e}_B^2 \Delta P_{Bmf}\, N_1/N}{1 - \bar{e}_B\, N_1/N} \quad (5.8)$$

Where

$$\Delta P_{Bmf} = \rho_s g\left(1 - e_{mf}\right) H_{mf} \quad (5.9)$$

Once more time the variance between the pressure drips across the two units because of the jets formed above the active orifices, according to (Fakhimi et al. 1970) is given by

$$\Delta P_s = (1 - 2/\pi)\frac{h_s \Delta P_{Bmf}}{H_{mf}} \quad (5.10)$$

Uniting the difference with that due to occurrence of the bubbles, we obtain:

$$\Delta P_{B2} - \Delta P_{B1} = \Delta P_b + \Delta P_s$$
$$= \bar{e}_B \Delta P_{Bmf} + \frac{\bar{e}_B^2 N_1/N}{1 - \bar{e}_B N_1/N}\Delta P_{Bmf} + (1 - 2/\pi)\frac{h_s \Delta P_{Bmf}}{H_{mf}} \quad (5.11)$$

0.1 to 0.2 is the value of the bubbles voidage e_B. Therefore, Eq. (5.11) can be manipulated as the second stint on the right hand of is comparatively minor and can be deserted. Equating Eq. (5.5) and (5.11),

$$\frac{\rho_f}{2gC_D^2\emptyset^2}\left(U_1^2 - U_{mf}^2\right) = \bar{e}_B \Delta P_{Bmf} + (1 - 2/\pi)\frac{h_s \Delta P_{Bmf}}{H_{mf}} \qquad (5.12)$$

Re-arranging the above equation, we can get

$$U_1 = \left[\frac{\Delta P_{Bmf}\left\{\bar{e}_B + (1 - 2/\pi)\frac{h_s}{H_{mf}}\right\}}{\frac{\rho_f}{2gC_D^2\emptyset^2}} + U_{mf}^2\right]^{1/2} \qquad (5.13)$$

However,

$$U = \frac{N_1}{N}\left(U_1 - U_{mf}\right) + U_{mf} \qquad (5.14)$$

Or

$$\frac{N_1}{N} = \left(U - U_{mf}\right)/\left(U_1 - U_{mf}\right) \qquad (5.15)$$

Putting the value of U_1 from Eq. (5.13) in Eq. (5.15), we get,

$$\frac{N_1}{N} = \frac{U - U_{mf}}{\left[\Delta P_{Bmf}\left\{\bar{e}_B + (1 - 2/\pi)\frac{h_s}{H_{mf}}\right\} \times 2gC_D^2\emptyset^2/\rho_f + U_{mf}^2\right]^{1/2} - U_{mf}} \qquad (5.16)$$

The relation between U_{mf} obligatory and number of lively nozzle holes in the plate is shown in Eq. 5.16. According to this as U_{mf} increases, there is decrease in the number of lively holes in distributor plate. If coarser size particles are fired the required U_{mf} increases and some of the nozzles in distributor plate become sedentary. Due to insufficient source of air near these nozzles, agglomeration and de-fluidization may happen.

5.4 Results:

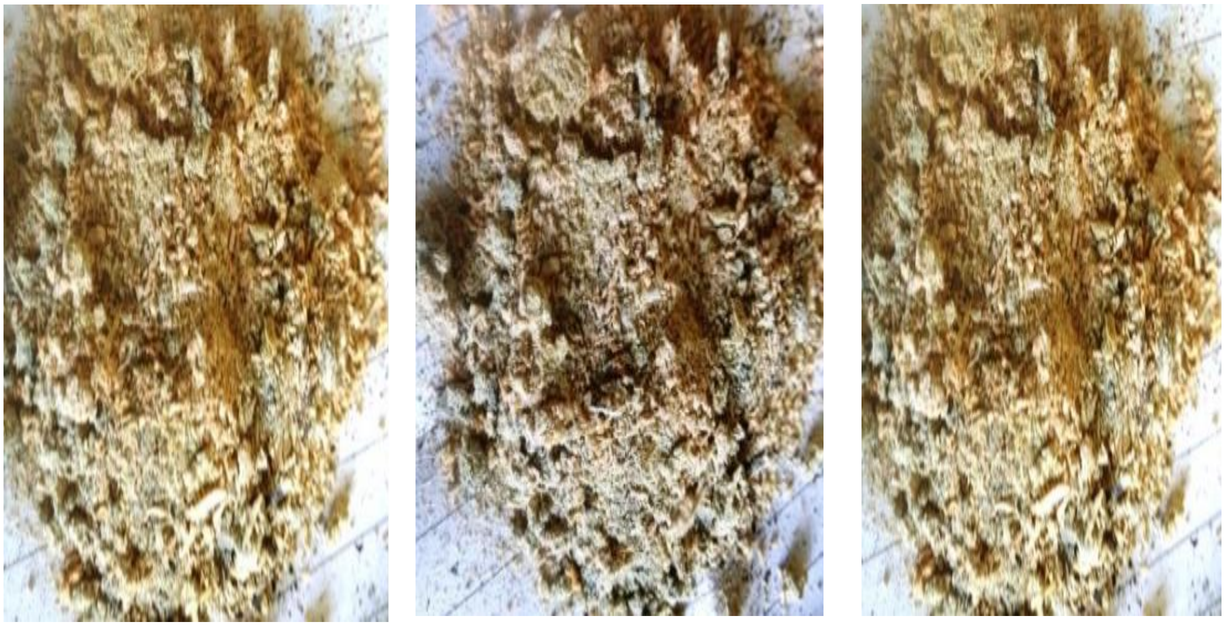
The results obtained from the present work also implies with the same behavior of rice husk ash as discussed above. It is clear from chemical composition that rice husk and coal samples has majority of silica content which will result in high SiO_2 content in their respective ashes. The average bed temperature is around 900°C, while AFT is around 1500°C for these types of ashes. Therefore, the rice husk ash (80-90% SiO_2) would not fuse, but rather sinter (Fig. 5.3) causing no agglomeration with bed. The results are in agreement with the studied plant Trident Ltd., Barnala, Punjab where boiler is co-fired with 30% rice husk with 70% coal and no bed agglomeration is reported in the plant.

(a) **(b)** **(c)**

Figure 5.3: Sintered ash without any sign of fusion with bed: (a) RH and coal S-III (co-fired); (b) RH and coal S-II (co-fired); (c) RH and coal S-I (co-fired)

The results are also in agreement with another plant in Tha Toom, Thailand which co-fires 50% RH with anthracite coal with no bed agglomeration. The results are also in agreement with the study performed by Fernando (2012).

Another biomass fuel that is sugarcane bagasse is co-fired with three different coal samples for predicting the agglomeration. The results are similar to above results but size of sintered particles is very large as compared to the ashes of rice husk blends as shown in Fig. 5.4.



(a) **(b)** **(c)**

Figure 5.4: Sintered ash with large sticky particles: (a) BG and coal S-III (co-fired); (b) BG and coal S-II (co-fired); (c) BG and coal S-I (co-fired)

Another factor that can help in agglomeration is FSI. All the individual samples were tested for FSI and results are mentioned in Table 5.3. As discussed earlier FSI is measured with top of crucible covered which will cut the air supply and there will not be any combustion. This similar phenomenon is generally observed in FBC boilers, due to variable size of coal and rice husk, finer size particles present in fuel mixture were trapped in air supply nozzles, will become inactive and air supply near these nozzles will be insufficient. At that time if the fuel has large FSI then particles will swell and behave like jelly resulting in formation of large agglomerates.

Table 5.3: FSI of various fuel samples.

Sample	**FSI**
S-I	7-8
S-II	5-6
S-III	0-1
Rice husk	0-1
Bagasse	4-5

S-III and rice husk has very low value of FSI which lowers the chances of agglomeration. On the other hand S-I, S-II and bagasse has relative higher values than other fuels. There are good chances of agglomeration when higher FSI fuels burned in FBC boilers.

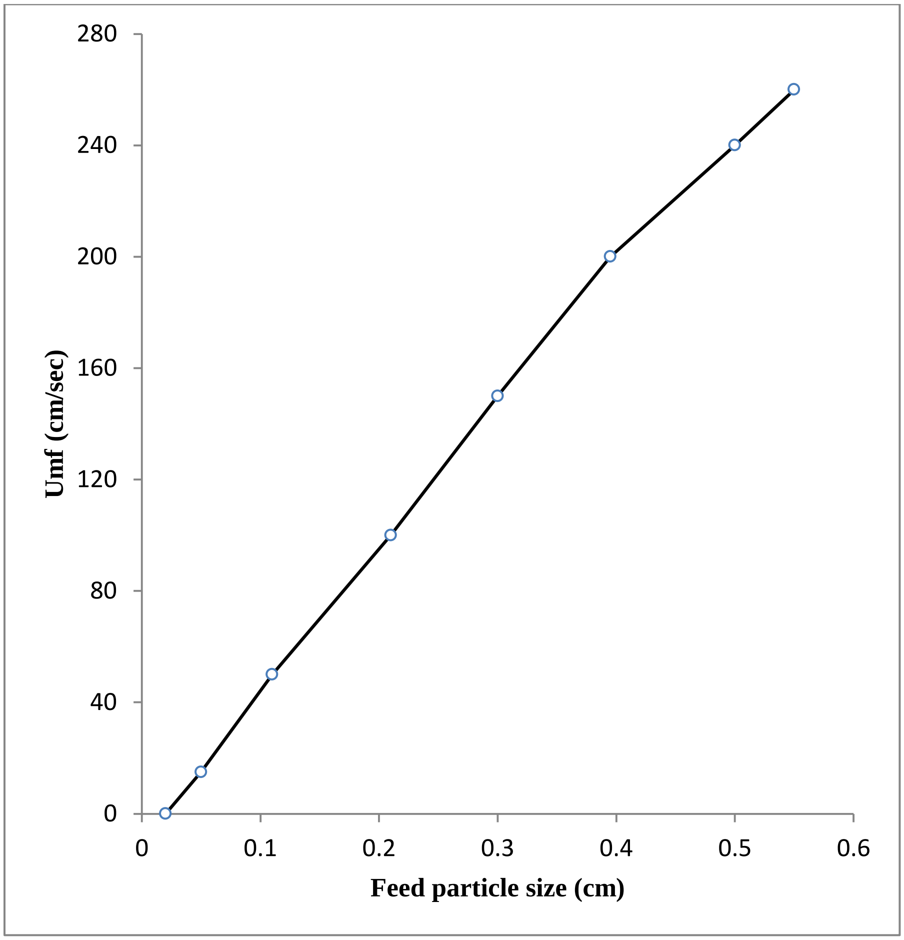


Figure 5.5: Effect of particle size on minimum fluidization velocity (Reddy et al. 1999)

Figure 5.5 displays the distinction of minimum fluidization velocity with feed particle size. With increase in particle size the velocity to initiate fluidization increases. It has been observed that as the feed particle size surges the ash content increases which increase the density of particles or in other words, coarser particles are denser.

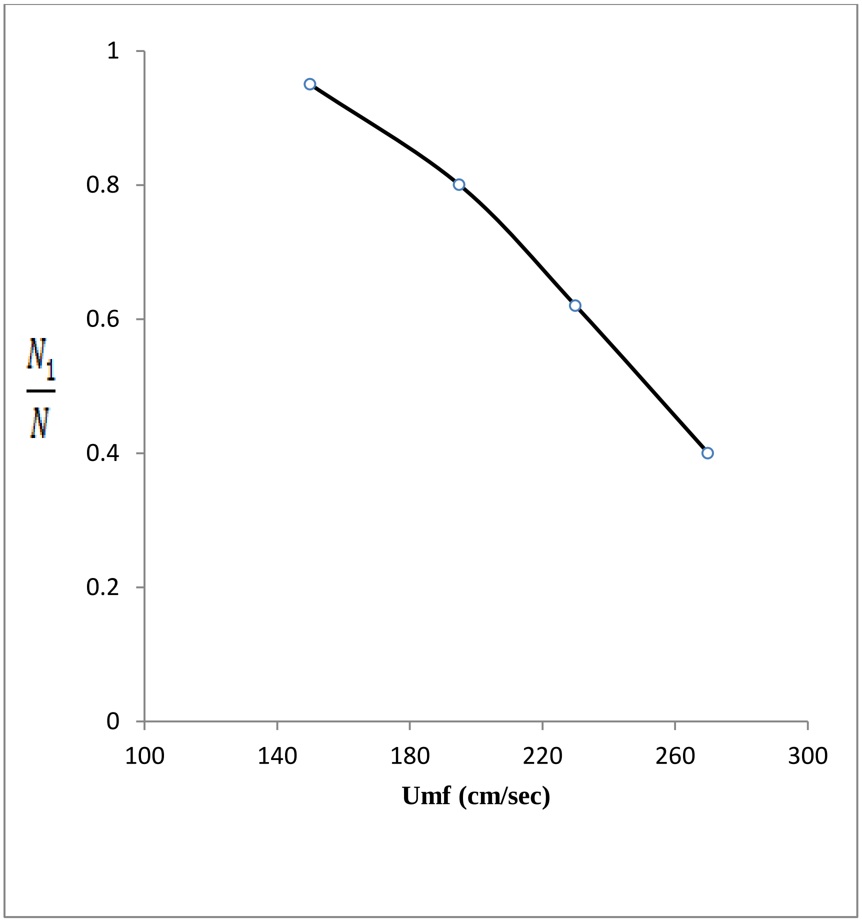


Figure 5.6: Effect of fluidization velocity on fraction of active number of holes.

The association among minimum fluidization velocity and the portion of lively holes is obtained from Eq. 5.16 and is shown in Fig. 5.6. It is clear that as the number of coarser feed particles increases, the number of slothful holes in distributor plate upsurges. Near these inactive holes air supply will be insufficient for fluidization and whole incineration. The temperature near these nozzles will be sufficient for making particles sticky and soft. These sticky and soft particles form large agglomerates leading to de-fluidization of entire bed.

CHAPTER 6

ECONOMIC ANALYSIS

6.1 Introduction:

In recent chapters various technical aspects were discussed about the feasibility of a 20 MW FBC based co-fired thermal power plant. One other important factor that involves is the cost of co-firing. As discussed in literature some plants are economically good whereas at the same time some are very costly. Depending on the type of biomass fuel and location, the cost of co-firing can be lower or higher as compared to pure coal firing. Economics of co-fired plant are greatly affected by biomass prices, transportation cost etc. In this present study economic analysis of 20 MW co-fired thermal power plant is carried out. Biomass fuel used is rice husk which replaces 30% of coal by weight. The rice husk fuel is collected from nearby areas. There is no cultivation of rice husk in the plant. So there is no generation cost involved for rice husk.

6.2 Methodology:

Break-even analysis approach is used to carry out economic analysis of the plant. This analysis is conducted for one year taking 2015 as a base year. Data for fixed cost, variable cost, revenue generated and operating hours for year 2015 was collected. Then total annual cost was calculated, as the sum of total fixed cost and total variable cost. To locate break-even point, total annual cost and annual revenue generated was plotted against number of operating hours. The total revenue line starts from origin whereas total cost line starts from annual fixed cost point on graph. Break-even point is located as the intersection point of total revenue and total cost. That point provides operational hours for year 2015, below which the plant is in loss and above that point plant is in profit. Net annual profit can be expressed as:

$$Annual\ net\ profit = Total\ annual\ variable\ cost + Total\ annual\ fixed\ cost - Anuual\ revenue\ generated \quad (6.1)$$

6.3 Results:

For evaluating the economic analysis various costs were taken from the plant for the year 2015. The plant worked for 8500 hours in 2015. Rice husk purchased from nearby areas is kept in open like coal. No separate storage system is available.

Table 6.1: Annual profit analysis of plant taking into account fuel consumption and fuel cost, total fixed cost, total variable cost and total revenue generated.

Fuel consumed (in metric ton (MT)) and fuel cost (Rupees per MT) for year 2015	
Coal consumed	32130
Rice husk consumed	13770
Total fuel consumption	45900
Average cost of fuel	3760
Annual fixed cost in Rupees for year 2015	
Wages of workers	3600000
Wages of employees	4800000
Diesel cost	28993000
Plant machinery cost taking plant life 25 years	400000000
Total fixed cost	437393000
Annual variable cost in Rupees for year 2015	
Inspection and Maintenance cost	4500000
Fuel cost including transportation cost	172584000
Total variable cost	217584000
Annual revenue generated in rupees for year 2015	
Net saleable energy in kWh	122640000
sale rate in Rupees per kWh	7
Total revenue Generated	858480000
Annual net profit in Rupees for year 2015	
Total revenue generated	858480000
Total fixed cost	437393000
Total variable cost	217584000
Total profit	203503000
Percentage profit	23.70%

Table 6.1 shows the profit analysis of plant evaluated using Eq. (6.1) consisting of detailed fixed, variable costs for the year 2015. Fuel consumption and fuel prices are also discussed in Table 6.1. As shown in the Table 6.1, the biggest cost involved is the plant machinery cost and it affects the total economics of the plant. Total machinery cost per year is obtained by dividing total machinery cost by plant life in years. Here total machinery cost includes the cost of land on which plant if situated. In this case plant life is taken as 25 years. The annual fuel cost is

obtained by multiplying fuel consumed with fuel cost per MT. sale rate per unit of electricity is rupees 7, which is quite high in Indian market and hence is the main reason for 23.70% annual profit. Fig. 6.1 shows the break-even analysis of plant in terms of operating hours. The break-even point comes out to be 5831.8 hours and below this point plant will not fetch any profit or we can say plant is in loss. After 5831.8 hours plant starts to give profit and that profit was mentioned in Table 6.1.

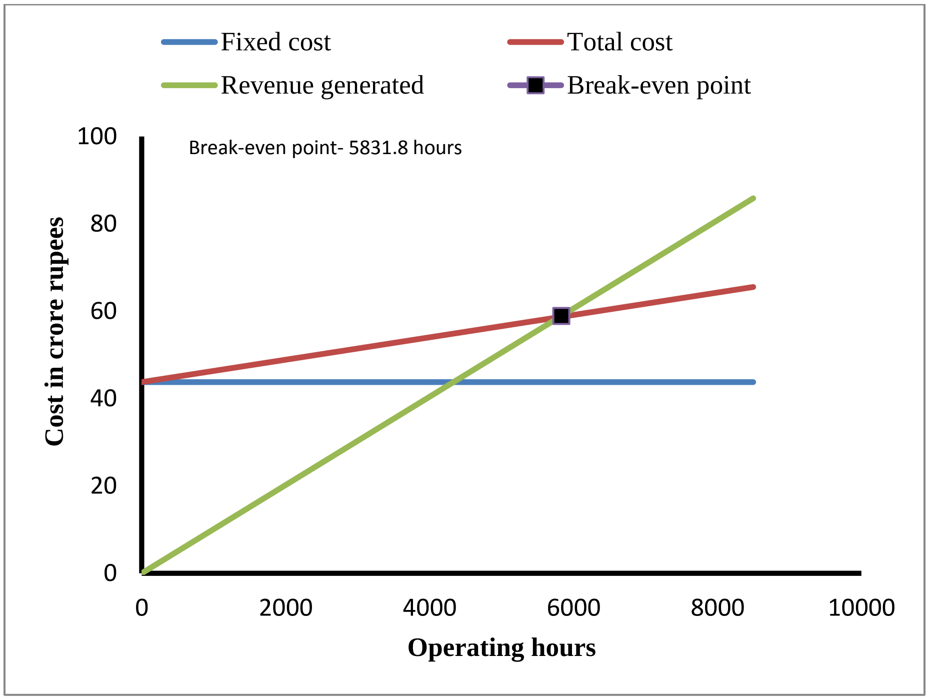


Figure 6.1: Break-even point analysis in terms of operating hours.

Sale rate of electricity is the main reason for high profit of plant, if this price is gone down then definitely profit will come down and break-even point will come late on the graph.

Change in fixed cost and variable cost also affect the break-even point (shown in Fig. 6.2 and 6.3). Reducing 20% of fixed cost will drop the break-even point to 4665.4 hours and profit will be increased by 43% whereas reducing 20% of variable cost will take break-even point to 5399.8 hours and profit increase will be 21.38%.

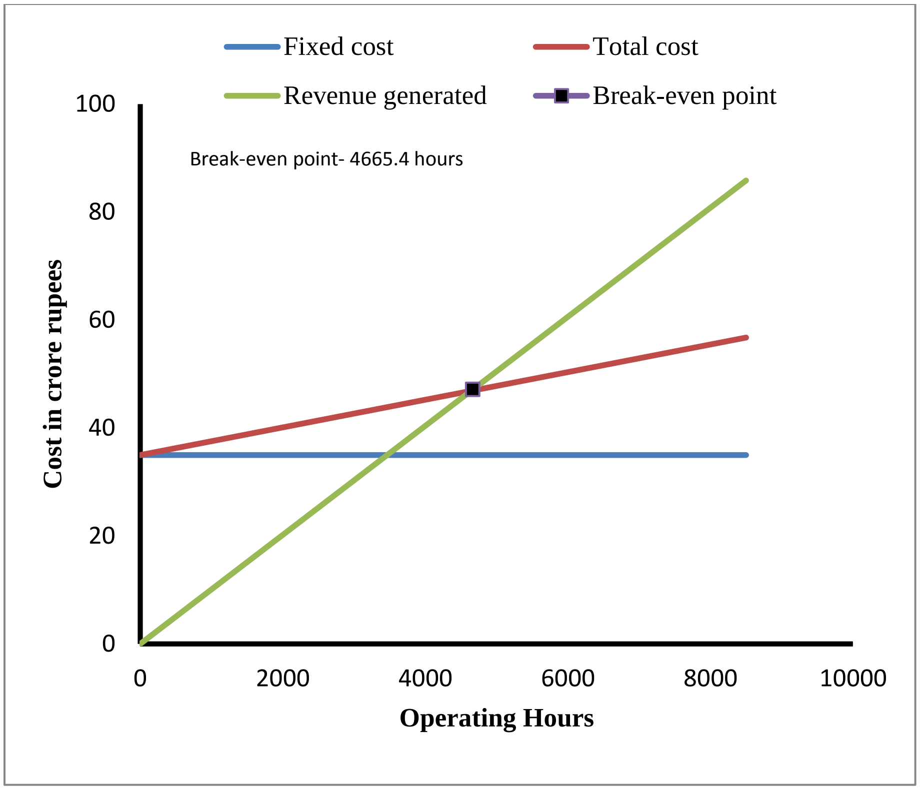


Figure 6.2: Break-even point analysis with 20% less fixed cost in terms of operating hours.

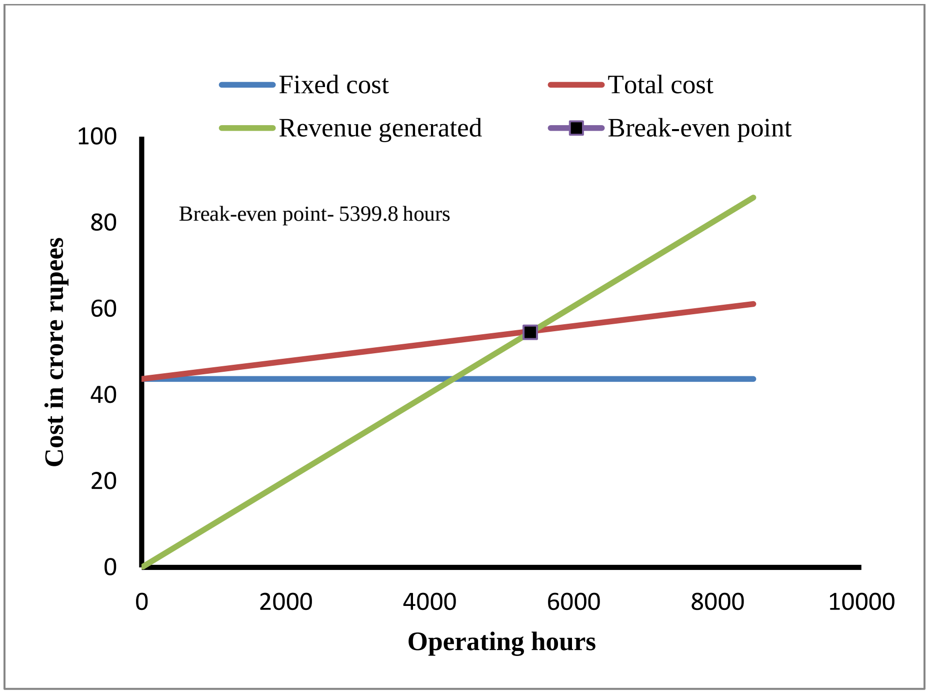


Figure 6.3: Break-even point analysis with 20% less variable cost in terms of operating hours.

It has been seen that operating hour point comes earlier on reducing fixed cost by 20% than reducing variable cost by same amount which is clear from the fact that fixed cost contributes more in total cost than variable cost contributes. Also, profit obtained is more in reducing the fixed cost. So it is recommended that to reduce fixed cost by 20% to have maximum profit from the plant.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE OF WORK

7.1 Conclusions:

Present study investigated combustion and kinetic analysis of coal and rice husk co-fired power plant. In addition to this exergy analysis of boiler, agglomeration of ash particles with bed material and economic analysis of plant is done and following are conclusions of results obtained:

- Rice husk fuel has lower calorific value and higher volatile content than coal. So, its volatile content evaporates prior to coal. As seen from TG and DTG curves rice husk ignites easily than coal. On the other hand, their blends burned completely below 700°C.
- Co-combustion of coal and rice husk blends consists of mainly three stages i.e. moisture evaporation (below 140°C), volatile release (140-370°C) and char combustion (370-600°C). It can be interpreted from DTG curve that as the blending ratio of rice husk increases, the ignition temperature, burnout temperature and combustion rate of blends decreases.
- The kinetic parameters obtained by using Coats-Redferns method provided the best suitable solid state mechanism that could be used for kinetic analysis. The results are in agreement with TG and DTG data.
- Exergy analysis of boiler has been done and exergy destruction rate of boiler is calculated to be 55.46 MW. Also, the exergy efficiency of boiler is found to be 35.1%.
- For rice husk blends no agglomeration has been observed in stainless steel bowls due to high percentage of SiO_2 is fuel ash. SiO_2 has AFT of the order 1500°C whereas bed average temperature is 850°C. Similar results were observed for bagasse blends.
- FSI of S-III and rice husk shows values close to zero which explains the non-sticky nature of fuel particles in bed during combustion. For samples S-I, S-II and bagasse FSI values are high and can lead to formation of large agglomerates.
- High electricity sale rate of Rs. 7 per unit results in 23.70% profit of the plant. Breakeven

point in terms of operating hours was found to be 5831.8 hours which definitely will go up with decrees in sale rate.

- Break-even point in terms of operating hours arrive earlier on reducing fixed cost by 20% rather than reducing variable cost by 20%. Also, profit earned is more when fixed cost is reduced.

7.2 Future scope of work:

- Combustion behavior can be evaluated by co-firing coal with higher ratios of biomass fuels and by co-firing number of biomass fuels.
- Exergy analysis of other components can be done to find out exergy destruction efficiency of each component.
- The method adopted for the study of agglomeration along with EDS testing of agglomerates can be used for other fuels also.
- Break-even point in terms of operating hours can be lowered by various costs leading to more profit.

CHAPTER 8

REFLECTIONS AND PUBLICATIONS

8.1 Reflections:

- During determination of moisture content, the crucible is generally placed in a desiccator before placing them into the muffle furnace. During the transfer of crucible from desiccator to muffle furnace, there are chances of errors in the readings due to inclusion of external moisture.
- There are chances of errors in values obtained by thermo-gravimetric analyzer due to vibrations in equipment.
- There are chances of non-uniformity in the holes prepared on stainless steel bowls used during testing of agglomeration.

8.2 Publications:

- **Conference paper:** Kumar, S., Saini, N., and Mohapatra, S.K. 2016. Producer gas production from cotton stalk and sugarcane bagasse in a downdraft gasifier: composition and higjer heating value investigation. *Journal of Basic and Applied Engineering Research* 3 (12): 10341037.
- Kumar, S. and Mohapatra S.K. 2017. Study of combustion and kinetic characteristics of rice husk co-fired with coal in different proportions in a 20MW power plant. *Energy Soures, Part A: Recovery, Utilization, and Environmental Effects*- Under Review.
- Kumar, S. and Mohapatra S.K. 2017. Bed agglomeration and economic analysis of co-firing based 20 MW fluidized bed thermal power plant. *Case studies in thermal engineering*- Under Review.

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