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A COMPARATIVE TECHNO-ECONOMIC ANALYSIS ON FURNACE OIL AND RETROFITTED BRIQUETTE BOILERS

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ABSTRACT

Furnace oil is atomized with air in the burner and fired, which produces hot flue gases that pass into the boiler tubes to generate steam. The furnace oil fired boilers contribute to green house gas emissions and secondary pollutants. Briquette as a fuel to address these problems is a better alternative. This work deals with the fuel system conversion of an existing fire tube boiler running with furnace oil to saw dust briquettes. Further the boiler capacity is increased by mounting a water wall assembly. The efficiency of this combined fire tube and water tube boiler is determined by using indirect method approach also called as heat-loss method as per Indian Standard for boiler efficiency testing IS - 8753 as well as by American Society of Mechanical Engineers, Power Test Code ASME PTC 4.1. The emission measurements are carried out by portable flue gas analyzer. The efficiency of boiler when fired with briquettes is found lower than that when fired with furnace oil. A significant reduction in the operating cost of boiler is achieved by fuel conversion technology. The emissions of furnace oil boiler are compared with that of briquette boiler. The sulphur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2) emission levels are low while firing briquettes. Carbon monoxide (CO) emission level due to incomplete combustion of fuel is more when firing briquettes. This conversion of fuel system utilizing briquettes in boiler offers many economical, social and environmental benefits.

Keywords: boiler, briquette, emissions, retrofication.

INTRODUCTION

The usage of fossil fuels has harmful effects on environment as well as on human. The emissions from the boilers include sulphur oxides, nitrogen oxides, carbon dioxide causing acid rains, global warming, respiratory problems, lung diseases, asthma etc. Fuel selection is one of the most important factors in minimizing the atmospheric emissions. Increasing energy demand, reduction in greenhouse emissions, and the need for reduced dependence on fossil based fuels has resulted in the need to use biomass for energy generation. Biomass is the name given to any organic matter which is derived from plants. Briquettes are one kind of biomass manufactured from agricultural and forest wastes. Briquetting is a way to convert loose biomass residues such as sawdust, straw or rice husk into high density solid blocks that can be used as a fuel. Sawdust, a milling residue is available in huge quantity which can be briquetted easily. These biomass briquettes replace fossil fuels for industrial processes. They are cleaner and easier to handle and cut greenhouse gas emissions. Furnace oil used in boiler can be totally substituted by briquettes with an equivalent ratio of 2.1:1 kg/l on the basis of calorific value [1].

The aim of this work is to provide a state-of-the-art overview of the grate firing of biomass (sawdust) briquette boiler used for steam generation in M/s ABC Ltd. The capacity of the boiler is enhanced by mounting a water wall assembly. The efficiency of the boiler before and after retrofitting is compared. The emissions of the boiler before and after retrofitting are measured and compared. The economic potential with the fuel system conversion is determined.

Manoj Kumar *et al,* [1] reviews methods used to convert furnace oil fired boiler to fire briquettes. A similar boiler fuel switch over from residual fuel oil to briquettes at Color Chem. Ltd. and Pfizer Limited is carried out as a Clean Development Mechanism (CDM) project under host country India, with CDM Executive Board of United Nations Framework Convention on Climate Change (UNFCCC) [2, 3]. L.S. Johansson [4] experimentally investigated that pellet boilers are ecologically sustainable heating options as they do not contribute to the climate change. O. Sippula [5] determined that heavy fuel oil combustion produced considerable SO_2 and NO_x emissions than those of wood boilers. V. K. Verma [6] experimentally determined that the NO_x emissions were found to be minimum for wood pellet boiler. Morten Tony Hansen, Anna Rosentoft jein [7] mention that flue gas emissions from wood pellet firing have the smallest environmental impact. Jo chau [8] reviews that combustion of wood biomass reduces over 3,000 tones of CO_2 equivalent greenhouse gases annually.

RETROFICATION OF BOILER

The existing boiler (Figure-1) in M/s ABC Ltd. is a horizontal fire-tube boiler fueled with furnace oil. Fuel shift from present oil firing to solid fuel becomes inevitable owing to the rise in fuel cost. In view of this, the fuel system of the boiler has been changed from furnace oil to briquettes. The technology involves a retrofitting operation where a burner firing furnace oil is removed and a biomass based externally fired grate system is arranged.

Figure-1. Furnace oil boiler (before retrofication).

Figure-2. Briquette boiler (after retrofication).

A forced draft fan delivers air to the furnace. Briquettes are fed from one end on to the grates and the ash formed due to combustion is collected at the bottom. With increase in steam requirement of the plant, the boiler capacity is also enhanced. The capacity of the boiler is increased by mounting a water wall assembly over the grates. It has a heating surface area of 46.00 m^2. A down comer header and a riser header interconnected with a set of 24 tubes constitute the water wall assembly. The down comer header is a steam drum and the riser header is a water drum. The external grate unit and water wall are surrounded by refractory brick construction. After retrofication, the modified boiler is a combination of fire tube and water tube boiler (Figure-2).

EXPERIMENTATION

Fuels

The physico-chemical and thermal characteristics of furnace oil and sawdust briquettes are as presented in Table-1. The carbon content of briquettes is 48.55 % and that of furnace oil is 87 %. The moisture and oxygen contents of briquettes are 37.98 % and 48.55 %.

Table-1. Properties of fuels.

Fuel properties	**Units**	**Furnace oil**	**Briquette** (saw dust)
Type of fuel	state	Liquid	Solid
Gross calorific value	kJ/kg	42 677	20 087
Specific gravity	----	00.93	----
Bulk density	----	----	00.65
Carbon	%m	87.00	48.55
Hydrogen	%m	11.00	06.99
Oxygen	%m	01.03	41.93
Sulphur	%m	03.50	00.10
Nitrogen	%m	---	00.80
Moisture	%m	---	37.98
Ash	%m	---	01.63

Briquettes have a density twice that of fuel wood. Porosity is very low and, accordingly, char produced during combustion is denser than wood. The manufacturing process is extremely simple. Raw materials fed into a hopper are forced-fed between the punch and die, resulting in high compression and hence high temperature. Cylindrical briquettes are formed owing to carbonization achieved by hardening of surface.

Combustion

Combustion refers to the rapid oxidation of fuel accompanied by the production of heat. Complete combustion occur when all of the energy in the fuel being burned is extracted and none of the carbon and hydrogen compounds are left unburned. Complete combustion will occur when the proper amounts of fuel and air (fuel/air ratio) are mixed for the correct amount of time under the appropriate conditions of turbulence and temperature. Complete combustion of a fuel is possible only in the presence of an adequate supply of oxygen (O_2).

$C + O_2 \rightarrow CO_2 + 33840$ kJ/kg of Carbon (1)

$2\,C + O_2 \rightarrow 2\,CO + 10172$ kJ/kg of Carbon (2)

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Control of the combustion process is very important to efficient boiler operation. Incomplete fuel combustion represents wasted energy and results in increased CO emissions. Although combustion of liquid and gaseous fuels typically produces very low CO emissions, control of unburned carbon in boilers that burn solid fuel is an important design and operating concern. Carbon burnout is dependent on fuel properties, boiler and firing system characteristics, and unit operating conditions. In most instances, the loss due to unburned carbon from solid fuel combustion is controllable to below 0.5 % of the fuel fired [9]. CO can be regarded as a good indicator of combustion quality. For a given system, CO emissions will be lowest at a specific air to fuel ratio, higher excess air will result in decreased combustion temperatures, while lower excess air will result in inadequate mixing conditions. It is critical that the introduction of air to reduce CO emissions is done accurately by Van Loo, *et al*, [10]. The rate of CO emissions from combustion sources depends on the oxidation efficiency of the fuel [11-14].

SO_x emissions are generated during oil combustion from the oxidation of sulphur contained in the fuel [15-21]. Uncontrolled SOx emissions are almost entirely dependent on the sulphur content of the fuel and are not affected by boiler size, burner design, or grade of fuel being fired.

Oxides of nitrogen formed in combustion processes are due to thermal NOx, or fuel NOx [15-20]. Fuel nitrogen conversion is an important NOx forming mechanism in residual oil fired boilers [22-30]. It can account for 50 % of the total NOx emissions from residual oil firing.

Emission measurement

The furnace oil boiler is a fire-tube boiler equipped with an oil burner and atomizer. During the experimentation boiler was operated at constant output. For the briquette boiler, briquettes were manually loaded on the grates of the combustion chamber.

Emission measurement was carried out by using a portable gas analyzer. The gas analyzer used here works on micro-flow NDIR principle to determine CO, CO_2, NO_x and SOx, and electro chemistry principle for O_2 measurement. The flue gas emission measurement involved the measurement of CO_2, CO, O_2, SOx, and NO_x as shown in Table-2.

Table-2. Flue gas emission measurement.

Gaseous emissions	Units	Furnace oil	Briquette (saw dust)
Oxygen (O_2)	% Vol.	06.50	3.50
Carbon dioxide (CO_2)	% Vol.	11.00	8.60
Carbon monoxide (CO)	ppm	61	120
Sulphur Oxides (SO_x)	ppm	1343	70
Nitrogen Oxides (NO_x)	ppm	345	12

Performance measurement

The ambient temperature is measured by using a Sling psychrometer. Feed water flow rate is measured by a flow meter. Fuel consumption rate of furnace oil is carried out by flow meter and briquette consumption is measured by a digital weighing machine. Feed water temperature, fuel temperature, steam temperature, and boiler surface temperatures are measured by an infrared thermometer. Steam pressure is measured by pressure gauge. The measurements are tabulated in Table-3.

Table-3. Experimental values.

Measurement	Units	Furnace oil	Briquette (saw dust)
Fuel consumption rate	kg/h	55.80	320.04
Feed water flow rate	liter/h	630.00	1249.20
Steam pressure	MPa	0.39	0.78
Dry bulb temperature	K	303	306
Wet bulb temperature	K	297	300
Combustion zone temperature	K	363	780
Feed water temperature	K	324	328
Steam temperature	K	416	430
Surface temperature of boiler	K	358	440
Flue gas temperature	K	441	447

The efficiency of the boiler is determined by heat loss method as per IS – 8753 and ASME PTC 4.1. The efficiency can be arrived at, by subtracting the heat loss fractions from 100. The principal losses that occur in a boiler are loss of heat due to the following:

a) Dry flue gas

Percentage heat loss due to dry flue gas= $\frac{m_g * C_{pg} * (T_f - T_{db})}{\text{GCV of fuel}} * 100$

Where, m_g = mass of dry flue gas in kg/kg of fuel, c_{pg} = specific heat of flue gas (kJ/kg-K), T_f = flue gas temperature, T_{db} = dry bulb temperature, GCV= gross calorific value (kJ/kg).

b) Evaporation of water formed due to hydrogen in fuel

Percentage heat loss due to evaporation of water formed due to hydrogen in fuel = $\frac{9 * H_2\{584 + C_{ps}(T_f - T_{db})\}}{\text{GCV of fuel}} * 100$

Where, H_2 = percentage of hydrogen in 1 kg of fuel, C_{ps} = specific heat of superheated steam, 584 = latent heat corresponding to partial pressure of water vapour.

c) Evaporation of moisture in fuel

Percentage heat loss due to evaporation of moisture present in fuel= $\frac{m_m * \{584 + C_{ps}(T_f - T_{db})\}}{\text{GCV of fuel}} * 100$

Where, m_m = percent moisture in 1kg of fuel.

d) Moisture present in combustion air

Percentage heat loss due to moisture present in air $= \frac{\text{AAS} * \text{humidity factor} * C_{ps}(T_f - T_{db})}{\text{GCV of fuel}} * 100$

Where, AAS = actual mass of air supplied per kg of fuel, Humidity factor = kg of water/kg of dry air

e) Incomplete combustion

Percentage heat loss due to incomplete combustion = $m_{co} * 5744$= CO $*$ 10 $*$ $m_f$$*$ 28 $*$ 5744

Where CO = carbon monoxide formed in flue gas, m_f = fuel consumption, m_{co}= carbon monoxide formation, 5744 = heat loss due to partial combustion of carbon

f) Unburnt fuel in flyash

Percentage heat loss due to unburnt fuel in fly ash $= \frac{\text{Total ash /kg of fuel burnt} * \text{GCV of fly ash}}{\text{GCV of fuel}} * 100$

g) Unburnt fuel in bottom ash

Percentage heat loss due to unburnt fuel in bottom ash $= \frac{\text{Total ash/kg of fuel burnt} * \text{GCV of bottom ash}}{\text{GCV of fuel}} * 100$

h) Radiation and other unaccounted losses

Percentage heat loss due to radiation and other unaccounted

loss= $0.548 * [(T_s/55.55)^4 - (T_{db}/55.55)^4] + .957 * (T_s - T_{db})^{1.25}\sqrt{[196.85V_m + 68.9/68.9]}$

Where T_s = surface temperature of boiler, V_m = wind velocity

Boiler efficiency (η_b) = 100 – losses due to (i + ii +iii + iv + v + vi + vii + viii)

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Table-4. Water analysis.

Property	Units	Furnace oil	Briquette (saw dust)
Feed water TDS	ppm	100	675
Feed water p^H	ppm	8.0	7.5
Blow down water TDS	ppm	3500	9700
Blow down water p^H	ppm	12.0	11.5

Table-5. Specific heats and humidity factor.

Property	Units	Furnace oil	Briquette (saw dust)
Specific heat of flue gas	kJ/kg-K	1.046	1.046
Specific heat of superheated steam	kJ/kg-K	2.092	1.8828
Humidity factor	------	0.014	0.017

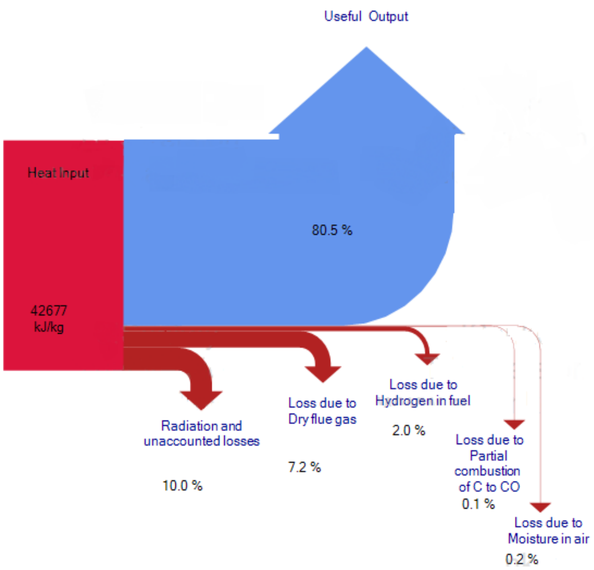

Figure-3. Sankey diagram of Furnace oil boiler.

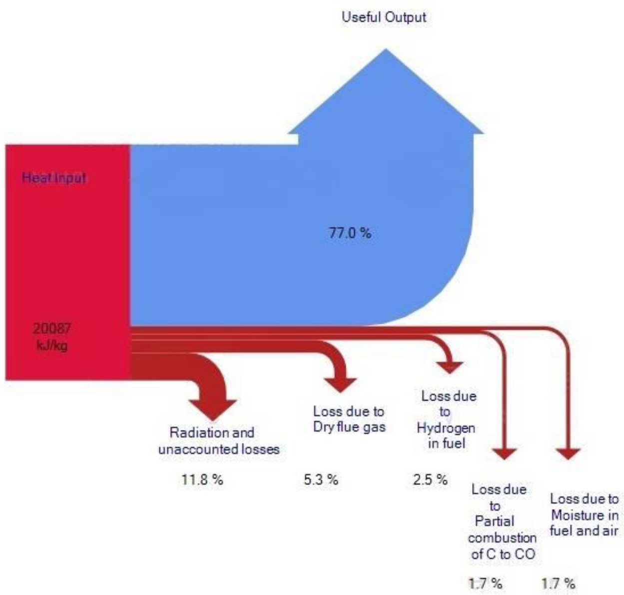

Figure-4. Sankey diagram of Briquette boiler.

RESULTS AND DISCUSSIONS

Economics of fuel conversion technology

With the conversion of fuel system of the boiler from furnace oil to briquettes the company has yielded a savings of 26 000 with a consumption of 1 000 liter of furnace oil equivalent to 2 100 kg of briquettes daily. The saving potential with fuel conversion is illustrated in the following Table-6.

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Table-6. Saving potential with fuel conversion

S. No.	**Daily furnace oil consumption** (liter/day)	**Equivalent briquette consumption** (kg/day)	**Savings** (₹/day)
1	1 000	2 100	26 000
2	2 000	4 200	52 000
3	3 000	6 300	88 000
4	4 000	8 400	1 14 000
5	5 000	10 500	1 40 000
6	10 000	21 000	2 60 000

The ratio of the calorific values of furnace oil and briquettes is 2.1:1. The average furnace oil consumption of M/s ABC Ltd. is 1 000 liter per day and its equivalent briquette consumption is 2 100 kg. The cost of furnace oil is ₹38 per liter and briquettes are ₹5.30 per kg. It brings about ₹26 000 saving to the plant by converting the fuel system of the boiler from furnace oil to briquettes.

Efficiency of boiler

It is to be noted that boilers are very rarely operated at full load. The rated capacity of the boiler is 10.54 kg (f)/cm^2 whereas the requirement of the company is only 8 kg (f)/cm^2. With the conversion of fuel system the efficiency of the boiler (Table-7) has decreased from 80.47 % to 76.95 %.

The total steam generation after retrofitting is meeting the requirement of the company. So there is no effect of decrease in efficiency of boiler on the steam production. Moreover the operating cost of the boiler is reduced enormously with the fuel system conversion.

From the heat balance sheet (Table-7) it is evident that the losses due to dry flue gases is lower during briquette firing, having positive effect on efficiency but the losses due to moisture content in fuel, partial combustion of C to CO and radiation losses are dominant and have become the reasons for decrease in efficiency during briquette combustion.

Heat loss through flue gases in briquette boiler has decreased because of the reduced excess air supply.

A higher loss due to the moisture content in the fuel is observed during briquette combustion because of the moisture content in briquettes which utilized considerable amount of thermal energy to convert into superheated vapour. This moisture loss is made up of sensible heat to bring moisture to boiling point, latent heat of evaporation and superheat required to bring this steam to temperature of exhaust gas. Furnace oil has no moisture content in it which resulted in no moisture loss condition during its combustion

Table-7. Comparison of efficiency of furnace oil and briquette boilers.

Input/output parameter	Furnace oil boiler	Briquette boiler
Heat input in fuel	100 %	100 %
Various heat losses in boiler	Percentage (%)	Percentage (%)
Dry flue gas loss	7.20	5.34
Loss due to hydrogen in fuel	2.02	2.54
Loss due to moisture in fuel	0.00	1.53
Loss due to moisture in air	0.19	0.14
Partial combustion of C to CO	0.15	1.70
Radiation and unaccounted losses	9.97	11.8
Total losses	19.53	23.05
Boiler efficiency	80.47	76.95

Partial combustion of C to CO has occurred because of the reduced excess air supply during briquette firing and the presence of high moisture content in the briquettes. The reduced air supply has caused incomplete combustion i.e., more unburnt fuel after combusting resulting higher CO. The moisture presence in the briquettes has reduced the temperature of combustion zone leading to incomplete combustion of carbon resulting higher heat loss during briquette combustion. From the equations of combustion (1) and (2) it is seen that higher amounts of heat is liberated when CO_2 is the product of reaction and lower amounts of heat is liberated when CO is the product of reaction. It implies that formation of CO is an indication of incomplete combustion.

Radiation loss during briquette combustion is higher because of higher surface temperatures of boiler while briquette firing. The radiation of heat from combustion zone to the surrounding environment is high during briquette combustion. This is because the combustion temperature during briquette combustion is 730 K and 363 K during furnace oil combustion as referred in Table-3.

Flue gas emissions

There is a reduction in NO_x, SO_x, CO_2 emissions and increase in CO level of the flue gases (Table-8) after retrofication of boiler.

Table-8. Comparison of emissions of furnace oil and briquette boilers.

Parameter	Units	Furnace oil boiler	Briquette boiler	Change
NO_x	ppm	345	12	↓
SO_x	ppm	1343	70	↓
CO	ppm	61	120	↑
CO_2	% Vol.	11.0	08.6	↓
O_2	% Vol.	06.5	03.5	↓

The NO_X emissions of furnace oil are 345 ppm and that of briquettes is 12 ppm. This is because the excess air supplied for furnace oil (44.83 %) is more than that of briquettes (20 %). The oxidation rate is higher at higher excess air supplies. The NO_X emissions are at higher levels for excess supply range of 25 % - 45 %. The excess air consists of 3.76 nitrogen molecules for every molecule of oxygen that passes through the boiler. Thus reduced excess air supply has reduced the availability of nitrogen leading to reduced NO_x emissions during briquette combustion. The rate of combustion in the boiler is higher during furnace oil combustion because furnace oil is liquid fuel that can atomize easily. Whereas saw dust briquettes are solid fuel and their rate of combustion is lower. The higher the rate of combustion the higher will be the NO_x formed.

SO_X emissions of 1343 ppm while firing furnace oil and 70 ppm when firing briquettes are observed. The sulphur content of furnace oil is 3.5 % and that of briquettes is 0.1 %. The SO_X emissions are directly related to the content of sulphur in the fuel. This higher levels of sulphur content resulted in higher sulphur oxide emissions during furnace oil combustion from the oxidation of sulphur contained in the fuel.

It has been observed that the CO emission of briquette firing is 120 ppm and that of furnace oil is 61 ppm. The reduced excess air supply and higher moisture content in briquettes have lead to incomplete combustion of carbon resulting in higher CO levels during briquette combustion. All fuels combust in the gaseous state only. The rate of CO emissions from combustion sources depends on the oxidation efficiency of the fuel. Furnace oil, as it is a liquid fuel easily vaporizes and the vapours react with oxygen in the combustion zone. The saw dust briquettes being solid fuel, their temperature should be raised enough so that they can diffuse into the vapour state before they could combust. So the levels of unburnt fuel left after combustion is more when firing briquettes than furnace oil. By controlling the combustion process carefully, CO emissions can be minimized. If a unit is operated improperly or not well maintained, the resulting concentrations of CO increase by several orders of magnitude. Various combustion modifications for NOx reduction can produce conditions that increase CO emissions.

A higher level of CO_2 emissions of 11 % is observed for furnace oil and 8.6 % for briquettes. The carbon content of furnace oil is 87 % and that of briquettes is 48.55 %. The CO_2 emissions are directly related to the amount of carbon content of the fuel and hence higher CO_2 emissions during furnace oil combustion is observed.

The oxygen concentration is 3.5 % during briquette combustion and 6.5 % during furnace oil combustion. The reduced excess air supply has yielded lower oxygen levels during briquette combustion. The management of flue gas oxygen content requires the flue gas oxygen concentration to be managed between an upper and lower limit. The lower limit is established to ensure the majority of fuel resource is combusted and the upper limit to ensure minimum thermal energy loss.

CONCLUSIONS

It has been found that utilizing briquettes in boilers offers many economical, social and environmental benefits such as financial net saving, conservation of fossil fuel resources and emissions reduction thereby reducing the air pollution. The project has evident contribution to sustainable development, which are as follows:

- The retrofit technology used to convert the fuel system of boiler from furnace oil to briquettes is safe and environmentally sustainable.
- Reduction in efficiency due to retrofitting is observed. But the reduction of boiler efficiency has no effect on the steam production rate of the plant after retrofitting.
- Significant reduction in the operating cost of boiler.
- Conserving the fossil fuel reserves i.e., reducing petroleum oil requirement by use of renewable source of energy can be achieved.
- Reduction in the amount of green house gas emissions i.e. CO_2 emission reduction is obtained.
- Higher CO emissions are observed during briquette combustion. However the emissions due to incomplete combustion from grate-fired boilers can be effectively controlled by an optimized combustion process, i.e., enhanced mixing, sufficient residence time at high temperatures, as well as by the appropriate choice of grate assembly. Combustion of solid saw dust briquettes on fluidized bed combustion chambers is an approach to minimize incomplete combustion.
- Reduction of secondary pollutants i.e., SO_x and NO_x is achieved.

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