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An Approach towards Efficient Operation of Boilers

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Abstract— Presently the world has enormous advancement in science and technology the topic considered here is just a drop out of an ocean of knowledge. Higher product quality, better reliability, better availability of plants, optimization of cost and efficient working of boilers is the chief concern now a days. Generally the production can be increased by the efficient use of boilers and hence there is a lot of scope to minimize the boiler operation cost. Thus in this paper an attempt is made to understand the way by which boilers can be used efficiently.

Index Terms— Boilers, Boiler operation, Boiler efficiency, Blow down, Boiler Systems, Boiler Water Treatment.

1 INTRODUCTION

A Boiler is an enclosed vessel that provides a means for combustion heat to be transferred into water until it becomes heated water or steam. The hot water or steam under pressure is then usable for transferring the heat to a process [1] [2]. Water is a useful and cheap medium for transferring heat to a process. When water is boiled into steam its volume increases about 1,600 times, producing a force that is almost as explosive as gunpowder. This causes the boiler to be extremely dangerous equipment that must be treated with utmost care. The process of heating a liquid until it reaches its gaseous state is called evaporation. Heat is transferred from one body to another by means of (1) radiation, which is the transfer of heat from a hot body to a cold body through a conveying medium without physical contact, (2) convection, the transfer of heat by a conveying medium, such as air or water and (3) conduction, transfer of heat by actual physical contact, molecule to molecule. The heating surface is any part of the boiler metal that has hot gases of combustion on one side and water on the other. Any part of the boiler metal that actually contributes to making steam is heating surface. The amount of heating surface a boiler is expressed in square meters. The larger the heating surface a boiler has, the more efficient it becomes. The quantity of the steam produced is indicated in tons of water evaporated to steam per hour.

Indian Boiler Regulation [3]

The Indian Boilers Act was enacted to consolidate and amend the law relating to steam boilers. Indian Boilers Regulation (IBR) was created in exercise of the powers conferred by section 28 & 29 of the Indian Boilers Act.

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TYPICAL BOILER SPECIFICATION

Boiler Make & Year : XYZ & 2003
MCR (Maximum Continuous Rating):10TPH (F & A 100°C)
Rated Working Pressure : 10.54 kg/cm² (g)
Type of Boiler : 3 Pass Fire tube
Fuel Fired : Fuel Oil

IBR Steam Boilers means any closed vessel exceeding 22.75 liters in capacity and which is used expressively for generating steam under pressure and includes any mounting or other fitting attached to such vessel, which is wholly or partly under pressure when the steam is shut off.

IBR Steam Pipe means any pipe through which steam passes from a boiler to a prime mover or other user or both, if pressure at which steam passes through such pipes exceeds 3.5 kg/cm² above atmospheric pressure or such pipe exceeds 254 mm in internal diameter and includes in either case any connected fitting of a steam pipe.

Boiler Systems

The boiler system comprises of feed water system, steam system and fuel system. The feed water system provides water to the boiler and regulates it automatically to meet the steam demand. Various valves provide access for maintenance and repair. The steam system collects and controls the steam produced in the boiler. Steam is directed through a piping system to the point of use. Throughout the system, steam pressure is regulated using valves and checked with steam pressure gauges. The fuel system includes all equipment used to provide fuel to generate the necessary heat. The equipment required in the fuel system depends on the type of fuel used in the system.

The water supplied to the boiler that is converted into steam is called feed water. The two sources of feed water are: (1) Condensate or condensed steam returned from the processes and (2) Makeup water (treated raw water) which must come from outside the boiler room and plant processes. For higher boiler efficiencies, the feed water is preheated by economizer, using the waste heat in the flue gas.

2. PERFORMANCE EVALUATION OF BOILERS

The performance parameters of boiler, like efficiency and evaporation ratio reduces with time due to poor combustion, heat transfer surface fouling and poor operation and maintenance. Even for a new boiler, reasons such as deteriorating fuel quality, water quality etc. can result in poor boiler performance. Boiler efficiency tests help us to find out the deviation of boiler efficiency from the best efficiency and target problem area for corrective action.

Boiler Efficiency

Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilised to generate steam. There are two methods of assessing boiler efficiency [4].

1) **The Direct Method:** Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) **The Indirect Method:** Where the efficiency is the difference between the losses and the energy input.

a. Direct Method

This is also known as 'input-output method' due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula

$$\text{Boiler Efficiency} = \frac{\text{Heat Output}}{\text{Heat Input}}$$

Parameters to be monitored for the calculation of boiler efficiency by direct method are:

1. Quantity of steam generated per hour (Q) in kg/hr.
2. Quantity of fuel used per hour (q) in kg/hr.
3. The working pressure (in $kg/cm^2(g)$) and superheat temperature (^oC), if any
4. The temperature of feed water (^oC)
5. Type of fuel and gross calorific value of the fuel (GCV) in kcal/kg of fuel.

$$\text{Boiler efficiency } (\eta) = \frac{Q \times (hg - hf)}{q \times GCV} \times 100$$

Where,
hg - Enthalpy of saturated steam in kcal/kg of steam
hf - Enthalpy of feed water in kcal/kg of water

Example: - Find out the efficiency of the boiler by direct method with the data given below:

1. Type of boiler: Coal fired
2. Quantity of steam (dry) generated : 8 TPH
3. Steam pressure(gauge) / temp :10 $kg/cm^2(g)$/ 180 ^0C
4. Quantity of coal consumed : 1.8 TPH
5. Feed water temperature : 85^0 C
6. GCV of coal : 3200 kcal/kg
7. Enthalpy of steam at 10 kg/cm^2 pressure: 665 kcal/kg (saturated)
8. Enthalpy of feed water : 85 kcal/kg

$$\text{Boiler efficiency } (\eta) = \frac{8 \times (665 - 85)}{1.8 \times 3200} \times 100$$

It should be noted that boiler may not generate 100% saturated dry steam, and there may be some amount of wetness in the steam.

Advantages of direct method:

1. Plant people can evaluate quickly the efficiency of boilers.
2. Requires few parameters for computation.
3. Needs few instruments for monitoring.

Disadvantages of direct method:

1. Does not give clues to the operator as to why efficiency of system is lower.
2. Does not calculate various losses accountable for various efficiency levels.

b. Indirect Method

There are reference standards for Boiler Testing at Site using indirect method namely British Standard, BS 845: 1987 and USA Standard is 'ASME PTC-4-1 Power Test Code Steam Generating Units'.

Indirect method is also called as heat loss method. The efficiency can be arrived at, by subtracting the heat loss fractions from 100. The standards do not include blow down loss in the efficiency determination process. A detailed procedure for calculating boiler efficiency by indirect method is given below. However, it may be noted that the practicing energy mangers in industries prefer simpler calculation procedures.

The principle losses that occur in a boiler are:
1. Loss of heat due to dry flue gas
2. Loss of heat due to moisture in fuel and combustion air
3. Loss of heat due to combustion of hydrogen
4. Loss of heat due to radiation
5. Loss of heat due to unburnt

In the above, loss due to moisture in fuel and the loss due to combustion of hydrogen are dependent on the fuel, and cannot be controlled by design.

The data required for calculation of boiler efficiency using indirect method are:

1. Ultimate analysis of fuel (H_2, O_2, S, C, moisture content, ash content)
2. Percentage of Oxygen or CO_2 in the flue gas
3. Flue gas temperature in ^0C (T_f)
4. Ambient temperature in ^0C (T_a) & humidity of air in kg/kg of dry air.
5. GCV of fuel in kcal/kg
6. Percentage combustible in ash (in case of solid fuels)
7. GCV of ash in kcal/kg (in case of solid fuels)

Solution:
Theoretical air requirement =
$[(11.43 \times C) + [\{34.5 \times (H_2 - O_2/8)\} + (4.32 \times S)]/100$ kg/kg of fuel

$$\text{Excess Air supplied (EA)} = \frac{O_2\% \times 100}{(21 - O_2\%)}$$

Actual mass of air supplied/kg of fuel (AAS) =
{1 + EA/100} x theoretical air

I. Percentage heat loss due to dry flue gas.

$$= \frac{m \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$$

m = mass of dry flue gas in kg/kg of fuel

m = (mass of dry products of combustion / kg of fuel) + (mass of N_2 in fuel on 1 kg basis) + (mass of N_2 in actual mass of air we are supplying).

C_p = Specific heat of flue gas (0.23 kcal/kg)

II. Percentage heat loss due to evaporation of water formed due to H_2 in fuel

$$= \frac{9 \times H_2 \{584 + C_p (T_f - T_a)\} \times 100}{\text{GCV of fuel}}$$

Where,
H_2 percentage of H_2 in 1 kg of fuel
C_p – Specific heat of superheated steam (0.45 kcal/kg)

III. Percentage heat loss due to evaporation of moisture present in fuel

$$= \frac{M \{584 + C_p (T_f - T_a)\} \times 100}{\text{GCV of fuel}}$$

Where,
M – % moisture in 1kg of fuel
C_p – Specific heat of superheated steam (0.45 kcal/kg)

IV. Percentage heat loss due to moisture present in air

$$= \frac{\text{AAS} \times \text{humidity factor} \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$$

C_p – Specific heat of superheated steam (0.45 kcal/kg)

V. Percentage heat loss due to unburnt in fly ash

$$= \frac{\text{Total ash collected / Kg of fuel burnt} \times \text{G.C.V of fly ash} \times 100}{\text{GCV of fuel}}$$

VI. Percentage heat loss due to unburnt in bottom ash

$$= \frac{\text{Total ash collected /kg of fuel burnt} \times \text{G.C.V of bottom ash} \times 100}{\text{GCV of fuel}}$$

VII. Percentage heat loss due to radiation and other unaccounted loss

The actual radiation and convection losses are difficult to assess because of particular emissivity of various surfaces, its inclination, air flow pattern etc. In a relatively small boiler, with a capacity of 10 MW, the radiation and unaccounted losses could amount to between 1% and 2% of the gross calorific value of the fuel, while in a 500 MW boiler, values between 0.2% to 1% are typical. The loss may be assumed appropriately depending on the surface condition.

Efficiency of boiler (η) = 100 – (I + II + III + IV + V + VI + VII)

Boiler Evaporation Ratio

Evaporation ratio means kilogram of steam generated per kilogram of fuel consumed.

Typical Examples: Coal fired boiler : 6
Oil fired boiler : 13

i.e. 1 kg of coal can generate 6 kg of steam

1 kg of oil can generate 13 kg of steam

However, this figure will depend upon type of boiler, calorific value of the fuel and associated efficiencies.

3. BLOWDOWN CALCULATIONS

Suspended solids entering boilers through feed water will remain behind when steam is generated. After a while the concentration of solids makes the operation of the boiler unsatisfactory [5]. The quantity of blowdown required to control boiler water solids concentration is calculated by using the following formula:

$$\text{Blow down (\%)} = \frac{\text{Feed water TDS x \% Make up water}}{\text{Maximum Permissible TDS in Boiler water}}$$

If maximum permissible limit of TDS as in a package boiler is 3000 ppm, percentage make up water is 10% and TDS in feed water is 300 ppm, then the percentage blow down is given as:

$$= \frac{300 \times 10}{3000}$$

$$= 1\ \%$$

If boiler evaporation rate is 3000 kg/hr then required blow down rate is:

$$= \frac{3000 \times 1}{100}$$

$$= 30\ \text{kg/hr}$$

Benefits of Blowdown

Good boiler blow down control can significantly reduce treatment and operational costs that include:

- Lower pre-treatment costs
- Less make-up water consumption
- Reduced maintenance downtime
- Increased boiler life
- Lower consumption of treatment chemicals

Boiler Water Treatment

Producing quality steam on demand depends on properly managed water treatment to control steam purity, deposits and corrosion. A boiler is the sump of the boiler system. It ultimately receives all of the pre-boiler contaminants. Boiler performance, efficiency, and service life are direct products of selecting and controlling feed water used in the boiler. When feed water enters the boiler, the elevated temperatures and pressures cause the components of water to behave differently. Most of the components in the feed water are soluble. However, under heat and pressure most of the soluble components come out of solution as particulate solids, sometimes in crystallized forms and other times as amorphous particles. When solubility of a specific component in water is exceeded, scale or deposits develop. The boiler water must be sufficiently free of deposit forming solids to allow rapid and efficient heat transfer and it must not be corrosive to the boiler metal.

Deposit Control

Deposits in boilers may result from hardness contamination of feed water and corrosion products from the condensate and feed water system. Hardness contamination of the feed water may arise due to deficient softener system. Deposits and corrosion result in efficiency losses and may result in boiler tube failures and inability to produce steam. Deposits act as insulators and slow heat transfer. Large amounts of deposits throughout the boiler could reduce the heat transfer enough to reduce the boiler efficiency significantly. Different type of deposits affects the boiler efficiency differently. Thus it may be useful to analyse the deposits for its characteristics. The insulating effect of deposits causes the boiler metal temperature to rise and may lead to tube-failure by overheating.

Impurities causing deposits

The most important chemicals contained in water that influences the formation of deposits in the boilers are the salts of calcium and magnesium, which are known as hardness salts.
Calcium and magnesium bicarbonate dissolve in water to form an alkaline solution and these salts are known as alkaline hardness. They decompose upon heating, releasing carbon dioxide and forming a soft sludge, which settles out. These are called temporary hardness-hardness that can be removed by boiling. Calcium and magnesium sulphates,

chlorides and nitrates, etc. when dissolved in water are chemically neutral and are known as non-alkaline hardness. These are called permanent hardness and form hard scales on boiler surfaces, which are difficult to remove. Non-alkalinity hardness chemicals fall out the solution due to reduction in solubility as the temperature rises, by concentration due to evaporation which takes place within the boiler, or by chemical change to a less soluble compound.

Silica

The presence of silica in boiler water can rise to formation of hard silicate scales. It can also associate with calcium and magnesium salts, forming calcium and magnesium silicates of very low thermal conductivity. Silica can give rise to deposits on steam turbine blades, after been carried over either in droplets of water in steam, or in volatile form in steam at higher pressures. Two major types of boiler water treatment are: Internal water treatment and External water treatment.

Internal Water Treatment [6]

Internal treatment is carried out by adding chemicals to boiler to prevent the formation of scale by converting the scale-forming compounds to free-flowing sledges, which can be removed by blowdown. This method is limited to boilers, where feed water is low in hardness salts, to low pressures- high TDS content in boiler water is tolerated, and when only small quantity of water is required to be treated. If these conditions are not applied, then high rates of blowdown are required to dispose of the sludge. They become uneconomical from heat and water loss consideration. Different waters require different chemicals. Sodium carbonate, sodium aluminates, sodium phosphate, sodium sulphite and compounds of vegetable or inorganic origin are all used for this purpose. Proprietary chemicals are available to suit various water conditions. The specialist must be consulted to determine the most suitable chemicals to use in each case. Internal treatment alone is not recommended.

External Water Treatment

External treatment is used to remove suspended solids, dissolved solids (particularly the calcium and magnesium ions which is a major cause of scale formation) and dissolved gases (oxygen and carbon dioxide). The external treatment processes available are: ion exchange; demineralization; reverse osmosis and de-aeration. Before any of these are used, it is necessary to remove suspended solids and colour from the raw water, because these may foul the resins used in the subsequent treatment sections. Methods of pre-treatment include simple sedimentation in settling tanks or settling in clarifiers with aid of coagulants and flocculants. Pressure sand filters, with spray aeration to remove carbon dioxide and iron, may be used to remove metal salts from bore well water. The first stage of treatment is to remove hardness salt and possibly non-hardness salts. Removal of only hardness salts is called softening, while total removal of salts from solution is called demineralization.

The processes are:

Ion-exchange process (Softener Plant)
In ion-exchange process, the hardness is removed as the water passes through bed of natural zeolite or synthetic resin and without the formation of any precipitate. The simplest type is 'base exchange' in which calcium and magnesium ions are exchanged for sodium ions. The sodium salts being soluble, do not form scales in boilers. Since base exchanger only replaces the calcium and magnesium with sodium, it does not reduce the TDS content, and blowdown quantity. It also does not reduce the alkalinity. Demineralization is the complete removal of all salts. This is achieved by using a "cation" resin, which exchanges the cations in the raw water with hydrogen ions, producing hydrochloric, sulphuric and carbonic acid. Carbonic acid is removed in degassing tower in which air is blown through the acid water. Following this, the water passes through an "anion" resin which exchanges anions with the mineral acid (e.g. sulphuric acid) and forms water. Regeneration of cations and anions is necessary at intervals using, typically, mineral acid and caustic soda respectively. The complete removal of silica can be achieved by correct choice of anion resin. Ion exchange processes can be used for almost total demineralization if required, as is the case in large electric power plant boilers

De-aeration

In de-aeration, dissolved gases, such as oxygen and carbon dioxide, are expelled by preheating the feed water before it enters the boiler. All natural waters contain dissolved gases in solution. Certain gases, such as carbon dioxide and oxygen, greatly increase corrosion. When heated in boiler systems, carbon dioxide (CO_2) and oxygen (O_2) are released as gases and combine with water (H_2O) to form carbonic acid, (H_2CO_3).

Removal of oxygen, carbon dioxide and other non-condensable gases from boiler feedwater is vital to boiler equipment longevity as well as safety of operation. Carbonic acid corrodes metal reducing the life of equipment and piping. It also dissolves iron (Fe) which when returned to the boiler precipitates and causes scaling on the boiler and tubes. This scale not only contributes to reducing the life of the equipment but also increases the amount of energy needed to achieve heat transfer. De-aeration can be done by mechanical de-aeration, by chemical de-aeration or by both together.

Mechanical de-aeration

Mechanical de-aeration for the removal of these dissolved gases is typically utilized prior to the addition of chemical oxygen scavengers. Mechanical de-aeration is based on Charles' and Henry's laws of physics. Simplified, these laws state that removal of oxygen and carbon dioxide can be accomplished by heating the boiler feed water, which reduces the concentration of oxygen and carbon dioxide in the atmosphere surrounding the feed water. Mechanical de-aeration can be the most economical. They operate at the boiling point of water at the pressure in the de-aerator. They can be of vacuum or pressure type. The vacuum type of de-aerator operates below atmospheric pressure, at about 82^{o}C, can reduce the oxygen content in water to less than 0.02 mg/litre. Vacuum pumps or steam ejectors are required to maintain the vacuum. The pressure-type de-aerators operates by allowing steam into the feed water through a pressure control valve to maintain the desired operating pressure, and hence temperature at a minimum of 105^{o}C. The steam raises the water temperature causing the release of O_2 and CO_2 gases that are then vented from the system. This type can reduce the oxygen content to 0.005 mg/litre. Where excess low-pressure steam is available, the operating pressure can be selected to make use of this steam and hence improve fuel economy. In boiler systems, steam is preferred for de-aeration because:

- Steam is essentially free from O_2 and CO_2.
- Steam is readily available.
- Steam adds the heat required to complete the reaction.

Chemical de-aeration

While the most efficient mechanical desecrators reduce oxygen to very low levels (0.005 mg/litre), even trace amounts of oxygen may cause corrosion damage to a system. Consequently, good operating practice requires removal of that trace oxygen with a chemical oxygen scavenger such as sodium sulphite or hydrazine. Sodium sulphite reacts with oxygen to form sodium sulphate, which increases the TDS in the boiler water and hence increases the blowdown requirements and make-up water quality. Hydrazine reacts with oxygen to form nitrogen and water. It is invariably used in high pressures boilers when low boiler water solids are necessary, as it does not increase the TDS of the boiler water.

Reverse Osmosis

Reverse osmosis uses the fact that when solutions of differing concentrations are separated by a semi-permeable membrane, water from less concentrated solution passes through the membrane to dilute the liquid of high concentration. If the solution of high concentration is pressurized, the process is reversed and the water from the solution of high concentration flows to the weaker solution. This is known as reverse osmosis. The quality of water produced depends upon the concentration of the solution on the high-pressure side and pressure differential across the membrane. This process is suitable for waters with very high TDS, such as sea water.

Recommended boiler and feed water quality

The impurities found in boiler water depend on the untreated feed water quality, the treatment process used and the boiler operating procedures. As a general rule, the higher the boiler operating pressure, the greater will be the sensitivity to impurities. Recommended feed water and boiler water limits are shown in Table 1 and Table 2 [7].

Table 1 Recommended Feed Water Limits

Factor	Up to 20 kg/cm^2	21 - 40 kg/cm^2	41 - 60 kg/cm^2
Total iron (max) ppm	0.05	0.02	0.01
Total copper (max) ppm	0.01	0.01	0.01
Total silica (max) ppm	1.0	0.3	0.1
Oxygen (max) ppm	0.02	0.02	0.01
Hydrazine residual ppm	-	-	-0.02-0.04
pH at 25^{0}C	8.8-9.2	8.8-9.2	8.2-9.2
Hardness, ppm	1.0	0.5	-

Table 2 Recommended Boiler Water Limits

Factor	Up to 20 kg/cm^2	21 - 40 kg/cm^2	41 - 60 kg/cm^2
TDS, ppm	3000-3500	1500-2000	500-750
Total iron dissolved solids ppm	500	200	150
Specific electrical conductivity at 25°C (mho)	1000	400	300
Phosphate residual ppm	20-40	20-40	15-25
pH at 25°C	10-10.5	10-10.5	9.8-10.2
Silica (max) ppm	25	15	10

ENERGY CONSERVATION OPPORTUNITIES

The various energy efficiency opportunities in boiler system can be related to combustion, heat transfer, avoidable losses, high auxiliary power consumption, water quality and blow down. Examining the following factors can indicate if a boiler is being run to maximize its efficiency:

1. Stack Temperature

The stack temperature should be low as possible. However, it should not be so low that water vapor in the exhaust condenses on the stack walls. This is important in fuels containing significant sulphur as low temperature can lead to sulphur dew point corrosion. Stack temperatures greater than 200°C indicates potential for recovery of waste heat. It also indicates the scaling of heat transfer/recovery equipment and hence the urgency of taking an early shut down for water flue side cleaning.

2. Feed Water Preheating using Economiser

Typically, the flue gases leaving a modern 3-pass shell boiler are at temperatures of heat recovery must be worked out, as the flue gas temperature may be well below 200°C.

The potential for energy saving depends on the type of boiler installed and the fuel used. For a typically older model shell boiler, with a flue gas exit temperature of 260°C, an economizer could be used to reduce it to 200°C, increasing the feed water temperature by 15°C. Increase in overall thermal efficiency would be in the order of 3%. For a modern 3-pass shell boiler firing natural gas with a flue gas exit temperature of 140°C a condensing economizer would reduce the exit temperature to 65°C increasing thermal efficiency by 5%.

3. Combustion Air Preheat

Combustion air preheating is an alternative to feedwater heating. In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20 °C. Most gas and oil burners used in a boiler plant are not designed for high air preheats temperatures. Modern burners can withstand much higher combustion air preheat, so it is possible to consider such units as heat exchangers in the exit flue as an alternative to an economizer, when either space or a high feed water return temperature make it viable.

4. Incomplete Combustion

Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel. It is usually obvious from the colour or smoke, and must be corrected immediately. In the case of oil and gas fired systems, CO or smoke (for oil fired systems only) with normal or high excess air indicates burner system problems. A more frequent cause of incomplete combustion is the poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers or spinner plates. With coal firing, unburned carbon can comprise a big loss. It occurs as grit carry-over or carbon-in-ash and may amount to more than 2% of the heat supplied to the boiler. Non uniform fuel size could be one of the reasons for incomplete combustion. In chain grate stokers, large lumps will not burn out completely, while small pieces and fines may block the air passage, thus causing poor air distribution. In sprinkler stokers, stoker grate condition, fuel distributors, wind box air regulation and over-fire systems can affect carbon loss. Increase in the fines in pulverized coal also increases carbon loss.

5. Excess Air Control

The Table 3 gives the theoretical amount of air required for combustion of various types of fuel [7]. Excess air is required in all practical cases to ensure complete combustion, to allow for the normal variations in combustion and to ensure satisfactory stack conditions for some fuels. The optimum excess air level for maximum boiler efficiency occurs when the sum of the losses due to incomplete combustion and loss due to heat in flue gases is minimum. This level varies with furnace design, type of burner, fuel and process variables. It can be determined by conducting tests with different air fuel ratios.

Table 3 Theoretical Combustion Data – Common Boiler Fuels

Fuel	**kg of air req./kg of fuel**	**kg of flue gas/kg of fuel**	**m³ of flue/kg of fuel**	**Theoretical CO_2% in dry flue gas**	**CO_2% in flue gas achieved in practice**
Solid Fuels					
Bagasse	3.2	3.43	2.61	20.65	10-12
Coal (bituminous)	10.8	11.7	9.40	18.70	10-13
Lignite	8.4	9.10	6.97	19.40	9 -13
Paddy Husk	4.6	5.63	4.58	19.8	14-15
Wood	5.8	6.4	4.79	20.3	11.13
Liquid Fuels					
Furnace Oil	13.90	14.30	11.50	15.0	9-14
LSHS	14.04	14.63	10.79	15.5	9-14

Typical values of excess air supplied for various fuels are given in Table –4. [7] Controlling excess air to an optimum level always results in reduction in flue gas losses; for every 1% reduction in excess air there is approximately 0.6% rise in efficiency.
Various methods are available to control the excess air:

Portable oxygen analysers and draft gauges can be used to make periodic readings to guide the operator to manually adjust the flow of air for optimum operation. Excess air reduction up to 20% is feasible. The most common method is the continuous oxygen analyser with a local readout mounted draft gauge, by which the operator can adjust air flow. A further reduction of 10-15% can be achieved over the previous system. The same continuous oxygen analyser can have a remote controlled pneumatic damper positioner, by which the readouts are available in a control room. This enables an operator to remotely control a number of firing systems simultaneously. The most sophisticated system is the automatic stack damper control, whose cost is really justified only for large systems.

Table 4 Excess Air Levels for Different Fuels

Fuel	**Type of Furnace or Burners**	**Excess Air (% by wt)**
Pulverised coal	Completely water-cooled furnace for slag-tap or dry-ash removal	15-20
	Partially water-cooled furnace for dry-ash removal	15-40
Coal	Spreader stoker	30-60
	Water-cooler vibrating-grate stokers	30-60
	Chain-grate and travelling-gate stokers	15-50
	Underfeed stoker	20-50
Fuel oil	Oil burners, register type	15-20
	Multi-fuel burners and flat-flame	20-30
Natural gas	High pressure burner	5-7
Wood	Dutch over (10-23% through grates) and Hofft type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for draft and soda-pulping processes	30-40

6. Radiation and Convection Heat Loss

The external surfaces of a shell boiler are hotter than the surroundings. The surfaces thus lose heat to the surroundings depending on the surface area and the difference in temperature between the surface and the surroundings. The heat loss from the boiler shell is normally a fixed energy loss, irrespective of the boiler output. With modern boiler designs, this may represent only 1.5% on the gross calorific value at full rating, but will increase to around 6%, if the boiler operates at only 25 percent output. Repairing or augmenting insulation can reduce heat loss through boiler walls and piping.

7. Automatic Blowdown Control

Uncontrolled continuous blowdown is very wasteful. Automatic blowdown controls can be installed that sense and respond to boiler water conductivity and pH. A 10% blow down in a 15 kg/cm² boiler results in 3% efficiency loss.

8. Reduction of Scaling and Soot Losses

In oil and coal-fired boilers, soot buildup on tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. Elevated stack temperatures may indicate excessive soot buildup. Also same result will occur due to scaling on the water side. High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Waterside deposits require a review of water treatment procedures and tube cleaning to remove deposits. An estimated 1% efficiency loss occurs with every 22°C increase in stack temperature. Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature rises about 20°C above the temperature for a newly cleaned boiler, it is time to remove the soot deposits. It is, therefore, recommended to install a dial type thermometer at the base of the stack to monitor the exhaust flue gas temperature. Every millimetre thickness of soot coating increases the stack temperature by about 55°C. It is also estimated that 3 mm of soot can cause an increase in fuel consumption by 2.5%. Periodic off-line cleaning of radiant furnace surfaces, boiler tube banks, economizers and air heaters may be necessary to remove stubborn deposits.

9. Reduction of Boiler Steam Pressure

This is an effective means of reducing fuel consumption, if permissible, by as much as 1 to 2%. Lower steam pressure gives a lower saturated steam temperature and without stack heat recovery, a similar reduction in the temperature of the flue gas temperature results. Steam is generated at pressures normally dictated by the highest pressure / temperature requirements for a particular process. In some cases, the process does not operate all the time, and there are periods when the boiler pressure could be reduced. The energy manager should consider pressure reduction carefully, before recommending it. Adverse effects, such as an increase in water carryover from the boiler owing to pressure reduction, may negate any potential saving. Pressure should be reduced in stages, and no more than a 20 percent reduction should be considered.

10. Variable Speed Control for Fans, Blowers and Pumps

Variable speed control is an important means of achieving energy savings. Generally, combustion air control is affected by throttling dampers fitted at forced and induced draft fans. Though dampers are simple means of control, they lack accuracy, giving poor control characteristics at the top and bottom of the operating range. In general, if the load characteristic of the boiler is variable, the possibility of replacing the dampers by a VSD should be evaluated.

11. Effect of Boiler Loading on Efficiency

The maximum efficiency of the boiler does not occur at full load, but at about two-thirds of the full load. If the load on the boiler decreases further, efficiency also tends to decrease. At zero output, the efficiency of the boiler is zero, and any fuel fired is used only to supply the losses. The factors affecting boiler efficiency are:

As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.

- Below half load, most combustion appliances need more excess air to burn the fuel completely. This increases the sensible heat loss.

- In general, efficiency of the boiler reduces significantly below 25% of the rated load and as far as possible; operation of boilers below this level should be avoided.

12. Proper Boiler Scheduling

Since, the optimum efficiency of boilers occurs at 65-85% of full load, it is usually more efficient, on the whole, to operate a fewer number of boilers at higher loads, than to operate a large number at low loads.

13. Boiler Replacement

The potential savings from replacing a boiler depend on the anticipated change in overall efficiency. A change in a boiler can be financially attractive if the existing boiler is:

- Old and inefficient.
- Not capable of firing cheaper substitution fuel.
- Over or under-sized for present requirements.
- Not designed for ideal loading conditions.

The feasibility study should examine all implications of long-term fuel availability and company growth plans. All financial and engineering factors should be considered.

Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

CHECKLIST & TIPS FOR ENERGY EFFICIENCY

Boilers

- Preheat combustion air with waste heat.
- (22 ^{0}C reduction in flue gas temperature increases boiler efficiency by 1%)
- Use variable speed drives on large boiler combustion air fans with variable flows.
- Burn wastes if permitted.
- Insulate exposed heated oil tanks.
- Clean burners, nozzles, strainers, etc.
- Inspect oil heaters for proper oil temperature.
- Close burner air and/or stack dampers when the burner is off to minimize heat loss up the stack.
- Improve oxygen trim control (e.g. -- limit excess air to less than 10% on clean fuels).

(5% reduction in excess air increases boiler efficiency by 1% or: 1% reduction of residual oxygen in stack gas increases boiler efficiency by 1%)

- Automate/optimize boiler blowdown. Recover boiler blowdown heat.
- Use boiler blowdown to help warm the back-up boiler.
- Optimize desecrator venting.
- Inspect door gaskets.
- Inspect for scale and sediment on the water side.
- (A 1 mm thick scale (deposit) on the water side could increase fuel consumption by 5 to 8%.)
- Inspect for soot, fly ash, and slag on the fire side.

(A 3 mm thick soot deposition on the heat transfer surface can cause an increase in fuel consumption to the tune of 2.5%)

- Optimize boiler water treatment.
- Add an economizer to preheat boiler feedwater using exhaust heat.
- Recycle steam condensate.
- Study part-load characteristics and cycling costs to determine the most-efficient mode for operating multiple boilers.
- Consider multiple or modular boiler units instead of one or two large boilers.
- Establish a boiler efficiency-maintenance program. Start with an energy audit and follow-up, then make a boiler efficiency-maintenance program a part of your continuous energy management program.

Steam System

- Fix steam leaks and condensate leaks.
- (A 3 mm diameter hole on a pipe line carrying 7 Kg/cm^2 steam would waste 33 Kilo litres of fuel oil per year)
- Accumulate work orders for repair of steam leaks that can't be fixed during the heating season due to system shutdown requirements. Tag each such leak with a durable tag with a good description.
- Use back pressure steam turbines to produce lower steam pressures.
- Use more-efficient steam desuperheating methods.
- Ensure process temperatures are correctly controlled.
- Maintain lowest acceptable process steam pressures.
- Reduce hot water wastage to drain.
- Remove or blank off all redundant steam piping.
- Ensure condensate is returned or re-used in the process.
- (6^{0}C raise in feed water temperature by economiser/condensate recovery corresponds to a 1% saving in fuel consumption, in boiler)
- Preheat boiler feed-water.
- Recover boiler blowdown.
- Check operation of steam traps.
- Remove air from indirect steam using equipment.

(0.25 mm thick air film offers the same resistance to heat transfer as a 330 mm thick copper wall)

- Inspect steam traps regularly and repair malfunctioning traps promptly.
- Consider recovery of vent steam (e.g. -- on large flash tanks).
- Use waste steam for water heating.
- Use an absorption chiller to condense exhaust steam before returning the condensate to the boiler.
- Use electric pumps instead of steam ejectors when cost benefits permit
- Establish a steam efficiency-maintenance program. Start with an energy audit and follow-up, then make a steam efficiency-maintenance program a part of your continuous energy management program.

CASE STUDY.

Installing Boiler Economiser [7]

A paper mill retrofitted an economiser to existing boiler. The general specification of the boiler is given below:

Boiler Capacity (T/h)	Feed Water Temp (°C)	Steam Pressure (bar)	Fuel oil
8	110	18	Furnace oil

The thermal efficiency of the boiler was measured and calculated by the indirect method using flue gases analyser and data logger. The result is summarised below:

Thermal efficiency	:	81%
Flue gas temperature	:	315°C
CO_2 %	:	13
CO (ppm)	:	167

The temperature in the flue gas is in the range of 315 to 320°C. The waste heat in the flue gas is recovered by installing an economizer, which transfers waste heat from the flue gases to the boiler feed water. This resulted in a rise in feed water temperature by about 26°C.

Basic Data
Average quantity of steam generated: 5 T/hr
Average flue gas temperature: 315 °C
Average steam generation / kg of fuel: 14 kg
Feed water inlet temperature: 110oC
Fuel oil supply rate: 314 kg/hr
Flue gas quantity: 17.4 kg/kg of fuel

Cost Economics

Quantity of flue gases: 314 x 17.4 = 5463.6 kg/h
Quantity of heat available in the flue gases: 5463.6 x0.23 x (315-200) = 144512 kCal/h
Rise in the feed water temperature: 26 °C.
Heat required for pre-heating the feed water: 5000 x 1 x 26 = 130000 kCal/h
Saving in terms of furnace oil: 130000/10000 = 13 kg/h
Annual operating hours: 8600
Annual savings of fuel oil: 8600 x 13 = 111800 kg

Through recovery of waste heat by installation of an economizer, the paper mill was able to save 13 kg/hr. of furnace oil, which amounts to about 1,11,800 kg of furnace oil per annum.

CONCLUSION

This paper is briefly focused on the various aspects of Efficient Operation of Boiler. Efficient Operation of Boiler is expected to play even much bigger role in years to follow, as industries worldwide are going through an increasing and stiff competition and increased automation of plants. The down time cost for such systems is expected to be very high. To meet these challenges, it is clearer by the case study given in the paper. We have to use latest technology and management skills in all spheres of activities to perform its effective role in profitability of the company.

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