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Boiler Efficiency Monitoring

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Abstract: In this paper, we introduce a successfully proven package which provides an online reading and trend analysis of the key parameters in a boiler which are then used as online boiler efficiency calculation. We also discuss the benefits of installing this package on a steam boiler.

Key words: Boiler Efficiency, Blow-down, Air fuel ratio,

1. Introduction

Pollution norms and market fuel prices impose stringent rules on efficient use of steam boilers as one of the main industrial equipments in production plants and medium/large heating systems. Boiler efficiency represents the efficiency with which the energy input gets converted into useful output. Ideally one would want to equalize it. However there are inherent losses in the system, which result in lower efficiency.

A typical boiler will consume many times the initial capital expense in fuel usage annually, consequently a difference of just a few percentage points in boiler efficiency can translate into substantial saving.

Based on BS845 [1] as the reference for indirect boiler efficiency calculation method, the major losses are stack loss, enthalpy loss, radiation loss, un- burnt loss and blow down loss. Knowing the values of above losses is of prime concern in boiler efficiency monitoring, but generally lack of suitable instruments/ software make this somewhat difficult.

Almost all utility managers have a fair idea of their efficiency, because they know how much fuel is consumed, and roughly how much steam they generate. However, the actual amount of steam generated can vary substantially from the “guess”, and the utilization of the steam is another area where wastage can occur. If we are to increase the efficiency of our boilers, knowing exactly what’s happening is crucial. The basic requirement for improvement is to know exactly where we are today, where we want to be, and a plan for how to get there.

In this paper, after a review of key parameters involved in boiler efficiency calculation, a proven method/hardware is introduced for online boiler efficiency monitoring and the key parameters it can monitor are explained.

2. Boiler Efficiency Definition

Formal methods of boiler efficiency determination can be classified as either direct or indirect. In the direct method, efficiency is calculated by dividing energy delivered by the boiler by energy input as fuel.

This method, while numerically correct, has limited practical application. It is difficult to measure fuel flow accurately, and in any case just knowing efficiency is not enough; one needs to know the source of losses to be able to minimize them.

The method most standards (including IS8753, BS845 etc.) now follow the indirect efficiency calculation method. In this method, each loss is individually calculated, and the sum of these losses is then subtracted from 100 to give efficiency %, so:

$$\%Efficiency = 100 - (Sum\ of\ all\ losses)$$

This method has one big advantage. Since each loss is individually measured, we have quantitative data which we can use to actually reduce an individual loss, thereby increasing efficiency. So this method tells us where we are, and how to get where we want to be.

In a typical boiler there are following losses to consider:

a) Loss due to water and hydrogen in fuel:
This is the difference between GCV and NCV of a fuel, and needs to be considered if efficiency is calculated on GCV. Not much can be done to reduce this loss, as it is a function of fuel constituents alone.

b) Stack loss:
Improper combustion is responsible for this loss. In most burners, the manufacturer specifies a minimum level of excess air required to ensure that complete combustion of the fuel takes place. However, typically, excess air levels are higher than this specification, so fuel is being spent to heat air from ambient to flue gas temperature. Further, since the amount of air required depends on amount of fuel (which in turn depends on load on the boiler), it varies continuously, making it that much more difficult to ensure that the excess air levels are kept within specified levels. This loss presents the greatest opportunity for energy conservation schemes, whether manual or through automation. Stack loss can increase if the damper is not correctly positioned, or if the burner nozzles need cleaning, or in the case of oil, even if oil temperature is not controlled.

The importance of excess air
As most combustion equipment operators know it is extremely undesirable to operate a burner with less than stoichiometric combustion air.

C_nH_n + Air Deficient $\longrightarrow$ $CO + H_2 + CO_2 + H_20 + N_2$ + Heat

Not only is likely to result in smoking stack, but it will significantly reduce the energy released by the fuel. If a burner is operated with a deficiency of air, carbon monoxide & hydrogen will appear as products of combustion. CO & H_2 are the result of incomplete combustion & are known as combustibles. Anything more than a few hundred parts per million of combustibles in flue gas indicate inefficient burner operation since both CO & Hydrogen are fuels. In actual applications, it is impossible to achieve stoichiometric combustion because burners cannot mix fuel & air perfectly.

To ensure that all the fuel is burned & that little or no combustibles appear in the flue gas, it is common practice to supply some amount of excess air. Not long ago, it was not considered unusual to run a boiler with large amount of excess air in order to avoid smoking stack. Today this is recognized as a highly wasteful practice.

Too little excess air is inefficient because it permits unburned fuel, in the form of combustibles, to escape up the stack. But too much excess air is also inefficient because it enters the burner at ambient temperature and leaves the stack hot, thus stealing useful heat from the process. This leads to the fundamental role of combustion efficiency. “Maximum combustion efficiency is achieved when the correct amount of excess air is supplied so that sum of both unburned fuel loss and flue gas heat loss is minimized”.

But how is the correct amount of excess air determined? By far the most widely accepted practice is to measure the percentage oxygen is flue gas, which is direct measure of excess air. It is then possible to control the supply of excess air so that combustion efficiency can be maximized.

c) Flue gas heat loss

Flue gas heat loss is the largest single energy loss in every combustion process. It is generally impossible to eliminate flue gas heat loss because the individual constituents of flue gas all enter the system cold and leave at elevated temperatures. But reducing the amount of excess air supplied to the burner can minimize flue gas heat loss.

Flue gas heat loss increases with both increasing excess air & temperature. As both the carbon dioxide & oxygen levels are directly related to amount of excess air supplied either a CO2 or an O2 flue gas analyzer can be used to measure and control flue gas heat loss. However in recent years CO2 level in flue gas has fallen out of favor.

A particular CO2 level in flue gas can indicate either an excess or deficiency of combustion air. The dual meaning is unacceptable in combustion control systems. Development of more reliable & faster response zirconium oxide oxygen sensor has virtually eliminated the use of carbon dioxide flue gas analyzers.

Since Flue gas analyzer is a universal device it can be mounted on any boiler irrespective of capacity & fuel used without any modification or calibration.

Savings from flue gas analyzer

A typical 1% rise in Oxygen from optimum value will result in approximate 0.5% drop in boiler efficiency & 1% fall in oxygen from optimum value will result in 1% drop in efficiency.

Let us establish above fact:
Boiler under consideration:
Load = 5 TPH, Working Pressure = 10.54Kg/cm^2 (g) & Fuel = FO fired.
Percentage of O_2= 5%, CO_2 = 11.86%, Stack Temperature=220^{0}C, Ambient temperature=40^{0}C

Loss due to excess air (L_2) :
Equation (1) L_2 $= k \times (t_g - t_a) / CO_2\%$
$= 0.51(220-40)/11.86$
$= 7.72\%$

Now if this can optimized to O_2 = 3%, stack temperature will also come down by approx 2^{0}C due to increase of dwell time within the boiler.
Percentage of O_2= 3%, CO_2 = 13.36%, Stack Temperature=220^{0}C, Ambient temperature=40^{0}C
Loss due to excess air (L_2) :
Equation (2) L_2 $= k \times (t_g - t_a) / CO_2\%$
$= 0.51(218-40)/13.36$
$= 6.78\%$

The previous stack loss can very well be reduced by optimizing excess air percentage by approximate damper settings.

The stack temperature in addition to excess air percentage also depends on following factors:

1. Furnace design & burner design
2. Boiler smoke tube soot
3. Boiler water side scaling.

The first parameter is establishment by boiler design whereas 2nd & 3rd parameter can be controlled by optimum air to fuel ratio & water quality & TDS respectively.

However if excess air % is maintained correctly the denominator value is maximum, hence stack temperature valve will have less effect.

For example: If stack temperature increases by 12^{0}C in equation 1 due to sooting & scaling.
Equation (3) L_2 $= k \times (t_g - t_a) / CO_2\%$
$= 0.51(230-40)/13.36$
$= 7.24\%$

This will drop boiler efficiency by (7.24 – 6.78) = 0.46%.

For oil fired boiler if damper settings is not done approximately, O_2 % can be as high as 10-12% & even higher at low loads. This also results in 10 – 12^{0}C rise in stack temperature.

In this extreme case the stack loss will become:

Percentage of O_2= 11%, CO_2 = 7.42%, Stack Temperature=230^{0}C, Ambient temperature =40^{0}C
Loss due to excess air (L_2) :

Equation (4) L_2 =k x (t_g -t_a)/ CO_2%
=0.51(230-40)/7.42
=13.044%

Now if you compare equation 2 & 4 you will see stack loss increases 6.264% that indicates 6.264 % drop in boiler efficiency &corresponding rise in fuel consumption.

What excess air % has to be maintained in the boiler?
Typically for a good Indian burner the excess air Oxygen % is 2.5-3.5%on high loads &3.5-5% on low loads. More Important this can only be maintained without getting un-burnt provided burner nozzle tip is of right dimensions, fuel temperature & fuel pressure is appropriately maintained. Normally suppose nozzle opening increases due to wear & tear, fuel temperature & pressure decreases the above mentioned excess air %cannot be maintained. An operator normally compensates this by increasing the excess air %. This results in reduced boiler efficiency as per above-mentioned formulae.

A prudent operator should take corrective action by changing burner nozzle & setting appropriate fuel temperature & pressure & operate the boiler on recommended excess percentage levels as per flue gas readings.

d) Radiation and convection losses:
This is a function of temperature gradient between the boiler water and the ambient, quality of insulation and surface area of the boiler. It is typically specified by the boiler manufacturer at full load conditions (say 1% for a packaged boiler). However, since it is a constant loss, at half load it will be double as a percentage. Accordingly, if steam flow is known, we can work out the instantaneous radiation loss.

e) Loss due to combustible matter in ash & grit:
This is applicable only to solid fuels. This is based on multiplying the quantity of ash collected in a particular time period by the amount of carbon content in it and dividing it by the quantity of fuel burnt in that time. This loss contributes to around 1 percent in solid fuels .An online analyses is not possible in this case but can be used as user fed input.

3. Boiler Efficiency and Blow-Down

Most standards for computation of boiler efficiency, including BS845 and IS 8753 are designed for a spot measure of boiler efficiency. Invariably, they ask that the blow-down valve be kept shut throughout the efficiency determination process, and therefore remove blow-down from the perspective. However, depending on feed water quality, boiler blow-down can be between 2 and 5 % of steam generation, and is a huge loss by itself. As utility managers, we are not really as interested in the absolute value of efficiency as per some specified method, but more in the steam/unit fuel figure. Accordingly, the blow-down loss is of utmost importance in reduction of a boiler's operating cost.

Effect of feed-water quality on boiler losses
Blow-down loss is not considered while calculating the boiler efficiency. However it plays an important role in fuel conservation.

Better the quality of feed-water, less of blow-down required but water treatment cost goes up correspondingly. Hence an appropriate balance is the quantity of blow-down required but water treatment cost goes up correspondingly. Three most common water treatment methods are:

1. Water softener by chemical dosing: In this method the hard salts viz. Calcium & Magnesium is replaced by soft salt sodium. By this scaling on tubes is avoided. However TDS doesn't decreases, in fact it increases slightly. The blow-down requirement goes up slightly. The water treatment cost in India is Rs. 4/KL.

2. Reverse Osmosis plant: In this method TDS comes down in addition to hardness. The treatment cost in India is Rs.27/KL. Maintenance cost is high due to replacement of membranes at regular interval.

3. DM plant: In this method, TDS & hardness comes down drastically. The water treatment cost in India is Rs. 30/KL & maintenance cost ids moderate due to recharging the resins required.

In a boiler house the operator carries out blow-down as per thumb rules. For 10.5 Kg/cm^2(g) boiler, 2'' blow-down valve size the typical blow-down quantity is 10 kg/sec. For 60 sec. this will correspond to 600 kg of hot water.

How much blow-down is required?
Blow-down quantity depends on feed-water quality, boiler water quantity, boiler water recommended TDS levels & boiler steaming rate. The boiler operator carries out blow-down as per the rules irrespective of above parameters. Measurements show a lot of difference in TDS from shift to shift. In order to maintain recommended TDS it will call for an operator continuously modulating the blow-down valve as per TDS readings.

The automatic blow-down control system precisely does this job of measuring at short interval & controlling valve accordingly.

How correct is manual sampling?
Even if blow-down is carried out as per TDS reading taken in Lab, there is likelihood of big errors if sample is not taken through sample cooler, rarely practical in industry.

Every time a sample is taken a lot of water is lost by flashing. Flash steam doesn't carry any TDS with it, hence sample in beaker has higher TDS than boiler water TDS than boiler water thus resulting on decision to carry out excessively more blow-down.

What happens if TDS is allowed to rise?
Higher TDS will result in foaming inside the boiler vessel, that in turn will result in wet steam that will reduce the equipment life due to pitting & also cause steam starvation since steam holding capacity reduces & water gets removed by moisture separator & trap resulting in less steam passed on to the process. The steam quality is adversely affected due to wetness fraction that will affect product quality.

Effect of feed-water temperature
Feed-water temperature doesn't affect the boiler efficiency but plays important role for optimizing steam to fuel ratio.

Every 6^{0}C rise in feed-water temperature will result in 1% fuel savings. Normally an operator mixes condensate plus make up water to meet boiler load. In most plants the make up water is added till feed-water tank is filled not paying any attention to feed-water temperature.

If feed-water temperature is continuously maintained & condensate & make up water ratio is optimized to ensure maximize feed-water temperature meeting boiler-steaming rate it will result significant fuel savings.

Taking all the parameters in considering you will observe there is possibility of 3- 10% fuel savings by optimizing boiler processor parameters. We are considering only 1.5% savings conservatively.

The typical capital cost of 5 TPH boiler in Inida with all accessories & mostly is typically Rs.30 – 40 L. What is operating cost of a 5 TPH boiler annually? Consider a 5 tph, 10 kg/cm2 (g) oil fired boiler operating at a steam to fuel ratio of 13: 1 the annual running cost will be:
Boiler load: 5tph, Oil consumption: 5000/13 = 384.16 kg/hr.
Considering oil density of 0.91 this will work out to 422.65 L/hr.
Annual running cost of boiler considering 8000 hrs operation this will be: 3381234.15 litres.
Considering average fuel cost of Rs. 10.5/- per litre in India, this will be: Rs. 3, 55, 02,958/- per annum (Rs Three crore fifty five lakhs per annum)

You will observe the capital cost is of boiler is only 10% of boiler running cost.

Now consider 1.5% savings of boiler running cost. This worth to be:
This will work out to Rs. 5, 32,544/- per annum.

4. Proving these with Effimax package

All the above mentioned parameters are bared on well proven practices in industry. This can be well proven provided following care is taken. Fuel should be accurately quantified by mass flow meter or accurate dip stick method & let the some fuel batch run on manual mode for 1 week & run with EffiMax for 1 week & you will observe the difference.

The EffiMax Boiler Efficiency Package
Forbes Marshall combines years of steam & instrumentation expertise to introduce EffiMax 2000, the first packaged Total efficiency Monitoring & data acquisition package for your boilers performance.
The package consists of all the equipment you need to measure each loss and it automatically calculates the boiler efficiency on-line, and in general accordance with the BS845: Part 1: 1987 of the British Standard for assessing thermal performance of boilers, concise procedure. Below is a picture of Effimax2000.

Picture 1: Effimax 2000

The EffiMax package includes:

- Oxygen analyzer for excess air measurement in flue gas.
- Stack temperature measurement
- Feed-water temperature measurement for enthalpy calculation
- High accuracy ,Low pressure drop vortex type steam flow meter
- Steam temperature measurement for enthalpy calculation
- Automatic Blow-down control System .
- Computation & display unit
- Data acquisition & diagnostic software package.

The EffiMax Package provides online recording and trend analysis for the following parameters:

- Boiler efficiency %
- Stack loss %
- Enthalpy loss %
- Combustion loss %
- Radiation loss %
- Total blow-down loss , % blow-down loss & Average blow-down loss
- Steam to fuel ratio

- Rs lost per annum
- Steam temperature
- Feed-water temperature
- Stack temperature
- Ambient temperature
- O2 %
- Steam mass flow
- Fuel type menu
- TDS ppm in boiler water

The benefits of installing this package on a steam boiler include:

- Continuous indication and recording of efficiency parameters prompts immediate corrective action and continuous fuel saving: For example, typically in the third shift, consumption of steam is lower than in the first two shifts. If the operating data can be monitored, recorded and analyzed, it is possible to determine the correct damper position for the third shift to optimize combustion.
- Better combustion makes the boiler pollute less.
- Assists in preventive maintenance: The EffiMax presents information which is useful in scheduling of boiler maintenance to ensure optimal efficiency e.g. tuning of burner, cleaning burner nozzles, de-scaling of tubes etc.
- Provides advance information about the health of the boiler, thereby making boiler operation safer and more reliable.
- Automates and optimizes the tedious blow-down control.
- Functions as a diagnostic tool for quality of feed water by totalizing blow-down.
- Cleaner boiler water means cleaner steam.

User friendly data acquisition & diagnostic software package:

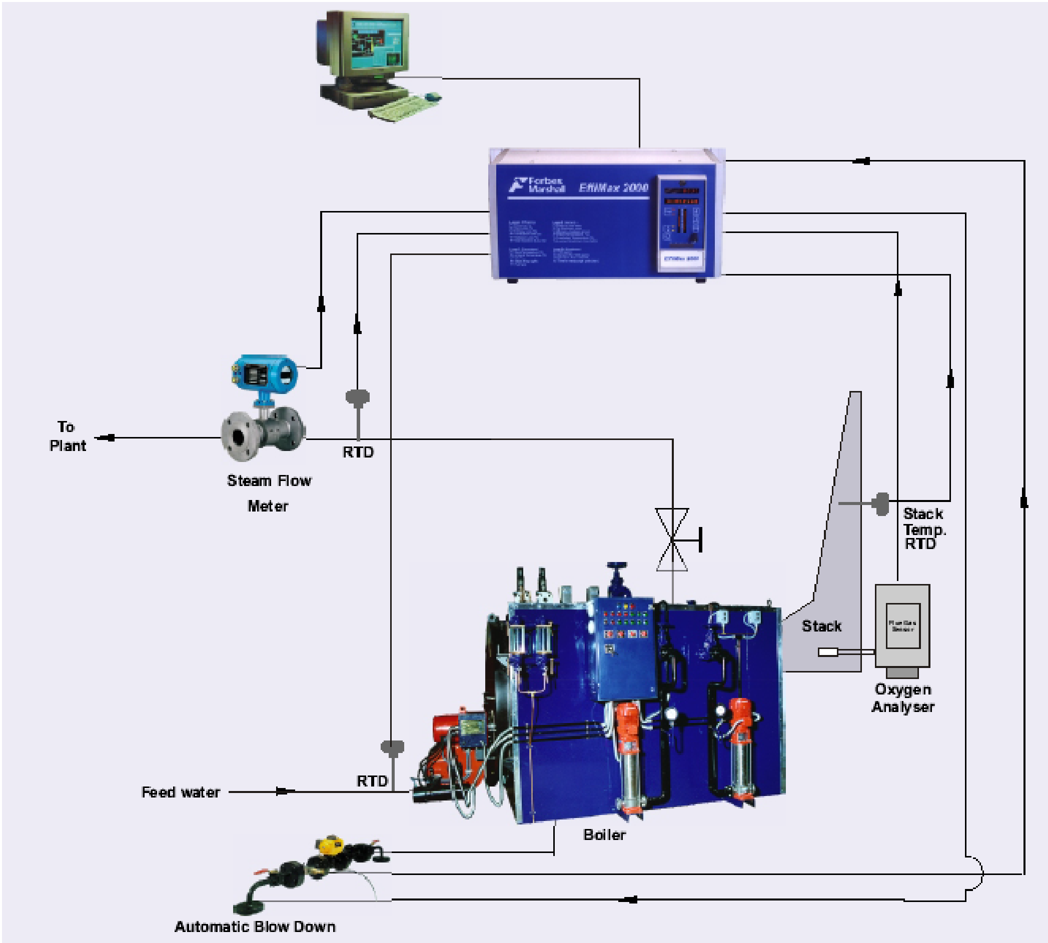
- General mimic page displays complete boiler equipment on screen with instantaneous value of all measured parameters
- Parameter screen displays graphical trends for measured parameters, losses & efficiency parameters.
- Alarm & Diagnostic screen displays all deviations from desired results with diagnostic tips to resolve the same.
- PC can be located 700 meters from the computation unit in central control room or utility managers cabin as per user convenience.
- Data log screen indicates all important parameter & trends suitable for hard copy shift or daily reports.

The Effimax package costs just a fraction of savings possible. Even if the boiler is smaller, or is fired by alternative fuels such as coal, husk or bagasse, the package normally pays for itself within a year. The table below shows the possible annual savings for a 3% improvement in efficiency & payback in months, based on Indian prices:

Table 1: A sample payback calculation

Boiler	**Coal**		**Oil**		**Natural Gas**	
TPH	**Rs. / year**	**Months**	**Rs. / year**	**Months**	**Rs. / year**	**Months**
2	2,41,543	23	5,17,275	22	1,82,982	30
3	3,62,315	15	7,75,914	15	2,74,473	20
5	6,03,858	9	15,48,269	6	4,57,455	12
10	12,07,716	4	25,86,381	3	9,14,910	6
15	18,11,574	3	38,79,571	2	13,72,364	4
20	24,15,432	2	51,72,763	1.5	18,28,819	3

The below picture shows, the device and how it is connected to the boiler and its peripherals.



Picture 2: Effimax connected to a boiler and required extra instruments

5. Conclusion

In order to minimize fuel consumption & maintenance needs it is utmost important to continuously monitor important boiler parameters and make adjustments accordingly. In this paper, a package is introduced which accomplish this task by accepting input from Oxygen analyzer, Feed water TDS, Feed water temperature sensor, stack temperature sensor, ambient temperature sensor and steam flow meter to calculate & indicate the following parameters: Boiler efficiency %, Individual losses of boiler i.e:Radiation loss, enthalpy loss & stack loss, Steam flow rate & total consumption, blow-down rate & totalisation, Excess air %, Feed water temperature, Steam temperature & steam /fuel ratio. The control loops automatically controls the TDS ppm in boiler & minimizes blow down loss.

5. References

[1] British Standard BS845 : Part 1 : 1987 for assessment of thermal performance