

Influence of Flue Gas and Feed Water Temperatures on Boiler Efficiency – An Analysis

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ABSTRACT: The production of power and heat in industrialized countries is mostly based on the combustion of fuels. Usually combustion takes place in a furnace of boilers. Well-designed boilers have high thermal efficiency of more than 90% as per First law (FL) analysis. This can be achieved depending on the selected fuel or boiler. These high thermal efficiencies suggest that combustion processes are highly optimized and do not need any further improvement with regard to their thermodynamic performance. However, second law analysis shows that thermodynamic losses are much higher than, indicated by FL. So, this indicates the requirement of further investigation to utilize the work potential of the boiler completely. In fact, any examination of energy utilization is the search for the minimum of energy consumption. This paper deals with the influence of feed water temperature and flue gas temperature on the efficiency of the boilers by using various types of fuels (coal, furnace oil and bagasse) that are widely used in process and power plants. Since boilers are the major component in these industries makes it desirable to evaluate the energy efficiency of boiler both quantitatively and qualitatively.

KEYWORDS: Boilers, Energy analysis, first law analysis, flue gas temperature, feed water temperature

I. INTRODUCTION

Energy is the most important factor for automation and modernization. Automation and modernization are increasing rapidly in the industrial sector. The Indian power sector is at third place of the power production in the world. The total installed capacity of India stands at about 2,81,423 MW [1]. Of this, the major share – 1,95,604 MW [1] – or 70 per cent is thermal. So, thermal plants are the mainstay of the power sector in India, but power sectors are struggling to overcome chronic power shortages and poor quality of power supply. With demand exceeding supply, peak around 5% [1] and energy shortages around 4% [1] continue to plague the sector. Shortages exacerbated by inefficiencies in the end-use systems are mainly due to technological obsolescence of industrial processes and equipment, irrational tariffs, etc.

In thermal power plants Boilers, Turbines, Generators, Condensers and cooling tower are the major components and Boilers play a crucial part in the operations of turbines and generators. Boiler efficiency has an influence on heat transfer to the water where various losses by hot flue gas, radiation, unburnt fuel, moisture content of the air and fuel and blowdown etc. as the temperature of the flue gas leaving a boiler typically ranges from 150-250 0C, about 10-40% of the heat energy is lost [2]. Increased efficiency can often contribute in a major way to achieving energy security in an environmentally acceptable way by the direct reduction of losses. Energy efficiency improvement in the industrial sector is the most important option to save energy as well as emission reduction [3, 4]. With increasing oil prices and higher environmental taxes, many industrial processes can make substantial cost savings by installing a heat recovery system. During the last 15 years, oil prices have been increased to 60-70% . Heat recovery gives direct savings in terms of reduction of fuel consumption as well as indirect savings in reducing the environmental impact [5,6,7]. From the above discussion and literatures, it is found that analysis of energy is crucial for energy planning, resource optimization, global

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 1, January 2016

environmental issue, regional and national pollution reduction.

The aim of this study is to analyze the influence of feed water temperature and flue gas temperature on the efficiency of the boilers by using various types of fuels (coal, furnace oil and bagasse) that are widely used in process and power plants. Since, boilers are the major component in the industries makes it desirable to evaluate the energy efficiency of boiler both quantitatively and qualitatively.

II. BACK GROUND

First Law analysis of boilers

The First law efficiency of the boiler can be calculated by two methods, direct and indirect method. Direct method of efficiency calculation includes only the input and the output energies, but does not include the various heat losses occurring in the boiler. The efficiency can be measured easily by measuring all the losses occurring in the boilers. The disadvantages of the direct method can be overcome by this method, which calculates the various heat losses associated with boiler. The efficiency can be arrived at, by subtracting the heat loss fractions from 100.

The losses from the boiler include the following:

- Dry flue gas loss (L1)
- Heat due to moisture and hydrogen in fuel.(L2)
- Losses due to the combustibles.(L3)
- Losses due to sensible heat in ash(L4)
- Radiation losses.(L5)
- Unaccounted losses(L6)

$$\begin{aligned} \text{Boiler Efficiency} &= 100 - \text{Total losses} \\ &= 100 - (L1+L2+L3+L4+L5) \end{aligned} \tag{1}$$

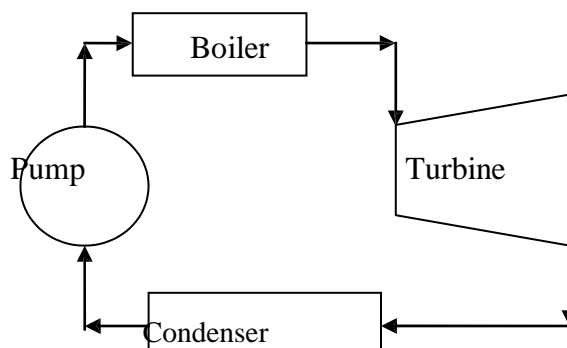


Fig. 1 schematic diagram of simple steam power plant.

Direct method:

The energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

$$\eta_{\text{Boiler}} = \frac{\text{Steam flow rate} \times (\text{steam enthalpy} - \text{feed water enthalpy})}{\text{Fuel firing rate} \times \text{Gross calorific value}} \times 100 \tag{2}$$

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Indirect method:

In this method, efficiency is the difference between the losses and the energy input.

$$\eta_{boiler} = \frac{\text{Energy input} - \text{Energy losses}}{\text{Energy input}} \times 100 \quad (3)$$

Energy Balance

The Energy balance is a calculation procedure that basically checks if, directly or indirectly measured energy flows are in agreement with the energy conservation principles. This balance is of the utmost importance and is an indispensable tool for a clearer understanding of the energy situation achieved in practice.

In order to use it correctly, the following procedure may be used.

- i. Clearly identify the problem to be studied.
- ii. Define a boundary that encloses the entire system or sub-system to be analyzed. Entering and leaving mass and energy flows must be measured at the boundary.
- iii. The boundary must be chosen in such a way that
 - a) All relevant flows must cross it, all non-relevant flows being within the boundary.
 - b) Measurements at the boundary must be possible in an easy and accurate manner.
- iv. Select an appropriate test period, depending on the type of process and product.
- v. Carry out the measurements.
- vi. Calculate the energy and mass flow.
- vii. Verify an energy and mass balance. If the balances are outside acceptable limits, then repeat the measurements.
- viii. The energy release or use in endothermic and exothermic processes should be taken into consideration in the energy balance.

III. METHODOLOGY

Analysis has been carried out by varying the temperature of the flue gas and the feed water, to study the influence of its effect on the efficiency of the boiler for different types of fuels. The analysis was carried out by varying the feed water temperature from 96 °C to 115°C and the flue gas temperature leaving the stack from 190°C to 170°C. For the analysis purpose, the following fuels were considered. The composition of the fuels used for the analysis are given in **Table 1**.

Table 1

Constituents	As received mass fraction (%)						
	Coal 1	Coal 2	Coal 3	Coal 4	Coal 5	Bagasse	Furnace Oil
C	41.65	60	57.4	56	63.98	23.4	85.9
H	2.04	5	4.2	5	4.51	2.8	12
O	14.48	4.8	4.5	4	6.91	20	0.7
N	1.6	2	0	0	1.26	0.1	0.5
S	0	0.2	0	0	2.52	0.6	0.5
Ash	8.63	18	18.9	25	9.7	1.1	0.05
H ₂ O	31.6	10	15	10	11.12	52	0.35
GCV (kJ/kg)	14659	26635	24639	25408	27110	7389	41335

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Relations used for the analysis

(a) Energy input:

$$\text{Heat supplied from fuel} \quad (Q_f) = m_f \times GCV \quad (4)$$

$$\text{Heat from feed water (sensible heat)} \quad (Q_w) = m_w \times C_{pw} \times (T_{fg} - T_a) \quad (5)$$

(b) Energy output:

$$\text{Heat available in steam} \quad (Q_s) = m_w * (h_s - h_w) \quad (6)$$

(c) Energy losses:

i. Heat loss due to dry flue gas :

This is the greatest boiler loss and can be calculated with the following formula:

$$Q_{dfg} = m_{fg} \times C_{pg} \times (T_{fg} - T_a) \quad (7)$$

ii. Heat loss due to evaporation of water formed due to H₂ in fuel:

The combustion of hydrogen causes a heat loss because the product of combustion formed is Water. This water is converted to steam and this carries away heat in the form of its latent heat.

$$Q_h = m_f \times H \times 9 \times [h_{fg} + C_{ps} (T_{fg} - T_a)] \quad (8)$$

iii. Heat loss due to moisture present in fuel :

Moisture entering the boiler with the fuel leaves as a superheated vapour. This moisture loss is made up of the sensible heat to bring the moisture to boiling point, the latent heat of evaporation of the moisture, and the superheat required to bring this steam to the temperature of the exhaust gas. This loss can be calculated with the following formula

$$Q_m = m_f \times M \times [h_{fg} + C_{ps} (T_{fg} - T_a)] \quad (9)$$

iv. Heat loss due to moisture present in air:

Vapour in the form of humidity in the incoming air, is superheated as it passes through the boiler. Since this heat passes up the stack, it must be included as a boiler loss. To relate this loss to the mass of coal burned, the moisture content of the combustion air and the amount of air supplied per unit mass of coal burned must be known.

$$Q_{ma} = m_a \times \text{humidity factor} \times C_{ps} \times (T_f - T_a) \quad (10)$$

v. Heat loss due to incomplete combustion:

The products formed by incomplete combustion could be mixed with oxygen and burned again with a further release of energy. Such products include CO, H₂, and various hydrocarbons and are generally found in the flue gas of the boilers. Carbon monoxide is the only gas whose concentration can be determined conveniently in a boiler plant test.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

$$Q_{ic} = m_f \left[\frac{\%CO \times C}{\%CO + \%CO_2} \right] \times 24050 \quad (11)$$

vi. Heat loss due to radiation and convection:

Heat losses from a boiler consist of the loss of heat by radiation and convection from the boiler casting into the surrounding boiler house. Normally surface loss and other unaccounted losses are assumed based on the type and size of the boiler as given below

For industrial fire tube / packaged boiler	= 1.5 to 2.5%
For industrial water tube boiler	= 2 to 3%
For power station boiler	= 0.4 to 1%

However, it can be calculated if the surface area of the boiler and its surface temperature are known as given below :

$$Q_R = 0.548 \times [(T_s / 55.55)^4 - (T_a / 55.55)^4] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{[(196.85V_m + 68.9) / 68.9]} \quad (12)$$

vii. Heat loss due to unburned carbon in fly ash and bottom ash:

Small amounts of carbon will be left in the ash and this constitutes a loss of potential heat in the fuel. To assess these heat losses, samples of ash must be analyzed for carbon content. The quantity of ash produced per unit of fuel must also be known.

viii. Heat loss due to unburnt in fly ash:

$$Q_{fa} = m_f * m_{ash} \times \text{G.C.V of fly ash} \quad (13)$$

ix. Heat loss due to unburnt in bottom ash:

$$Q_{ba} = m_f * m_{ash} \times \text{G.C.V of bottom ash} \quad (14)$$

x. Unaccounted heat loss:

Unaccounted heat loss is found by subtracting the above losses from heat input.

$$Q_{un} = (Q_f + Q_w) - (Q_s + Q_{dfg} + Q_{H_2} + Q_{wv} + Q_{ma} + Q_{IC} + Q_R + Q_{fa} + Q_{ba}) \quad (15)$$

By following the above mentioned principles and procedure, calculations was carried out for different types of fuels by varying feed water and flue gas temperatures. Results obtained from the calculations are further used for the analysis.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

IV. RESULTS AND DISCUSSION

Fuel: Coal 1

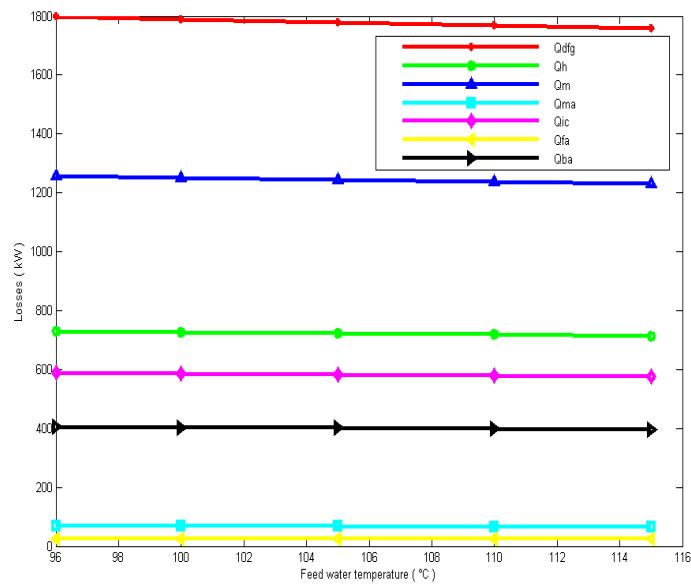


Fig. 2 Effect of feed water temperature on various losses for Coal 1

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.86% of total loss and enhances the efficiency by 0.55%

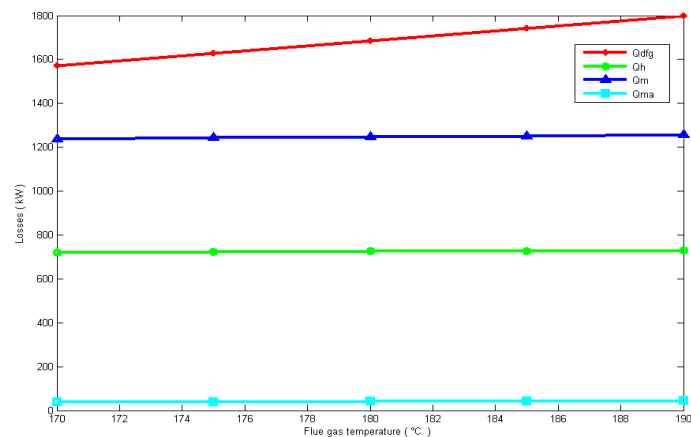


Fig.3 Effect of flue gas temperature on various losses for Coal 1

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

The above graph depict that 20⁰C reduction in flue gas temperature reduces 2.16% of total loss and increase in 1.30% of boilers efficiency.

Fuel: Coal 2

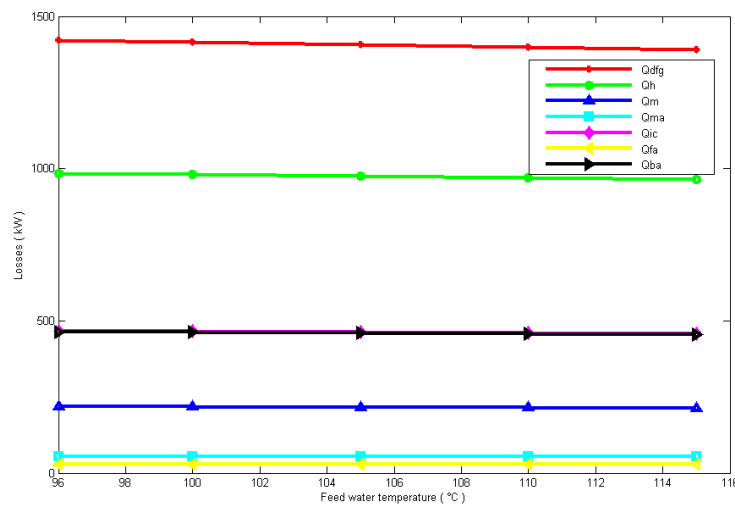


Fig. 4 Effect of feed water temperature on various losses for Coal 2

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.64% of total loss and enhances the boliers efficiency by 0.40%.

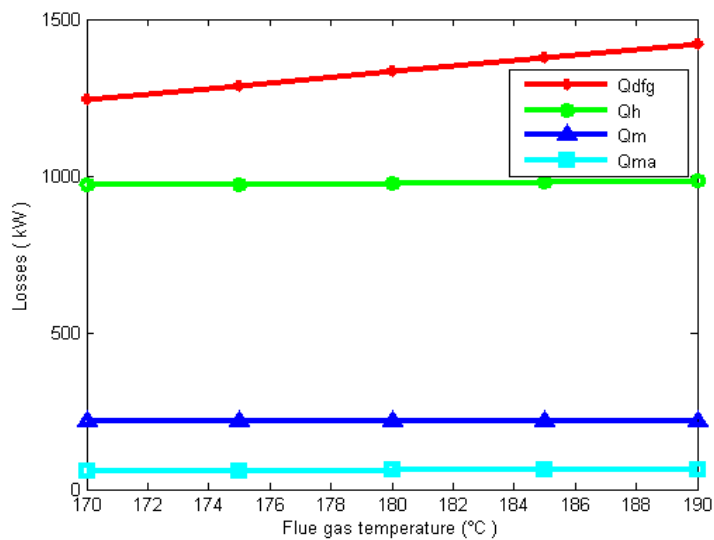


Fig. 5 Effect of flue gas temperature on various losses for Coal 2

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

It also infers that the 20⁰C reduction in flue gas temperature reduces 1.7% of total loss and increase in 1.11% of boilers efficiency.

Fuel: Coal 3

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.70% of total loss and enhances the boilers efficiency by 0.40%.

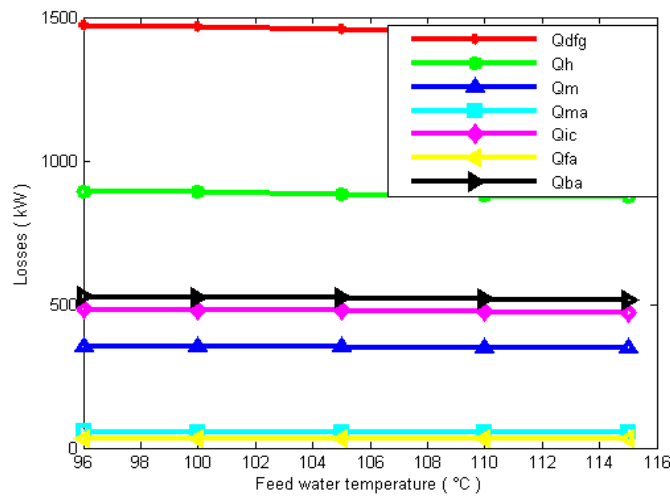


Fig. 6 Effect of feed water temperature on various losses for Coal 3

The Fig 7. depicts that the 20⁰C reduction in flue gas temperature reduces 1.32% of total loss and increase in 1% of boilers efficiency

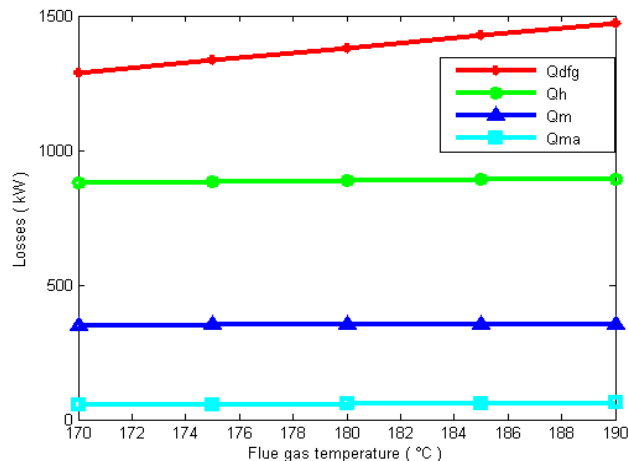


Fig.7 Effect of flue gas temperature on various losses for Coal 3

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Fuel: Coal 4

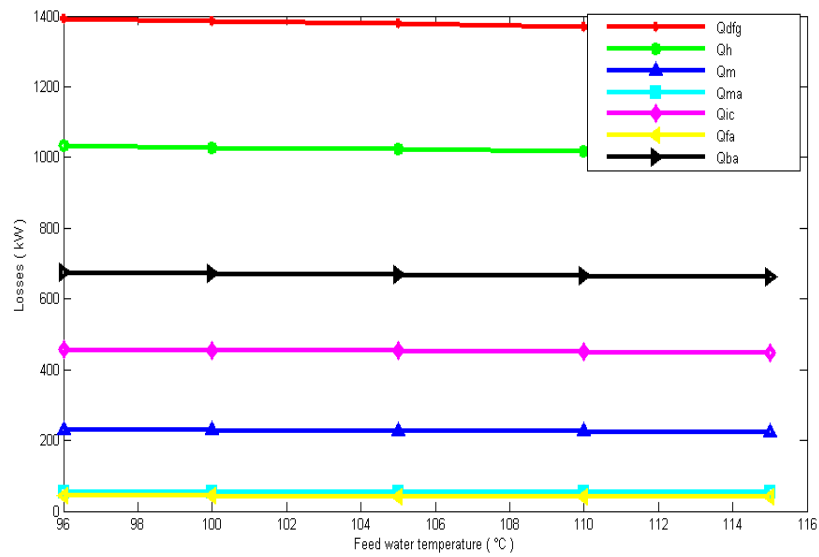


Fig.8 Effect of feed water temperature on various losses for Coal 4

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.70% of total loss and enhances the efficiency by 0.41%.

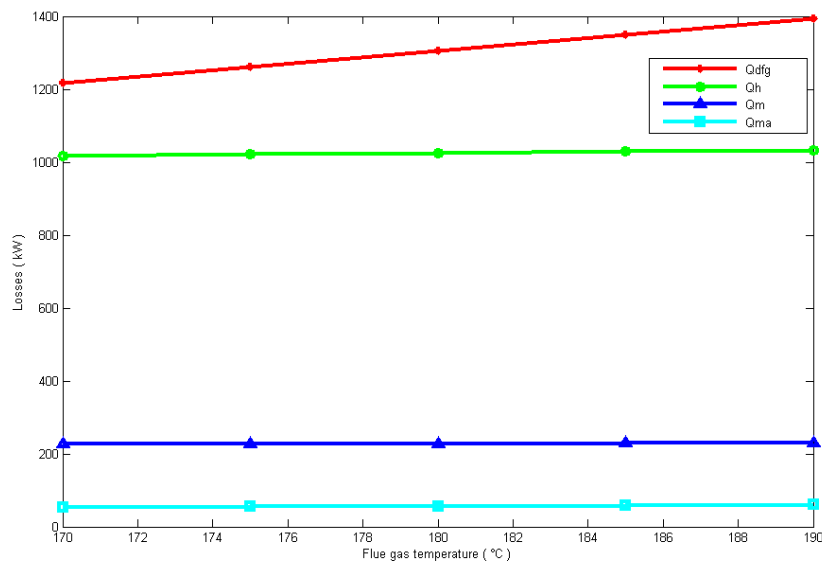


Fig.9 Effect of flue gas temperature on various losses for Coal 4

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Fig.9 depicts that the 20⁰C reduction in flue gas temperature reduces 1.71% of total loss and increase in 1% of efficiency.

Fuel: Coal 5

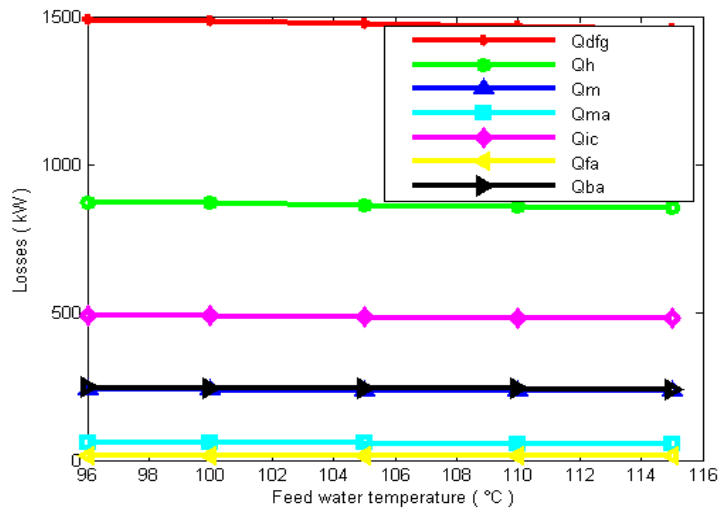


Fig.10 Effect of feed water temperature on various losses for Coal 5

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.60% of total loss and enhances the efficiency by 0.34%.

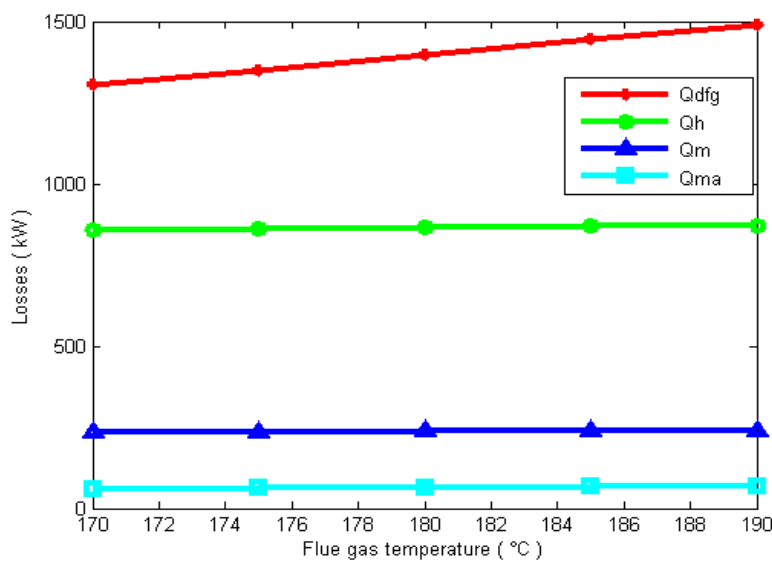


Fig.11 Effect of flue gas temperature on various losses for Coal 5

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Fig.11 depicts that the 20⁰C reduction in flue gas temperature reduces 1.76% of total loss and increase in 1% of efficiency.

Fuel: Bagasse

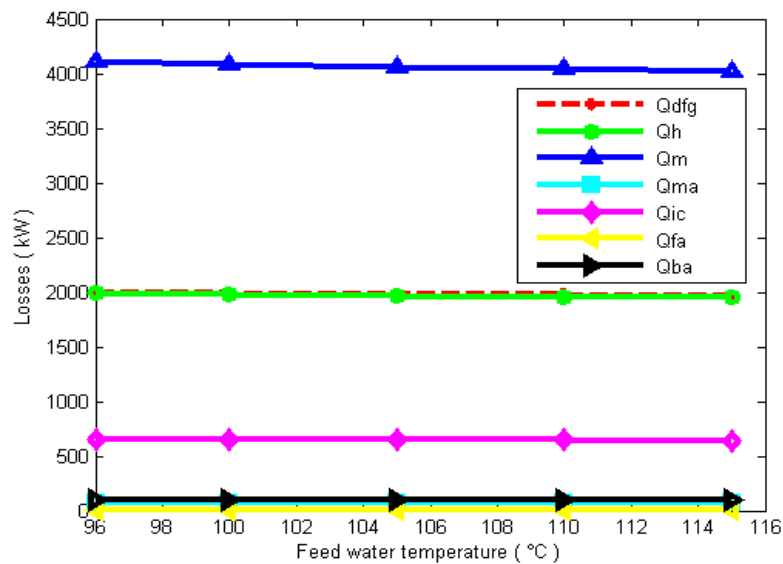


Fig.12 Effect of feed water temperature on various losses for Bagasse

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 1.57% of total loss and enhances the efficiency by 1.22%.

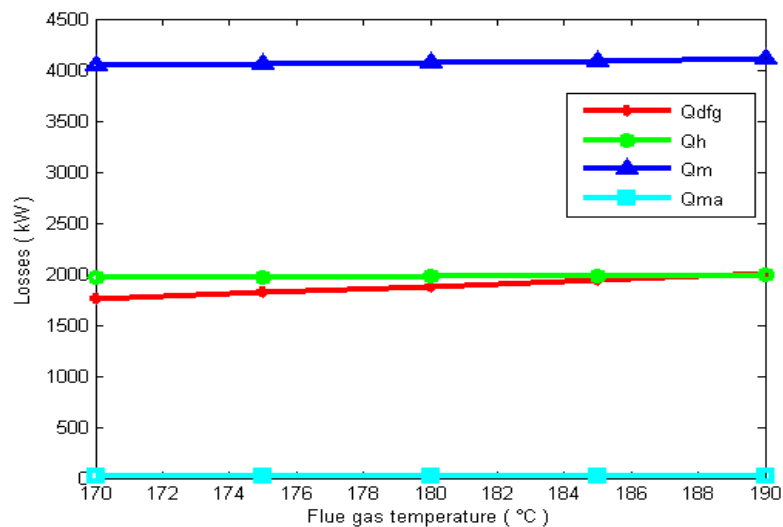


Fig. 13 Effect of flue gas temperature on various losses for Bagasse

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

From the Fig.13 it infers that the 20⁰C reduction in flue gas temperature reduces 2.86% of total loss and increase in 2.2% of efficiency.

Fuel: Furnace Oil

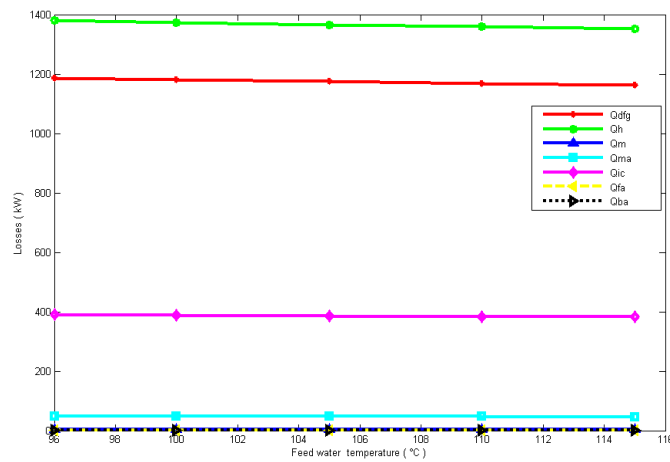


Fig. 14 Effect of feed water temperature on various losses for furnace oil

From the analysis, it infers that the 20⁰C rise in feed water temperature reduces 0.53% of total loss and enhances the efficiency by 0.30%.

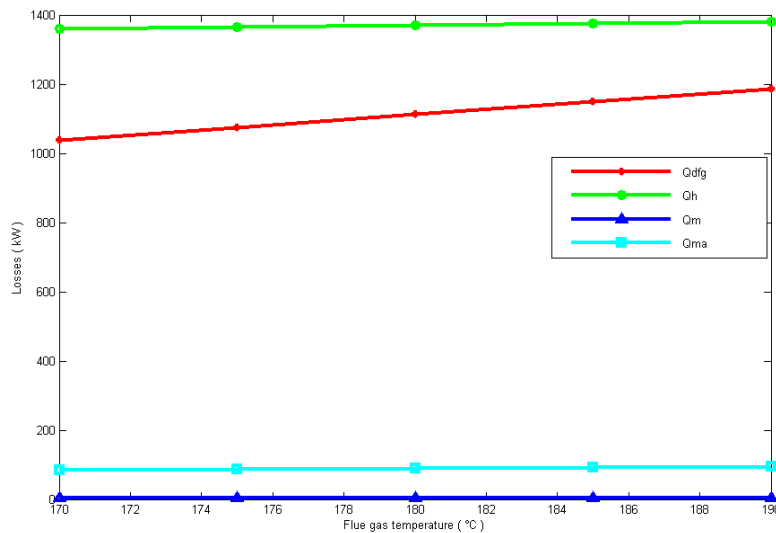


Fig. 15 Effect of flue gas temperature on various losses for furnace oil

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

Fig. 15 infers that the 20°C reduction in flue gas temperature reduces 1.51% of total loss and increase in 0.84% of efficiency.

Influence of Feed water temperature on total losses & efficiency for different fuels : Fig.16 & Fig.17 shows the comparison between fuels on the basis of total losses and efficiency, which infers that Furnace oil has a higher efficiency when compared to other fuels due to reduction in total loss.

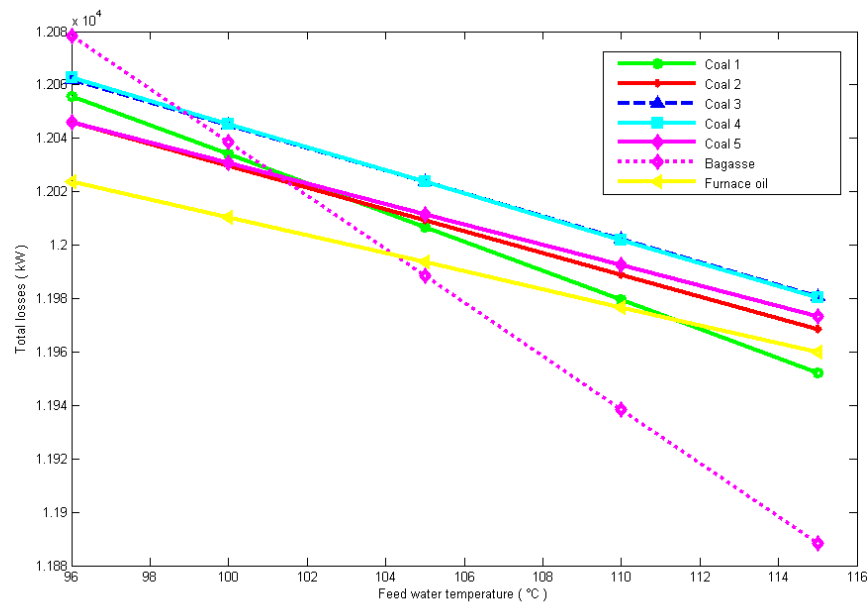


Fig.16 Effect of feed water temperature on total losses for various fuels

It is inferred from the analysis that with a 20% rise in feed water temperature, there is a reduction in the total loss of 1% and an increase in the efficiency of the boiler by 0.55% when coal is used as fuel. In the case of furnace oil, the reduction in the total loss was 0.5% with an increase in boiler efficiency of about 0.3%. Likewise, in the case of bagasse, the reduction in total loss was 1.5% with an increase in 1.2% of boiler efficiency.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

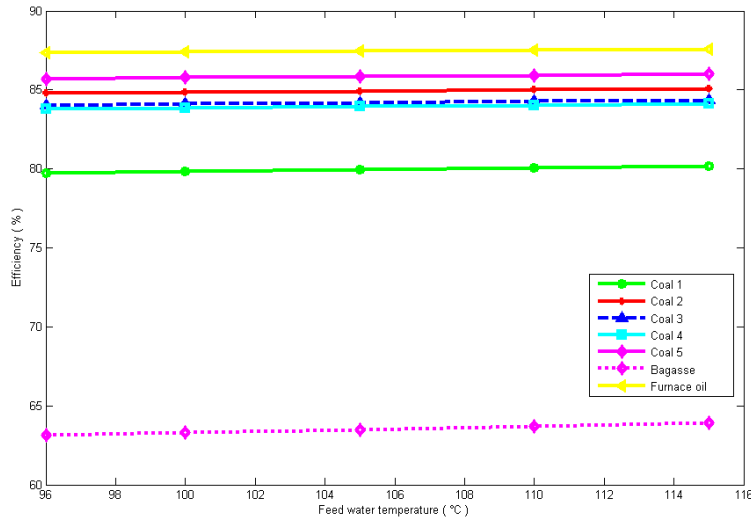


Fig.17 Effect of feed water temperature on efficiency for various fuels

Influence of flue gas temperature on total losses & efficiency for different fuels Fig.18 & Fig.19 shows the comparison between fuels on basis the of total losses and efficiency, which infers that Furnace oil has a higher efficiency when compared to other fuels due to reduction in total loss, on the other hand in Bagasse due to high total loss, the efficiency obtained is very low when compared to other fuels.

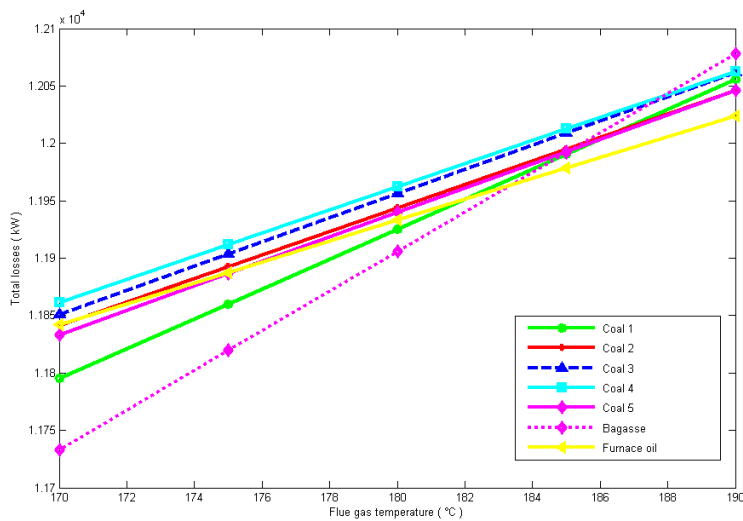


Fig.18 Effect of flue gas temperature on total loss for various fuels

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

It is inferred that with a 10.5% decrease in flue gas temperature, there is the reduction of total loss of 2.12% and 1.31% increase in boiler efficiency when coal was used as fuel. In the case of furnace oil, the reduction in the total loss was 1.5% with an increase in boiler efficiency of about 0.85%. Likewise, in the case of bagasse, the reduction in total loss was 2.86% with an increase in 2.2% of boiler efficiency.

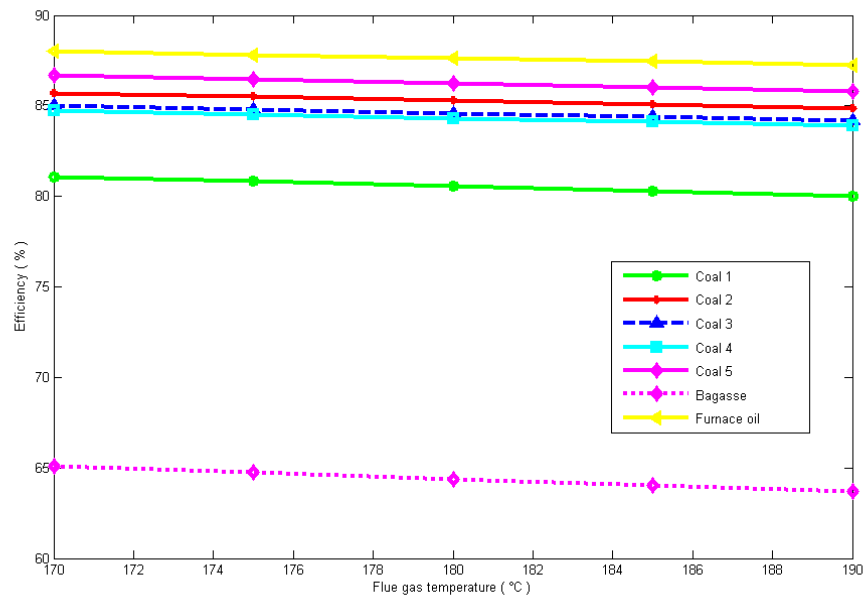


Fig.19 Effect of flue gas temperature on efficiency for various fuels

V. CONCLUSION

It is evident from the analysis that, Feed water and the Flue gas temperatures are the two important parameters that improve the efficiency of the boiler. This paper represents the results of the Influence of Feed water temperature on the efficiency of the boiler for different types of fuels such as Coal, furnace oil and bagasse. It is inferred from the analysis that with a 20% rise in feed water temperature, there is a reduction in the total loss of 1% and an increase in the efficiency of the boiler by 0.55% when coal is used as fuel. In the case of furnace oil, the reduction in the total loss was 0.5% with an increase in boiler efficiency of about 0.3%. Likewise, in the case of bagasse, the reduction in total loss was 1.5% with an increase in 1.2% of boiler efficiency. Further, in the analysis, it is inferred that with a 10.5% decrease in flue gas temperature, there is the reduction of total loss of 2.12% and 1.31% increase in boiler efficiency when coal was used as fuel. In the case of furnace oil, the reduction in the total loss was 1.5% with an increase in boiler efficiency of about 0.85%. Likewise, in the case of bagasse, the reduction in total loss was 2.86% with an increase in 2.2% of boiler efficiency. By optimizing the factors (as discussed above) which are responsible for the losses in the boilers, the performance of the boiler can be improved. Further, this study can help the designer to redesign the system components and the processes.

International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly Peer Reviewed Journal)

Vol. 5, Issue 1, January 2016

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