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Study and Evaluate the Energy Efficiency of Gas Boilers in Refineries NGL Sirri Island

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Abstract

Optimization of combustion reactions can play an effective role in energy optimization. Drop in boiler efficiency has four main causes: dry flue gas loss, latent heat of water vapor in exhaust gases, combustible drop or fuel drop, and thermal drop due to improper insulation or radiation and convection loss. In this research, in order to study energy loss in boilers of Sirri NGL plant, a numerical modeling has been utilized. To achieve this goal, after formulation of the problem, the results have been obtained using Visual Basic programming software. After calculation of boiler efficiency and drop due to each of the four reasons mentioned above, the effect of factors such as: fuel temperature, excess air percentage, relative humidity, inlet air heating, using the heat of flue gases, and heating value of fuel on boiler efficiency will be studied.

Introduction

Energy optimization is one of the most essential and most effective tools for achieving sustainable development all over the world. Energy optimization means selecting good patterns and implementing proper methods and policies in production and consumption of energy which in turn will not only lead to guaranteed economic growth, but will also minify the detrimental effects of improper usage of energy on the environment and the society and will prevent the destruction of energy sources.

Zhou and Cen (2004) [1] modeled and optimized effective parameters in NOX emission from boilers by utilizing artificial neural networks. Their model uses neural networks to approximately predict the value of effective parameters in emission of nitrogen oxides in large boilers which consume powdered coal as fuel.

Yu and Song (2012) [2] conducted a research and proposed a simplified method for testing boiler efficiency. Current methods for boiler efficiency test must use analytic tools and procedures which are too time-consuming and expensive to be conducted regularly. Yu and Song proposed a simpler method with maximum of 5 percent error which can suitably replace currently employed methods.

Rusinowski and Stanek (2007) [3] proposed a method with an accompanying example for steam boilers which was the result of both calculation and neural network modeling. Their model describes correlation of some of the main operational parameters of the boilers such as the correlation between combustion product gases and the loss due to incomplete combustion.

Bujak (2009) [4] presented a mathematical model for simultaneous control of several boilers such that their cumulative energy loss is decreased. Bujak's model showed that energy losses decrease when more boilers working at lower rates were used; compared to the case where there were fewer boilers working at their maximum rates.

Pronobis (2006) [5] showed the effect of using biomass as fuel (instead of coal) on sedimentation level and efficiency of boilers. His results showed that addition of such fuels leads to reduction of boiler efficiency, but other operational parameters such as consumed water and produced ash improved. Thus, biomass fuels can replace coal in case of shortage.

Monedero (2012) [6] presented a new model in order to reduce costs and save fuel, and also to improve the quality of products in a petrochemical complex. This model has been created by using the data gathered from the petrochemical complex. By implementing this model, energy consumption can be optimized in the complex. Krzywanski (2012) [7] modeled the effective factors in heat transfer of boiler furnaces with the help of neural networks. This model predicts the values of effective factors for heat transfer in combustion chamber, boiler shells, and superheaters of a 260MW boiler.

Steam generation and distribution and condensate return unit in Sirri NGL plant contains two boilers with capacity of 55 tons per hour each, a continuous blowdown drum, an intermittent blowdown drum, a deaerator with capacity of 60 tons per hour, feed pumps, three chemical injection packages, a steam distribution network for eight different consumption purposes in plant, a de-superheater for steam path of amine regeneration tower, relief valves, two condensate return networks, a flash drum for returned condensate, condenser fans for flashed steam, and condensate return pumps. Performance of nearly all of these items can be improved in one way or another and this unit in Sirri NGL

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plant has a great potential for energy optimization. Boilers in Sirri NGL plant are of water-tube type and use gas fuel. Here, steam efficiency is defined as gross efficiency and boiler's control volume in this research conforms to PTC4 standard [8]. However, the boiler in Sirri NGL plant does not have subunits such as superheater, air preheater, and pre-combustion oil heater. In this research, in order to study energy loss in plant boilers, a numerical model has been utilized and the results have been obtained by Visual Basic programming software after problem formulation. It should be noted that the algorithm input data have been obtained by monitoring the real performance of the boiler during one hour of operation.

Problem Definition

Boiler performance and its efficiency deteriorate over time because of reduction in combustion efficiency, sedimentation, and weak maintenance. Loss of quality of fuel and water also affects the efficiency. Efficiency tests help us find the difference between current boiler efficiency and its ideal efficiency. In the end, any deviation from natural state should be investigated and can be corrected if need be. The term "boiler efficiency" refers to the total thermal energy that can be gained from the fuel. Part of the heat that enters the boiler control volume, cannot be transferred to water or steam, hence the boiler efficiency is always less than 100%. However, a number of thermal losses can be reduced with better operation and maintenance. Boiler efficiency losses are caused by four main factors:

The heat that gets out along with hot flue gases from the exhaust. This loss is usually known as dry flue gas loss. Increasing exhaust gas temperature and excess air in combustion are factors that contribute to this kind of loss.

Latent heat in water vapor which exists in exhaust gases: Water vapour is caused by combustion of the hydrogen present in the fuel, relative humidity of combustion air (the air is usually over saturated in Sirri Island), and moisture content of inlet fuel (usually happens at first start). Because water vapor contains more thermal energy compared to water, latent heat can only be retrieved if water vapor is allowed to condense before flue gases leave the boiler. This is not practical in current boilers because of corrosion and increased exhaust smoke. Therefore, the latent heat is not considered to be retrievable.

Unburned fuel and incomplete combustion products: These are solid combustible materials, boiler exhaust carbon, and all solid or gaseous materials in exhaust gases. This loss is usually called combustible loss or unburned fuel loss. Improper adjustment of combustion equipments or improper amount of excess air can increase this loss dramatically.

Thermal loss from boiler shells because of inappropriate insulation: This loss is usually known as radiation and convection loss and includes the heat that is transferred to the interior part of boiler by radiation, and the heat that the air surrounding the boiler walls takes from them. The amount of heat lost in this way is constant for different boiler combustion rates and as a result, in low combustion rates, it amounts for greater portion of total heat loss. Improper insulation and defective fireproof materials in boiler shells can lead to increase of this loss in all boiler loadings.

Modeling and formulation

Considering input and output streams of water and fuel to the boiler, the control volume for modeling and optimization study in boiler has been selected based on ASME PTC 4.1 and is displayed in figure 1.

Extracted equations in this section have been obtained by assuming this control volume as basis for modeling. General form of output boiler energy is as follows [9].

$$QrO = MrStz2(HLvz2 - HEnz1), \quad BTU/h(W) \qquad (1)$$

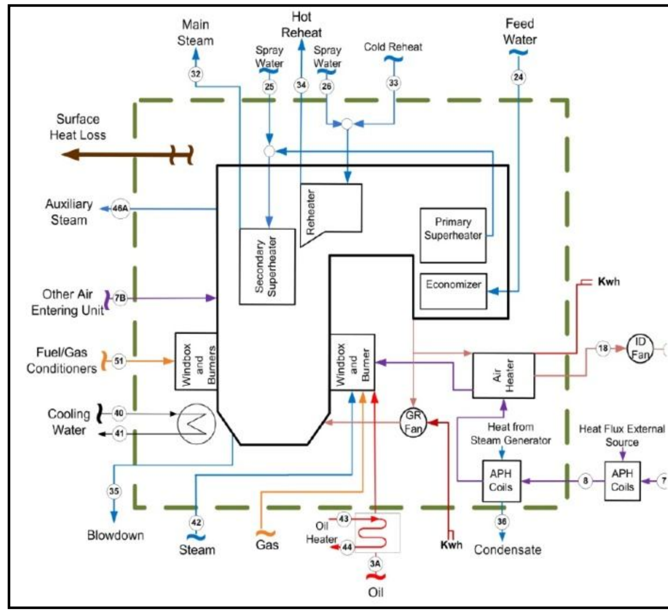

Figure 1: Steam boiler control volume according to PTC 4 standard [8].

In which, *Qro*: boiler output energy, *MrStz2*: output fluid mass flux at Z2 location, *HLvz2*: Fluid output enthalpy at Z2 location, *HEnzl*: Fluid input enthalpy at Z2 location.

Main steam's output energy is also given by equation (2).

$$QrO = (MrSt32 - MrW24)(HSt32 - HW24) \qquad (2)$$

In which, *MrSt32*: Mass flux of main steam stream, *MrW24*: Input water mass flux, *HSt32*: Enthalpy of main steam, *HW24*: Enthalpy of input water.

When there is a blowdown present, term (3) is added to the equation.

$$QrBd = MrW35(HW35 - HW24), BTU/h(W) \qquad (3)$$

Input is combustible potential energy. When the fuel burns completely, this will be the maximum available energy.

$$QrI = QrF = MrF\ HHVF, Btu/h(W) \qquad (4)$$

In which, *QrI*: Input energy to the boiler, *QrF*: Input energy from fuel to the boiler, *MrF*: mass flux of fuel stream to the boiler, *HHVF*: High fuel energy to the boiler.

With regard to the first law of thermodynamics, energy balance for the boiler's assumed control volume is generally determined by equation (5) [10].

$$Energy\ variations = Output\ energy - input\ energy \qquad (5)$$

Since boilers are tested under stable conditions:

$$Energy\ that\ exits\ from\ the\ system = Energy\ that\ enters\ the\ system \qquad (6)$$

Input energy is all the energy that enters the system by input streams through control volume's borders plus the energy needed to move auxiliary equipments such as pumps, fans, etc. Output energy is all the energy that exits the system by output streams through control volume's borders plus transferred heat from steam generation surfaces to the surrounding environment.

$$Qrf = QrO + Qb, Btulh\,(W) \quad (7)$$

In which, *Qb*: net sum of all input and output energies by streams intersecting control volume's borders (*QrO* and *QrI* excluded), the energy resulted from chemical reactions occurring inside control volume's borders, the energy needed to move auxiliary equipments, and the energy consumed in radiation and convection heat exchanges. Input and output energies through the borders of control volume are divided into two groups. One is heat loss group and the other is borrowed heat group.

$$Qb = QrL - QrB, Btu/h(W) \quad (8)$$

In which, *QrL*: Losses, which are the sum of exchanged energy from the system (*QrO* excluded) by streams leaving the borders of control volume, plus the received energy from endothermic chemical reactions within control volume's borders, plus the energy exchanged with the environment in the form of convection or radiation.

QrB: Loans, which are the sum of total energy given to the system (energy of fuel combustion excluded) by streams that enter the borders of control volume, plus the energy that is freed by exothermic chemical reactions within borders of control volume, plus the energy needed to move auxiliary equipments.

The energy balance is expressed collectively by the following equation:

$$QrF + QrB = QrO + QrL, Btu/h(W) \quad (9)$$

In energy balance method, the loss that leaves borders of control volume and input borrowed energies that enter control volume's borders are calculated. Considering the efficiency equation, in energy balance method efficiency is defined as follows:

$$EF = 100(QrF - QrL + QrB)/QrF, \% \quad (10)$$

Considering the efficiency equation, in energy balance method efficiency is defined as follows:

$$EF = 1100(QrF - QrL + QrB)/QrF, \% \quad (11)$$

Most losses and loans are defined based on fuel input energy as follows:

$$QpL = 100QrL/QrF \text{ and } QpB = 100QrB/QrF, \% \quad (12)$$

By placing equation (12) in equation (11), efficiency is calculated as follows:

$$EF = 100 - QpL + QpB \quad (13)$$

Dry air loan is given by equation (14).

$$QpBDA = 100\, MqDA \times HDAEn, \% \quad (14)$$

In which, *MqDA*: Total mass of dry input air to the boiler in (Kg/J) lbm/Btu.

HDAEn: Dry air enthalpy at mean input temperature (*TMnAEn*). This enthalpy is the weighted mean of various boiler input streams. If boiler has air preheater, air temperature before entering the preheater is used for calculating input enthalpy in *(J/Kg) Btu/lbm.* Moisture loan of input air is calculated from the following equation:

$$QpBWA = 100\, MFrWA \times MqDA \times HWvEn \quad (15)$$

In which, *HWvEn*: Steam enthalpy at mean temperature of boiler's input air(*TMnAEn*) in *(J/Kg) Btu/lbm.* Equation (16) gives input fuel's sensible heat loan.

$$QpBF = (100/HHVF)\, HFEn, \% \quad (16)$$

In which, *HFEn*: Fuel enthalpy in *(J/Kg) Btu/lbm* at the temperature in which the fuel enters control volume's borders of the boiler.

Boiler loss calculation

Dry smoke loss is defined by equation (17).

$$QpLDFg = 100MqDFg \times HDFgLvCr, \% \quad (17)$$

In which, *MqDFg*: Mass flow of dry smoke based on the excess air that leaves the steam generator. *HDFgLvCr*: Dry gas enthalpy at corrected temperature.

Equation (18) gives water formation loss due to hydrogen content in the fuel.

$$QpLH2F = 100MqWH2F \times (HStLvCr - HWRe) \quad (18)$$

In which, *MqWH2F*: Water formed due to hydrogen content of fuel in *lbm/Btu (Kg/J). HStLvCr*: Water vapor enthalpy at 1 psia.

HWRe : Water enthalpy at reference temperature TRe in *Btu/Lbm (J/Kg)* and is given by:

$$HWRe = TRe - 32 = 45, Btu/Lbm \quad (19)$$

It is worth noting that water vapor enthalpy only changes slightly at low partial pressures of exhaust gases or air. Moreover, actual measurement of water vapor's partial pressure is not reliable. The loss caused by water content of fuel is given by equation (20):

$$QpLWF = 100MqWF \times (HStLvCr - HWRe), \% \quad (20)$$

In which, *MqWF*: Water content of fuel in *lBm /Btu (Kg/J)*. Equation (21) calculates the loss caused by relative humidity of air:

$$QpLWA = 100MFrWA \times MqDA \times HWvLvCr \quad (21)$$

In which, *MFrWA*: The ratio of mass of moisture content of air over dry air mass, *MqDA*: Mass of dry air corresponding to the value of excess air used in dry smoke loss calculation, *HWvLvCr*: Water vapor enthalpy at corrected temperature of flue gases.

Difference between steam enthalpy (HSt) and water vapor enthalpy is that the reference temperature for steam enthalpy calculation is 32 degrees Fahrenheit (0 degrees centigrade) and includes latent heat of evaporation, but reference temperature for water vapor enthalpy is 77 degrees Fahrenheit (25 degrees Centigrade). The loss caused by nitrogen oxide formation can also be calculated by equation (22):

$$QpLNOx = DVpNOx \times MoDFg \times (HrNOx/HHVF), \% \quad (22)$$

In which, *DVpNOx*: The amount of *NOx* based on dry (in percent). *MoDFG*: Dry gas mols with excess air in (*moles/Kg*) *moles/lbm* fuel. *HrNOx*: *NOx* formation energy.
HHVF: High heating value of fuel in constant pressure in *(J/Kg) Btu/lbm.*

It is worth noting that *NOx* is usually measured in ppm and is expressed by dividing this number by 1000. In addition, *MoDFG* is measured at the same place where *NOx* is measured.

Results and Discussion

After calculating boiler efficiency for boilers in Sirri NGL plant with the aforementioned method, gross efficiency is predicted about 83%. 3% of the loss is caused by dry flue gas loss. This loss can be reduced by adjusting the excess air and decreasing the temperature of exhaust gases. To fine tune the percentage of excess air, in addition to installation of oxygen analyzer at chimney entrances of boilers, installation of a CO analyzer is also necessary. If combustion excess air is tuned to the best value shown on the diagram, this heat loss will decrease. The whole process is called combustion management. Temperature of boiler exhaust gases – which have a direct effect on reduction of heat loss-, can be decreased by using a heat exchanger in order to heat the input water to the boiler. This exchanger is called economizer and is one of the components which can be optimized to reduce the amount of input fuel used to heat water. Most of loss in Sirri NGL boilers is related to the moisture content in the fuel and in the inlet air. 10% of this loss is due to the moisture content in the input fuel and 3 percent of it is due to the high humidity of Sirri Island. Therefore, in order to improve system performance, the fuel must be heated before entering the combustion chamber. Preheating can be achieved via generated steam or via hot flue gases. As Sirri NGL plant is newly built, sedimentation and weak maintenance are not significant factors. Thermal loss from boiler shells is the smallest loss compared to other forms of loss (around 0.02%) and fortunately, the amount of unburned fuel in these boilers was also insignificant. Table 1 shows the results of modeling and software analysis based on high and low thermal values of the fuel.

Table 1: Result of modeling and software analysis

LHV	HHV	Boiler efficiency losses
3.31544 %	3.001174 %	Dry flue gas charge
0.772029 %	10.25545 %	Moisture content of fuel
0.27433 %	3.65963 %	Moisture content of inlet air
0.019648 %	0.0177702 %	Convection and boiler's surface radiation

Study of environmental and operational parameters effects on performance of boilers in Sirri NGL plant

Effect of fuel temperature on the efficiency of boilers in Sirri NGL plant

The diagram in figure (2) shows boiler efficiency versus its fuel temperature.

It can be observed that as the phase of moisture in fuel changes as a result of increase in fuel temperature, boiler efficiency is increased. Currently and in normal conditions, temperature of consumed fuel is 45°C. In this temperature, efficiency is about 83%. It is observed that boilers efficiencies can be increased by 4% if their input fuel is heated up to 85°C.

Effect of excess air on efficiency of boilers in Sirri NGL plant

Optimal adjustment of excess air in various operational and environmental conditions such as production rate, fuel type, etc, is one of the most important factors in improving boiler efficiency and preventing energy loss. Excess air affects the process from two aspects:

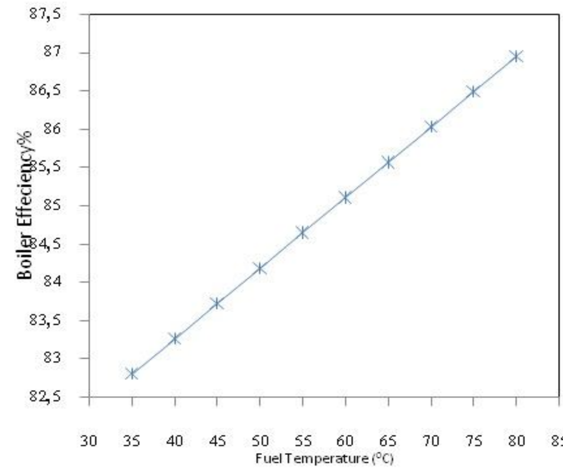

Figure 2: Effect of fuel temperature on boiler efficiency

More excess air causes flame temperature to decrease and thus results in less heat transfer. Maximum flame temperature for fast heat transfer to the environment is required when no excess air is used.

More excess air leads to generation of more flue gases per weight of consumed fuel and this in turn leads to increased thermal loss since air enters the torches at environment temperature and leaves the boiler at a higher temperature which means the air wastes much of available heat. Boiler manufacturer suggests 10 to 20 percent excess air for normal boiler operation, but it is usually operated at higher rates of excess air. Because the operators want to ensure that the boiler remains in service. They don't want any smoke to be visible at the chimneys, so they increase the rate of excess air. Moreover, if environmental conditions such as relative humidity, ambient temperature and ambient pressure even slightly change, excess air can easily convert to "less than normal air" and operating the boiler in this condition leads to dramatic drop in boiler efficiency and visible smoke at boiler's chimneys.

The diagram in figure (3) shows boiler efficiency versus percentage of excess air that enters the boiler. According to this diagram, maximum boiler efficiency is obtained at 12.5% of excess air and after that efficiency begins to drop. In practice, excess air setting is adjusted on 16% which leads to efficiency drop. In seasons with higher humidity, the impact of excess air on efficiency increases too. It is thus necessary that mechanical and instrument systems responsible for adjusting the air to fuel ratio, are maintained and calibrated regularly.

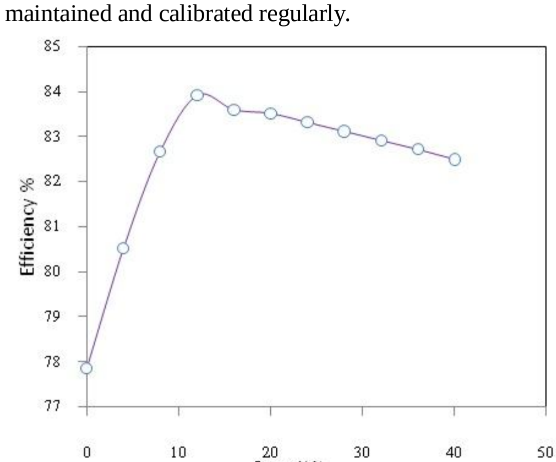

Figure 3: Impact of excess air on boiler efficiency

Effect of humidity on boilers in Sirri NGL plant

Figure (4) shows the effect of relative humidity of air on boiler efficiency. Highly humid climate of Sirri Island has led to 3% drop in these boilers' efficiencies.

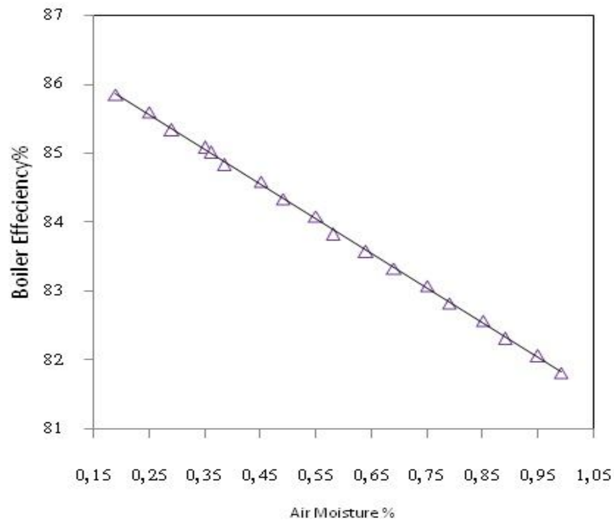

Figure 4: Effect of humidity on boiler's efficiency

Effect of inlet air preheating on boilers in Sirri NGL plant

Preheating the combustion chamber inlet air can lead to 10% decrease in fuel consumption. To achieve this, the heat from flue gases or generated steam can be used. All methods of preheating will lead to increased leakage of sulfur trioxide which increases corrosion in turn. When flue gases contain 150 ppm sulfur, the temperature of exhaust gases must be between 350-400°F to prevent corrosion. Finally, it is necessary for the temperature of flue gases to be 50°F higher than dew point temperature of sulfur trioxide [11].

Figure (5) shows the effect of heating inlet air on boiler efficiency. It can be seen that the efficiency increases with heating the air, the reason being phase transition of the moisture content of the air. As shown, if the temperature of inlet air to the boiler increases to 90 °C, efficiency is improved by 1%. This method is not as efficient as fuel heating and costs more in terms of equipments and energy.

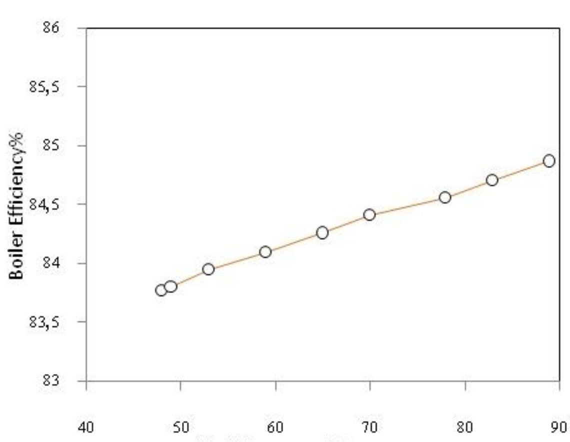

Figure 5: Effect of heating value of fuel on boiler efficiency

Effect of heating value of fuel on boilers in Sirri NGL plant

Figure (6) shows how boiler efficiency increases when the heating value of its consumed fuel increases.

By optimizing the economizer which preheats the input water, and by using the heat of flue gases for heating inlet fuel and inlet air, the goal to increase efficiency can be achieved.

Currently, flue gas temperature in economizer outlet is 121°C. If this temperature is reduced to 75°C, efficiency will increase by 6%. However, proper care must be taken in order to prevent condensation due to too much drop in flue gas temperature.

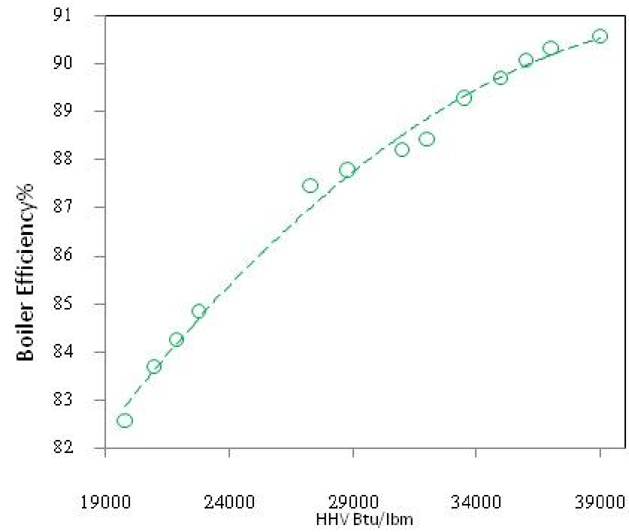

Figure 6: Effect of heating value of fuel on boiler efficiency

Figure 7 shows the extent to which boiler efficiency can be improved by using its own flue gas heat.

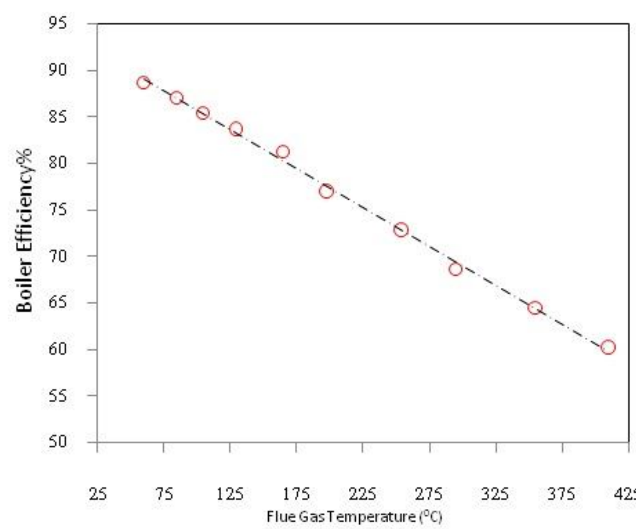

Figure 7: Effect of flue gas temperature drop on boiler efficiency

Conclusions

In this research, effect of various environmental and operational parameters on boilers' thermal behaviour was studied. By taking the effect of each factor on boiler efficiency into account, following suggestions are presented in order to improve energy consumption in boilers:

1. Main factors of efficiency loss in boilers are: Improper adjustment of excess air and dry flue gas loss, moisture content of fuel, and relative humidity of air. Besides, other factors such as incomplete combustion and heat transfer by convection and radiation from boiler surfaces, also lead to partial energy loss in boilers.

2. By increasing input fuel temperature, efficiency increases.
3. Optimum amount of excess air in order to achieve highest efficiency is 12.5%, and as excess air increases to higher amounts, efficiency drops. In seasons with higher air humidity, the impact of excess air percentage on efficiency intensifies. Therefore, mechanical and instrument systems responsible for adjusting air to fuel ratio in boilers must be constantly maintained and calibrated. Moreover, a CO analyzer must be installed besides the oxygen analyzer at chimney input of boilers.
4. Increase in air humidity causes efficiency drop in boiler.
5. Preheating inlet air results in efficiency improvement, but is less effective compared to fuel preheating.
6. Using flue gas energy to preheat water, fuel, and boiler inlet air, leads to considerable improvement in boiler efficiency.
7. Using fuels with higher heating values lead to increased efficiency while attenuating the effect of humidity.

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