Jr. of Industrial Pollution Control 34(1)(2018) pp 1825-1832
www.icontrolpollution.com
Review Article

A REVIEW OF INDIRECT METHOD FOR MEASURING THERMAL EFFICIENCY IN FIRE TUBE STEAM BOILERS

AHMAD MAHMOUDI LAHIJANI[1*], ERIS.E. SUPENI[2] AND FATEMEH KALANTARI[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

[2]Department of Landscape Architecture, Faculty of Design and Architecture, University Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

(Received 11 December, 2017; accepted 27 March, 2018)

Key words: Fire tube boiler, Boiler efficiency, Heat loss method

ABSTRACT

In this paper, the efficiency analysis of fire tube steam boilers according to pertinent parameters is presented. For this purpose the key parameters on efficiency of steam boilers and specially fire tube steam boiler have been investigated. There are two method for measuring the efficiency in steam boilers, direct method (input-output method) and indirect method (heat loss method). The errors in direct method make significant change in efficiency thus indirect method is more accurate method for measuring the efficiency. The indirect method is the focused method in this study, therefore various type of losses be evaluated. The amount of increasing of efficiency by reduce different losses be assumed. An important advantage of this method is that the errors in measurement do not make significant change in efficiency.

INTRODUCTION

Energy supply is an essential input for daily human necessities and activities, particularly for industrial growth. The increasing demand for energy supply results for additional capacity for power worldwide particularly in steam generation (Brooks, 2010). Steam generators and heat recovery boilers are common practice for power generation and process plant industries. However, the increasing fuel and energy costs have led various efforts to improve energy generation and utilization, and thus simultaneously minimizing the environmental pollution and harmful gas discharge (Durkin, 2006). Steam systems consume huge amount of energy worldwide as it serve an important role for delivering thermal energy into multiple fields ranging from heavy industries to commercial-residential systems. The main component of any steam system is the boiler. However, most boilers are very expensive to operate and possess potential hazardous impact to the environment (Brooks, 2010; Einstein, *et al*., 2001).

Steam boiler is a closed container in which the water is boiled into steam at required pressure. Similarly to the engine of a car, the oil central heating boiler generates sufficient heat to warm itself up. The volume of water increases about 1600 times as it is boiled into steam, producing energy that is as powerful as gunpowder. Therefore, this strong energy makes boiler a dangerous part of equipment and must be handled carefully (Ortiz,, 2011). From 200 B.C. to date, various improvements were made that helps us to classify steam boilers efficiently. One of the ways to categories steam generating boilers is the method of generation of steam and its consumption. The two common applications of boilers are the industrial steam generators and power generation boilers. Besides, they can also be classified as both fire and water-tube (Durkin, 2006; Hasanuzzaman, *et al*., 2011).

***Corresponding authors email: mahmoudi3678@gmail.com; eris@upm.edu.my; Fatimah.kalantari@gmail.com**

Water-tube boiler contains tubes filled with water and the tubes inscribed by combustion. The water-tube boiler profits are listed as steam generated with lower unit weight-per-pound, increment in steam pressure with lesser time, better flexibility, and a more ability to function at higher rates of steam generation (Patro, 2016). This kind contains of two main drums, in which the upper one is known as steam drum and the beneath one is known as mud drum. Both of them are linked to down-comer tubes and riser tubes depicted (Saidur, *et al*., 2010).

Fire-tube boilers consist of tubes surrounded with water by which allow the passage of combustion gases (Vasquez, *et al*., 2007). Moreover, the benefits are the simpler in both fabrication and process (Krishnanunni, *et al*., 2012). The disadvantages of fire-tube boilers would be longer procedure in steam generating, and capable of quick response to load alterations (Hasanuzzaman , *et al*., 2011; Krishnanunni, *et al*., 2012). The fire-tube boiler consists of tubes surrounded with fluid that helps to channel fire or hot fuel gases from the burner. The boilers trunk is mostly comprised by pressure vessel and fluid. Mostly, water using for circulated fluid either in the heating purposes or making the steam for following process (Brooks, 2010).

The present paper shows indirect method (heat loss method) is the most accurate method to determine boiler efficiency; In addition the main parameters that have a drastic effect on boiler efficiency are identified.

Efficiency in Steam Boiler

The idea of energy conservation was one of the most interested themes in designing boiler. However, designing a boiler with good energy saving require meticulous concerns on its Boiler Efficiency (Durkin, 2006). For example, it is important to take not that all fire-tube boilers have their own sets of key differences (Hasanuzzaman, *et al*., 2011). Therefore, tangible design considerations could be incorporated into the boiler in providing boiler with high efficiency output. Investigating some basic design differences between deferent boilers would provide valuable perceptions (Afgan, *et al*., 1996).

Number of Boiler Passes

These passes can be defined as how many times the hot ignition gasses transfer across the device (Bujak, 2008). The stack temperature of a 4-pass boiler is lower compared to boilers with less boiler passes with similar basic design and operating conditions. Therefore, the 4-pass boiler would provide better efficiency in heat-transfer coefficient as well as having lower fuel cost (Wulfinghoff, 1999).

Burner /Boiler Compatibility

The item “packaged boiler” is often being exploited by vendors despite having its boiler assembled to burner manufactured by different vendors respectively (Kuprianov, 2005). True packaged boiler/burner designs will have a single unit of burner and boiler manufactured together and will take accounts into its furnace geometry, radiant and convection heat transfer characteristics, and verified burner performance in the specific boiler package (Hasanuzzaman, *et al*., 2011; Kuprianov, 2005). Therefore, the manufacturing of a packaged unit will assure the proven and verified performance of that particular unit (Saidur, *et al*., 2010).

Repeatable Air/ Fuel Control

The boiler efficiency also takes accounts into the capability of the burner in providing suitable air to fuel combination (Kuprianov, 2005; Morgan, *et al*., 1986; Morgan, *et al*., 1987). Boiler with remarkable efficient would be able to provide proper air to fuel mixture throughout the firing rate without the need for complex set-up and adjustments (Shah and Adhyaru, 2011). With advancements in control technology, good boiler efficiency can be achieved through consistent, repeatable burner control (Kuprianov, 2005).

Heating Surface

It can be represented in square feet per boiler horsepower that shows how hard the vessel is working. Customarily, fire-tube boilers are designed with five square feet of heating surface per boiler horsepower. This standard was developed by Cleaver-Brooks to achieve high efficiency and improving the life expectancy of the boiler (Brooks, 2010). With advancements in computational fluid dynamics modeling, fire-tube boiler designs are now capable to deviate from the standard in achieving greater efficiency. Currently, fire-tube boiler can be designed to achieve similar or greater efficiency with heating surface as minimum as four square feet without compromising the vessel life expectancy (Bujak, 2008).

Vessel Design

Despite the design of pressure vessel being strictly regulated by ASME code requirements; various adjustments can be made to improve the boiler efficiency without disregarding the code requirements. Such pressure vessel design adjustments includes having appropriate water circulation, lower internal stresses, and providing easier access for examination and There are two types of fire-tube boilers, which are the dry back or wetback. Particular type of fire-tube boiler can be identified through its reversal (turnaround) chamber or the posterior portion of combustion chamber. The combustion chamber channels the fuel gasses from the furnace to second-pass tubes, providing heated water within the boiler (Huang, *et al*., 1988).

Effective Components in Efficiency of Steam Boiler

The efficiency of boiler as prescribed by ASME heat balance method includes the stack losses and convection and radiation losses (Kaag, 2000). The major factor that could significantly affect the boiler efficiency is the basic boiler design. A particular boiler design can be produced to be more efficient with some creativity in calculating the efficiency, as there is room for interpretation for its calculation. (Fig. 1) shows the fire tube boiler gas flow. The following are the key factors to understanding efficiency calculations (Bujak, 2008).

1. Temperature of the fuel gas
2. Convection and radiation losses
3. The temperature of ambient air
4. Excess air
5. The specification of fuel (Brooks, 2010).

INPUT-OUTPUT METHOD

A proportion of the output to input of the boiler is determined the Input-Output efficiency measurement technique. Besides, this method is assumed by measuring through instrumentation and the calculated data obtained will be utilized to calculate the fuel-to-steam efficiency. This computation for fuel-to-steam efficiency contains the division of the output to its input and then multiplied by 100 (Shah and Adhyaru, 2011).

HEAT LOSS METHOD

The Heat Balance efficiency can be measured by considering the temporal losses totally. Moreover,

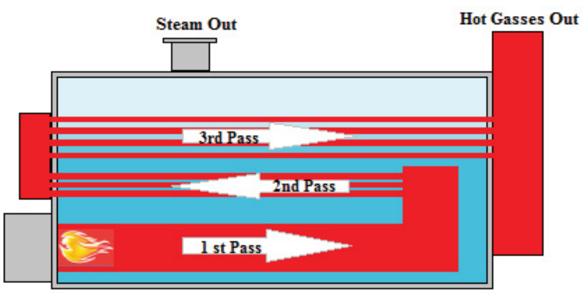

Fig. 1 Fire tube boiler gas flow (Ortiz, 2011).

the aforementioned can be assumed for both stack losses and the radiation and convection losses, too. Therefore, the values obtained can be used to calculate the heat balance efficiency (Krishnanunni, *et al*., 2012; Van and Jager, 2001). An important advantage of this method is that the errors in measurement do not make significant change in efficiency. Thus if boiler efficiency is 90%, an error of 1% in direct method will result in significant change in efficiency. i.e. 90 ± 0.9 = 89.1 to 90.9. In indirect method, 1% error in measurement of losses will result in Efficiency = 100 - (10 ± 0.1) = 90 ± 0.1 = 89.9 to 90.1

Deferent Losses and their Causes in the Steam Boiler

L_1: Caused by dry flue gas (sensible heat)

L_2: Hydrogen in fuel (H_2)

L_3: Moisture in fuel (H_2O)

L_4: Moisture in air (H_2O)

L_5: Carbon monoxide (CO)

L_6: Surface radiation, convection and other unaccounted

L_7: Fly ash (carbon)

L_8: Bottom ash (carbon) (Brooks, 2010; Hasanuzzaman, *et al*., 2011; Krishnanunni, *et al*., 2012)

Efficiency of Examined Boiler (3000 kg/hr)

In this case the parameters of fire tube boiler that use diesel as fuel in the stable condition be measured. Since the fuel is diesel, the fly ash and bottom ash losses are zero. The following parameters need to be measured, as applicable for the computation of boiler efficiency and performance:

Flue gas analysis

1. Percentage of CO_2 or O_2 in flue gas
2. Percentage of CO in flue gas
3. Temperature of flue gas

Flow meter measurements for

1. Fuel
2. Steam
3. Feed water
4. Condensate water
5. Combustion air

Temperature measurements for

1. Flue gas

2. Steam
3. Makeup water
4. Condensate return
5. Combustion air
6. Fuel
7. Boiler feed water

Pressure measurements for

1. Steam
2. Fuel
3. Combustion air, both primary and secondary
4. Draft

Water condition

1. Total dissolved solids (TDS)
2. pH
3. Blow down rate and quantity

Ultimate Analysis of Boiler (%)

Carbon = 92, Hydrogen = 16, Nitrogen = 0.5, Oxygen = 1.9, Sulphur = 1.8, Moisture = 0.5

GCV of fuel (diesel) = 10000 kCal/kg, Fuel firing rate = 2637.341 kg/hr, Surface Temperature of boiler = 82ºC, Surface area of boiler = 90 m^2, Humidity = 0.015 kg/kg of dry air

Wind speed = 3.7 m/s

Flue Gas Analysis of Boiler (%)

Flue gas temperature = 226ºC, Ambient temperature = 30ºC

CO_2% in flue gas by volume = 11.4, O_2% in flue gas by volume = 7.9

RESULTS AND DISCUSSION

Calculation of Efficiency of Boiler

The following steps need for calculation of efficiency:

Step 1: Find the theoretical air requirement.

$$= \frac{\left[(11.6*C)+\left\{34.8*\left(H2-\frac{O2}{8}\right)\right\}+(4.35*S)\right]}{100}(kg/kg\ of\ fule) \quad (1)$$

$$= \frac{\left[(11.6*92)+\left\{34.8*\left(16-\frac{1.9}{8}\right)\right\}+(4.35*1.8)\right]}{100} = 16.2357(kg/kg\ of\ fule)$$

Step 2: Find the percent excess air supplied (EA).

$$= \frac{(O_2*100)}{(21-O_2)} = \left[\frac{7.9}{21-7.9}\right]*100 = 60.3053\% \quad (2)$$

Step 3: Find the actual mass of air supplied.

$$= \left\{1+\left(\frac{EA}{100}\right)\right\}*Theoretical\ air = \left\{1+\left(\frac{60.30}{100}\right)\right\}*16.2357 = 26.0266\,kg/kg\ of\ coal \quad (3)$$

Step 4: Estimation of all losses

L_1: Dry flue gas loss (sensible heat).

$$L_1 = \frac{\left[m*C_P*(T_f-T_a)*100\right]}{GCV\ of\ fuel} \quad (4)$$

$$m = Mass\ of\ (CO_2+SO_2+N_2+O_2)\ in\ fuel\ gas + N_2\ in\ air\ we\ are\ sup\ plying \quad (5)$$

$$m = \left[\frac{0.92*44}{12}+\frac{0.015*64}{32}+0.005+\frac{7.9*32}{100}+\frac{26.0266*77}{100}\right] = 25.9828 kg/kg\ of\ fuel$$

$$L_1 = \frac{[(25.9828)*0.23*(226-30)*100]}{10000} = 11.7131\%$$

L_2: Heat loss due to evaporation of water formed due to hydrogen in fuel (H_2).

$$L_2 = \frac{\left[9*H_2*\left\{584+C_p*(T_f-T_a)\right\}\right]}{GCV\ of\ fuel}*100 \quad (6)$$

$$L_2 = \frac{\left[9*0.16*\left\{584+0.45*(226-30)\right\}\right]}{10000}*100 = 9.6797\%$$

L_3: Heat loss due to moisture present in fuel (H_2O).

$$L_3 \frac{\left[M*\left\{584+C_p(T_f-T_a)\right\}\right]}{GCV\ of\ fuel}*100 \quad (7)$$

$$L_3 \frac{\left[0.005*\left\{584+0.45*(226-30)\right\}*100\right]}{10000} = 0.0336\%$$

L_3: Heat loss due to moisture present in air (H_2O).

$$L_4 \frac{\left[AAS*humidity*C_p*(T_f-T_a)\right\}*100\right]}{GCV\ of\ fuel} \quad (8)$$

$$L_4 \frac{[26.0266*0.015*0.45*(226-30)*100]}{10000} = 0.3443\%$$

L_6: Heat loss due to surface radiation, convection and other unaccounted.

The radiation losses happen when the heat transfers from the side walls of the boiler to the outside. Moreover, they are not altering and are considered to be 1% as per BS 845.

Step 5 Calculate boiler efficiency by indirect method.

$$Efficiency = 100-(L_1+L_2+L_3+L_4+L_6) \quad (9)$$

$$Efficiency = 100-(11.7131+9.6797+0.0336+0.3443+1)$$

$$Efficiency = 77.2293\%$$

The Relationship between Efficiency and Fuel

One of the key factors that affect the efficiency is the fuel specification. For example, higher hydrogen content in gaseous fuels will produce more water vapor during combustion (Kulatilaka, 1993). However, the exchange of water phases in the combustion process uses energy and having higher water vapor loss during fuel firing would result in lower efficiency (Wienese, 2001). One of the most important parameters of the fuel is Gross Calorific Value (GCV) that shows the amount of heat made by the inflammation under steady and standard conditions.

The fuel that used in current experiments is Diesel; the gross calorific value (GCV) of this diesel is 10000 kCal/kg. For analyzing this values in examined boiler, MATLAB software used to illustrate the graph. (Fig. 2) shows the efficiency of the boiler in different GCV's the point that mentioned in the curve belong to the current fuel (diesel); besides, it illustrates the efficiency of the boiler (10000, 77.24), other fuels that used in boilers have GCV's from 3000 up to 11000. By simulating under these conditions, the different efficiencies according to the different fuels can be obtained, these efficiencies are not match with the real condition because the efficiency by solid fuels have effected by some parameters such as fly ash and bottom ash, but this simulation is helpful for analysis the effect of GCV's on the efficiency according to the formulas.

The Relationship between Efficiency and Flue Gas Temperature

Flue gas or stack temperature determined as the combustion gases temperature in the exhaust of the boiler. During an efficiency calculation or guarantee, checking the temperature of the flue gas comes to mind. This process should be close enough to reality. However, near or less than the saturation temperature, the equipment should be in a condition that vary in an effective way affect flue gas temperature positively (Payne, *et al.*, 2007). Therefore, the flue gas temperature can be confirmable in existing applications only if the efficiency value obtained is accurate. However, it should be always confident of the stack temperature (Einstein, *et al.*, 2001).

The flue gas temperature has an important effect on the efficiency of the steam boiler with analysis this data obtained from the boiler by using MATLAB; (Fig. 3) shows the effect of different flue gas temperature on efficiency of examined boiler. The decreasing in flue gas temperatures is due to the use of additional equipment in Boiler. These equipment such as economizer, turbulator, deaerator, and water softener, decline the flue gas temperature to about 100 °C and has a remarkable effect on improving the efficiency of boilers by 7 percent (Wulfinghoff and Donald, 1999).

The Relationship between Efficiency and Ambient Temperature

Another effective factor on efficiency is the ambient temperature. A change in ambient temperature with 40-degree variation is affective for the boiler efficiency by 1% or more (Schuster, *et al.*, 2009). Therefore, it is important to check the utilized air conditions when

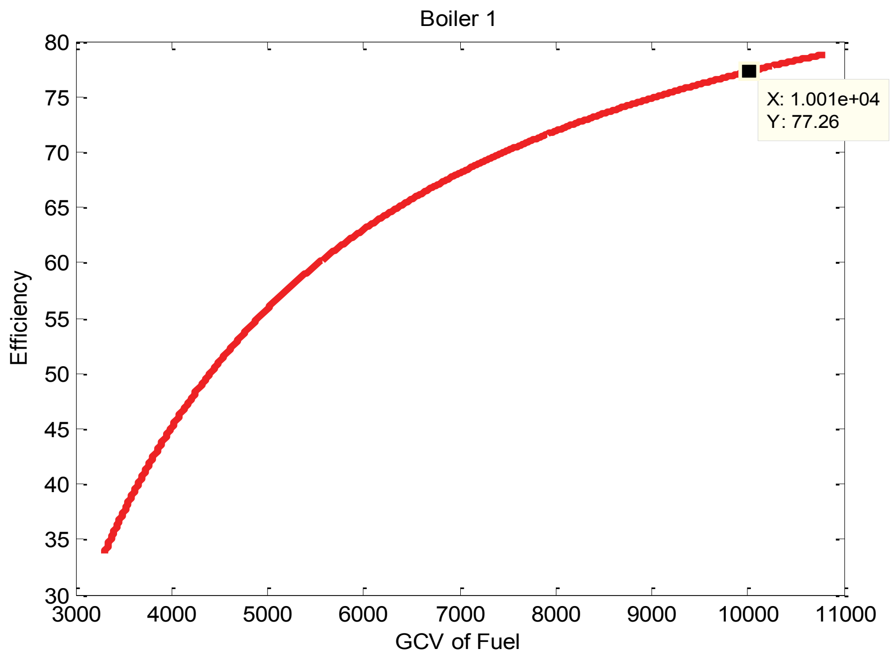

Fig. 2 Efficiency in different GCV of fuel.

reviewing an efficiency guarantee or calculation. Any utilization of ambient temperature at higher than 80° F value, would not be consistent with standard engineering practice (Yaverbaum, 1979). However, the actual efficiency will be lower if the boiler is placed outside regardless of the boiler design (Fig. 4). Therefore, it is essential to calculate the efficiency at lower ambient conditions to determine the actual fuel usage (Wang, *et al.*, 2011; Wang, *et al.*, 2008; Rego-Barcena, *et al.*, 2007).

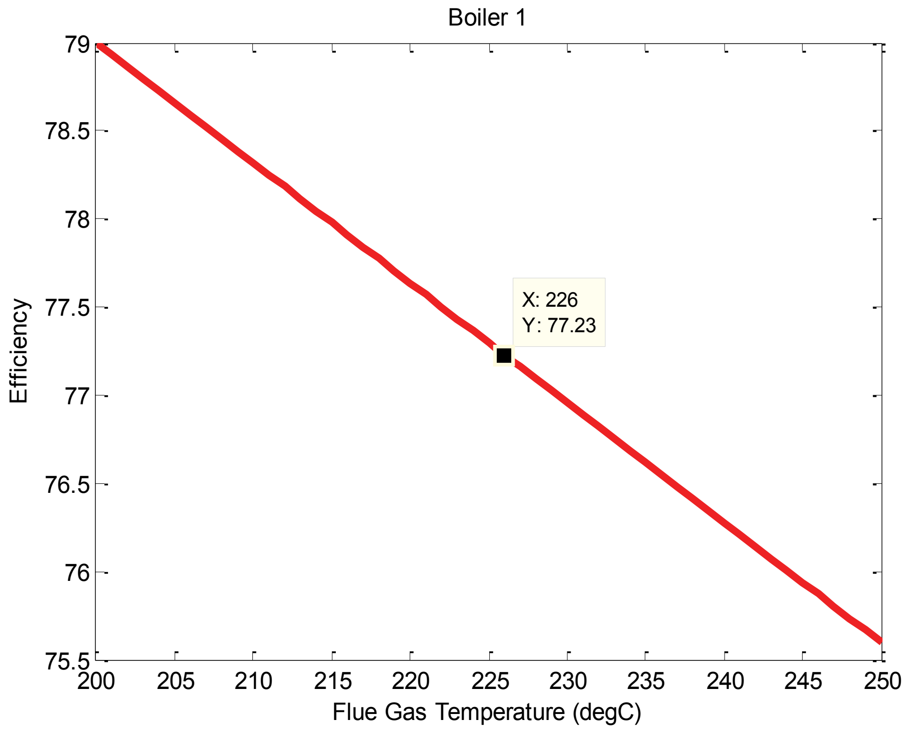

Fig. 3 Efficiency by different flue gas temperature.

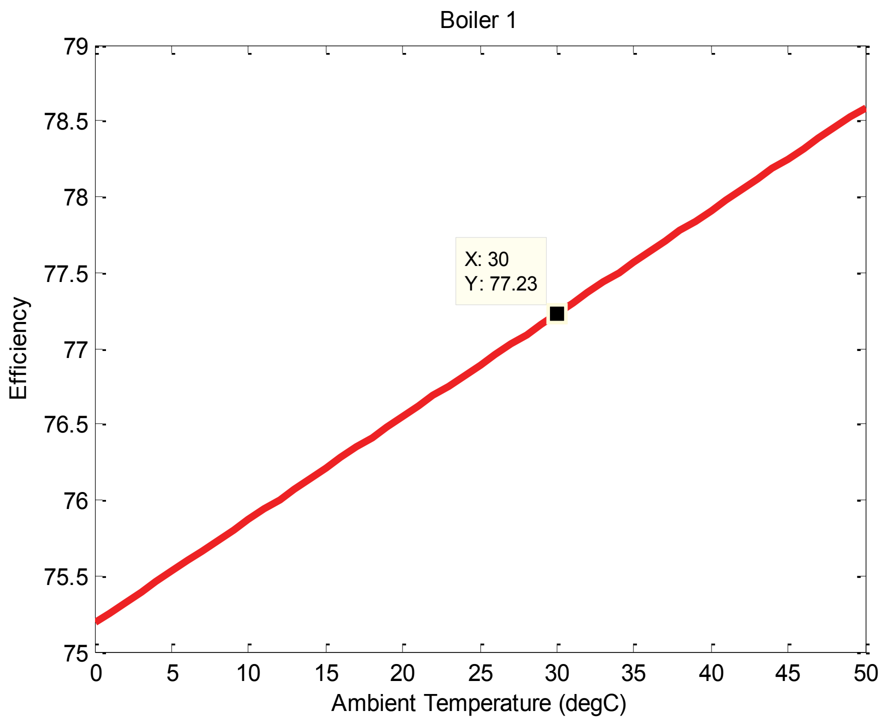

Fig. 4 Efficiency by different ambient temperature.

CONCLUSION

In this paper indirect method (heat loss method) is explored for boiler calculation of boiler efficiency. The indirect method is the most accurate method to determine boiler efficiency. In this method, the parameters that effect on efficiency be measured and different types of losses be calculated. Three of the most effective parameters are flue gas temperature, ambient temperature, and the fuel type. The heat loss method shows reduce the flue gas temperature and increasing the ambient temperature have a significant effect on improving the efficiency of steam boiler; in addition the fuels with higher gross calorific value are effective on the increasing the efficiency in fire tube steam boilers.

REFERENCES

Afgan, N., Carvalho, M. and Coelho, P. (1996). Concept of expert system for boiler fouling assessment. *Applied Thermal Engineering*. 16(10) : 835-844.

Brooks, C. (2010). Boiler efficiency guide. Cleaver Brooks: cleaverbrooks.com.

Bujak, J. (2008). Mathematical modelling of a steam boiler room to research thermal efficiency. *Energy*. 33(12) : 1779-1787.

Durkin, T.H. (2006). Boiler system efficiency. *ASHRAE Journal*. 48(7) : 51.

Einstein, D., Worrell, E. and Khrushch, M. (2001). Steam systems in industry: Energy use and energy efficiency improvement potentials. Lawrence Berkeley National Laboratory.

Hasanuzzaman, M., Rahim, N. and Saidur, R. (2011). Analysis of energy, exergy and energy savings of a fire tube boiler. Clean Energy and Technology (CET), 2011 IEEE First Conference IEEE.

Huang, B., Yen, R. and Shyu, W. (1988). A steady-state thermal performance model of fire-tube shell boilers. *Journal of Engineering for Gas Turbines and Power*. 110(2) : 173-179.

Kaag, C.S. (2000). Energy Efficiency Manual. *Reference & User Services Quarterly*. 40(2) : 186-186.

Krishnanunni, S., Josephkunju, P.C., Mathu, P. and Ernest, M.M. (2012). Evaluation of Heat Losses in Fire Tube Boiler. *International Journal of Emerging Technology and Advanced Engineering*. 1 : 301-305.

Kulatilaka, N. (1993). The value of flexibility: The case of a dual-fuel industrial steam boiler. *Financial management*. 271-280.

Kuprianov, V.I. (2005). Applications of a cost-based method of excess air optimization for the improvement of thermal efficiency and environmental performance of steam boilers. *Renewable and Sustainable Energy Reviews*. 9(5) : 474-498.

Mimura, T., et al., Development of energy saving technology for flue gas carbon dioxide recovery in power plant by chemical absorption method and steam system. *Energy Conversion and Management,* 1997. 38: p. S57-S62.

Morgan, P.A., Robertson, S.D. and Unsworth, J.F. (1986). Combustion studies by thermogravimetric analysis: 1. *Coal Oxidation. Fuel*. 65(11) : 1546-1551.

Morgan, P.A., Robertson, S.D. and Unsworth, J.F. (1987). Combustion studies by thermogravimetric analysis: 2. *Char Oxidation. Fuel*. 66(2): 210-215.

Ortiz, F.G. (2011). Modeling of fire-tube boilers. *Applied Thermal Engineering*. 31(16) : 3463-3478.

Patro, B. (2016). Efficiency studies of combination tube boilers. *Alexandria Engineering Journal*. 55(1) : 193-202.

Payne, R., Chen, S.L., Wolsky, A.M. and Richter, W.F. (2007). CO_2 recovery via coal combustion in mixtures of oxygen and recycled flue gas. *Combustion Science and Technology*. 1989 : 67 : 1-16.

Rego-Barcena, S., Saari, R., Mani, R., El-Batroukh, S. and Thomson, M. J. (2007). Real time, non-intrusive measurement of particle emissivity and gas temperature in coal-fired power plants. *Measurement Science and Technology*. 18(11) : 3479.

Saidur, R., Ahamed, J. and Masjuki, H. (2010). Energy, exergy and economic analysis of industrial boilers. *Energy Policy*. 38(5) : 2188-2197.

Schuster, A., Karellas, S., Kakaras, E. and Spliethoff, H. (2009). Energetic and economic investigation of Organic Rankine Cycle Applications Applied Thermal Engineering. 29 : 1809-1817.

Shah, S. and Adhyaru, D. (2011). Boiler efficiency analysis using direct method. Engineering (NUiCONE), 2011 Nirma University International Conference IEEE.

Van, D.W.M. and Jager, D.B. (2001). A review of methods for input/output selection. *Automatica*. 37(4) : 487-510.

Vasquez, R.J., Perez, R.R. and Moriano, S.J. (2007). System identification of the steam pressure variation process inside a fire-tube boiler. IFAC Proceedings. 40(1) : 232-237.

Wang, E.H., Zhang, H.G., Fan, B.Y., Ouyang, M.G., Zhao, Y. and Mu, Q.H. (2011). Study of working fluid selection of organic Rankine cycle (ORC) for engine waste heat recovery. *Energy*. 36 : 3406-3418.

Wang, L., Piao, X.L., Kim, S.W., Piao, X.S., Shen, Y.B. and Lee, H.S. (2008). Effects of Forsythia suspensa extract on growth performance, nutrient digestibility, and antioxidant activities in broiler chickens under high ambient temperature. *Poultry Scienc.* 87(7) : 1287-1294.

Wienese, A. (2001). Boilers, boiler fuel and boiler efficiency. *Proc. S. Afr. Sug. Technol. Ass*.

Wulfinghoff, D.R. (1999). Energy efficiency manual. Energy Institute Press Maryland. 3936.

Wulfinghoff. and Donald, R.D.R. (1999). Energy Efficiency Manual. *Energy*. 1531.

Yaverbaum, L.H. (1979). Energy saving by increasing boiler efficiency. *Naval Engineers Journal*. 63.