PERFORMANCE ANALYSIS OF COAL-FIRED BOILER AND NATURAL GAS FIRED BOILER AT MOREHEAD STATE UNIVERSITY POWER PLANT

A Thesis

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Master of Science

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by

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Accepted by the faculty of the College of Science & Technology, Morehead State University, in partial fulfillment of the requirements for the Master of Science degree.

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Devender Banne, M.S.
Morehead State University, 2009

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The thesis titled, "Performance Analysis of Coal Fired Boiler and Natural Gas Fired Boiler at Morehead State University Power Plant" involved analyzing the performance of the natural gas boiler and the coal fired boiler at Morehead state University power plant in terms of performance measures, economical measures and environmental measures. The data was collected in the form of log sheets from the power plant and was used to determine the boiler efficiency, thermal efficiency, and combustion efficiency. Also, the data collected from the log sheets was used to determine the boiler efficiency at part loads and the results obtained were used to plot a graph to understand the efficiency of each boiler at different load conditions. It was investigated that steam generation was cheaper with coal fired boiler over the natural gas fired boiler.

Accepted by: Ahmad Zargari, Chair

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Chapter I

1.1 Introduction

A boiler is a closed vessel in which water is heated. According to the power source for the boilers, boiler may be classified as a coal-fired boiler, oil-fired boiler or gas fired boiler. For years, thermal power plants have used coal fired boilers for steam generation in order to generate electricity. About fifty percent of the world's electricity is generated from thermal power plants and coal fired boilers are dominant among the boilers used in the thermal power plants. *(Stultz, S. C. Kitto J. B. Tomei G. L. 2005 Steam: Its Generation and Use. Boston: Babcock & Wilcox Company).*

One main concern about the coal fired boiler is the pollutants it produces after the combustion. Harmful pollutants like sulphur dioxide, carbon dioxide, some radioactive agents and fly ash are produced by the combustion of coal. For this reason, power plant operators are switching to natural gas fired boilers which are more environmentally friendly. At this point, a comparison between the coal fired boiler and the natural gas fired boiler on the basis of performance, economical measures and environmental measures gains importance.

1.2 Significance of the study

Morehead State University's power plant management has decided to replace the two old coal fired boilers as their expected life has been exceeded and they do not meet the current regulatory standards. Therefore, at this juncture, the comparison of the coal fired boiler and natural gas boiler on the basis of performance, economical measures, and environmental measures gains importance.

1.3 Objectives

The main objectives of this study are listed below:

1. To compare the coal fired and natural gas fired boiler on the basis of performance, economical measures, and environmental measures.
2. To calculate boiler efficiency at different load conditions and plot a graph for boiler efficiency with respect to different load conditions.

1.4 Assumptions

The following assumptions were made in this thesis:

1. The data collected from the log sheets of the Morehead State University Power Plant is accurate and recorded with no errors.
2. The data recorded in the log sheets of the Morehead State University Power Plant reflect the boiler's actual working conditions.
3. The dates for which the log sheets were selected represent the coldest days in a calendar year.
4. The conditions under which a boiler operates are same for the Coal fired boiler and natural gas fired boiler.

1.5 Limitations:

Limitations of this thesis are listed below:

1. The data used in this thesis is historical data and obtained from the log sheets which were recorded by the operating personnel of the Morehead State University Power Plant while a boiler is in operation.
2. The data recorded in the log sheets is for the boilers which are running in real time conditions and there is no way to control the working conditions in order to perform part load conditions in an experimental set up fashion.
3. The boilers which are analyzed in this thesis are not of the same age.

1.6 Definition of terms

This section explains the technical terms that are used in this report:

Sensible heat: Sensible heat can be defined as the heat required raising the temperature of water from room temperature to boiling point.

Latent heat: Latent heat can be defined as the heat absorbed by the boiling water to convert from liquid state to vapor.

Boiler efficiency: Boiler efficiency can be defined as the ratio of input to the boiler in the form of heat energy by the combustion of fuel to the heat absorbed by the working fluid in the boiler.

Thermal efficiency: Thermal efficiency can be defined as the effectiveness of the boiler to convey heat from the combustion process to the working fluid which is water in the boiler in this case.

Combustion efficiency: Combustion efficiency can be defined as the ratio of the actual heat energy released by the combustion process in the furnace to the total heat energy contained by the fuel.

Enthalpy: Enthalpy can be defined as the sum of internal energy of the system and the product of volume and pressure of the working system.

Chapter II

Review of Literature

2.1 Background

H. Schneider, Th. Frank, K. Pachler, K. Bernert (2002) in their research work "A Numerical Study of the Gas-Particle Flow in Pipe work and Flow Splitting Devices of Coal-Fired Power Plant," designed a bifurcator which would divide the pulverized fuel equally into multiple channels of the combustion chamber in order to avoid partial combustion and local NO_2 formation. The designed bifurcator was developed by conducting a series of experiments. The first experiment conducted was to test the effect of bouncing glass sphericals on the steel walls in vacuum condition. The next experiment was to test the effect of the impact of glass sphericals which are energized by CO_2 and N_2 on steel plates. The results obtained were incorporated in the numerical model and solved using ICEM/CFD-Hexa. The designed bifurcator can be used in the complex pipe work of a boiler since it would ease the design process.

E. Eddings, A. Molina, D. Pershing, A. Sarofim, K. Davis and M. Heap, T.Fletcher, H. Zhang (2000) in their research "Minimization of no emissions from multi-burner coal-fired boilers" have compared the NO_2 emissions of single burner and multiple burner coal fire boilers by changing the swirl of the burner and determined that multiple burners would yield higher emissions of NO_2. For this, first the NO_2 emissions from the burners in a controlled atmosphere were recorded in the laboratory. The results obtained were incorporated in the geometric model developed and analyzed.

Vuthaluru H. B. (1999) investigated that wet pretreatment of coal and the use of mineral additives reduces mitigating, fouling and slogging in brown coal-fired power utilities. These were developed by treating coal with aluminum solutions and sodium compounds and burning them in controlled conditions at a temperature range of 1000-1400°C. Both the techniques developed were proven effective by the experiments.

Kenneth P. Smith (1993) has examined the feasibility of using waste paper as an alternate to coal as a fuel. The problems he concluded that would arise if waste paper was used as a fuel are problems during combustion and increased emissions. This work was achieved by reading literature reviews and conducting personal interviews.

Mike Bockelie, Marc Cremer, Kevin Davis, in their report "NOx Control Options and Integration for US Coal Fired Boilers," developed cost effective analysis tools and techniques for demonstrating and evaluating low NOx control strategies and their possible impact on boiler performance for firing US coals.

G. Jinjikhashvily, Elbit Building, Hof Shemen, Haifa Yu. Wladislawsky and B. Dashevsky, in their research "Utilization of flue gases of coal fired power plants for greenhouses co2 enrichment" introduced the ways to enrich carbon dioxide emitted from burning coal.

After going through various thesis done by different researchers, it is concluded that the performance analysis of coal fired boiler and natural gas fired boiler in real time application has not been done before and there was a necessity of 0performing a comparison between coal fired boiler and natural gas fired boiler at Morehead State University Power Plant since the plant was required to replace existing coal fired boiler with a new boiler. Therefore, the thesis titled, "Performance Analysis of Coal Fired Boiler and Natural Gas Fired Boiler at Morehead State University Power Plant" would help in deciding between coal fired boiler and natural gas fired boiler.

2.2 Morehead State University Power Plant

The Morehead State University Power Plant owned by Morehead State University was once owned by the Maggord family. Morehead State University took over the plant in order to meet its heating applications and drinking water needs. This is the only plant owned and operated by a university authority. The power plant runs primarily on coal-fired water tube boiler which was manufactured by E. Keeler &Co. with a capacity of 60,000 pounds of steam/hr and has another coal fired, water tube boiler with the same manufacturer and a capacity of 30,000 pounds of steam/hr as a standby boiler and has a 3-pass boiler which is manufactured by Burnham Industrial with a capacity of 31,050 pounds of steam/hr, which runs on natural gas as fuel. When working on its full capacity, the Morehead State University Plant can supply drinking water to the entire city of Morehead. When the plant is in full swing, the steam is produced at 200Psi and returns to the plant at 70Psi. However, due to the shutting down of the coal-fired boilers, as of now the steam is supplied to university at 40psi. The layout of the plant is provided in Appendix A

The plant was shut down in March 2007 by the state authorities because the plant was not meeting the required standards set by the law for plants operating on coal-fired boilers. The standards which the plant didn't meet are explained in the next section. Since the shut down of coal-fired boilers, the plant is running on the natural gas and is delivering the steam required for heating applications and drinking water to the university.

2.3 Reasons for closing down the operation of coal-fired boiler

Some of the important reasons for shutting down the operation of the coal-fired boiler are listed below:

- According to the EPA regulations for coal fired boiler operations, the plant should be equipped with a standby feed pump which is driven by energy other than electricity from lines, so that in the case of a power loss from the distributing lines, there is equipment which pumps the water into the boiler in order to avoid boiler explosion by overheating. Boiler explosion occurs when the water in the boiler is completely converted into steam and leaves the boiler and there is no remaining water in the boiler which can absorb the enormous heat energy released by the combustion of fuel, therefore, resulting in heating the boiler itself and ultimately ending up in an explosion.

- Fly ash, sulphur dioxide, and Nitrogen oxides are the main emissions of the combustion of coal. These chemicals add to environmental pollution and are harmful to human beings when they are exposed to these chemicals. The emission control systems which were employed by the Morehead State University Plant were inadequate and the plant didn't have any methods for proper handling of the fly ash.
- The boilers, which were in operation have already completed their service life and even exceeded the service life. Running on boilers which have exceeded the service life might lead to improper combustion, undesired pressure and temperatures, increase in the emissions which might lead to increased consumption of fuel, increased pollution and might also produce a threat to safety for the people working in the plant.

2.4 Improvisations for the coal-fired boiler

After the shutdown of the coal-fired boiler, the authorities have made certain improvisations in order to get the coal-fired boilers back into operation. Following are the list of activities required according to the state law in order to get the coal-fired boilers back into the operation:

- Installation of standby feed water pump: A standby feed water pump is a water feeding pump to the boiler. It is an auxiliary piece of equipment which is driven by energy other than electricity from lines, so that in case of a power loss from the distributing lines, there is equipment which pumps the water into the boiler in order to avoid boiler explosion by overheating. The Morehead State University authorities have successfully installed a standby feed water pump which is driven by steam turbine.

- Emission control: Dealing with fly ash is a major problem associated with coal-fired boilers. Fly ash is the resultant of combustion of coal and is made up of fine particles of ash that it are easily carried away by the flue gases which contaminates the surrounding air with fly ash which when inhaled produces serious threats to health in the long run. So, Morehead State University authorities have proposed installing an electrostatic fly ash collector. The electrostatic fly ash collector attracts the fly ash particles in the flue gases and the fly ash is collected at the bottom of the equipment thereby preventing fly ash from entering into the surrounding air. The authorities have installed an Electro-static fly-ash collector in order to minimize fly ash emissions into the atmosphere in the month of January 2009.
- Replacement of old coal fired boilers: One of the reasons for closing down of the coal-fired boiler is that the coal fired boilers have exceeded their service life and need to be replaced. The concerned authorities have allotted a budget of $25,000,000 for the replacement of the two coal fired boilers during the years 2008-2010.

Chapter II

Methodology

3.1 Data collection

The data is obtained from the Morehead State University Power Plant log sheets. The log sheets have the hourly recordings of the boiler which is in operation recorded by the on duty boiler attendant. In order to be precise in calculations, the log sheets selected for the calculation purposes were from the coldest days of the year so that the boilers work under full load condition. The log sheets selected for the coal fired boiler were for the date 22nd of December 2003. The log sheets selected for the natural gas fired boiler were for the date 1st of January 2008. The simplified data obtained from the log sheets is provided in the Appendix B and C.

3.2 Restatement of the objectives

The main objectives of this study are listed below:

1. To compare the coal fired and natural gas fired boiler on the basis of performance measures, economical measures, and environmental measures.
2. To calculate boiler efficiency at different load conditions and plot a graph for boiler efficiency with respect to different load conditions.

3.3 Objective-1: Analysis of Coal fired boiler and natural gas fired boiler

The coal fired boiler and natural gas fired boiler are analyzed on the following basis:

- Performance measures:
  - Boiler efficiency
  - Combustion efficiency
  - Thermal efficiency
- Economical measures:
  - Operating cost
  - Maintenance cost
  - Floor space required for the same output of steam generated.
- Environmental measures:
  - Evaluation of the emission from the fuel combustion
  - Waste management

3.3.1 Boiler Efficiency: As defined earlier, boiler efficiency can be defined as the ratio of heat absorbed by the working fluid in the boiler to the input to the boiler in the form of heat energy by the combustion of fuel. (*Steam; Generation and its use; 41st edition)* Boiler efficiency can be given as,

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid}}{\text{Heat energy released by the combustion of the fuel}}$$

$$= \frac{Q_w}{Q_f} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

Heat absorbed by the working fluid (Q_w):

In order to obtain an equation for heat absorbed by the working fluid in the boiler, consider an open system in which mass and energy continuously enter and leave the system as shown in the figure 4.1

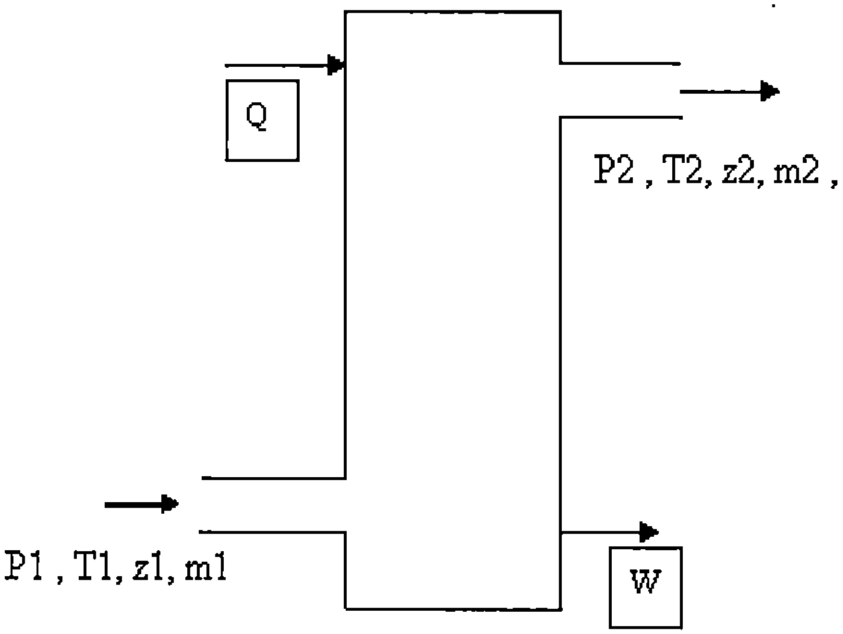


Fig. 4.1 Schematic representing an open system

Source: Steam; Generation and its use; 41st edition pg.2.7

where P_1 , T_1, z_1, m_1 , and V_1 are values of pressure, temperature, datum head , mass and volume at the inlet (1) of the process.

P_2 , T_2, z_2, m_2 , and V_2 are values of pressure, temperature, datum head , mass and volume at the outlet (2) of the process.

Using the law of conservation of energy, which states that energy can neither be created nor destroyed in a process, the energy balance equation can be written as

$$E_2 - E_1 = Q - W \text{..} (2)$$

Where Q is the energy input to the system and

W is the useful work done by the system.

The terms E_2 and E_1 denote the total energy contained by the fluid at outlet and inlet conditions respectively. They account for the internal energy, pressure energy, kinetic energy and potential energy contained by the system. E_2 and E_1 can be given as

E_2 , total energy contained by the fluid at the outlet,

$$= m_2^{\cdot} \, (u_2 + P_2 \, v + V^2/2g + z_2)$$

E_1, total energy contained by the fluid at the inlet,

$$= m_1^{\cdot} \, (u_1 + P_1 \, v + V^2/2g + z_1)$$

By substituting the above values in the energy balance equation, it can be written as

$$m_2^{\cdot} \, (u_2 + P_2 \, v + V^2/2g + z_2) - m_1^{\cdot} \, (u_1 + P_1 \, v + V^2/2g + z_1) = Q - W \text{.....} (3)$$

where u_2 ,$P_2 \, v$, $V^2/2g$ and z_2 represent the internal energy, pressure energy, kinetic energy and potential energy respectively at the outlet;

u_1,$P_1 \, v$, $V^2/2g$ and z_1 represent the internal energy, pressure energy, kinetic energy and potential energy respectively at the inlet;

m_1 and m_2 represent the mass flow rate of water at inlet and outlet respectively.

Since, in a boiler, the variation in velocity of working fluid is negligibly small, variation in velocity of working fluid is ignored. The same case exists with the datum head because the height of the inlet and outlet of the boiler with respect to ground are almost the same. Therefore, equation (3) can be reduced to

$$\dot{m_2}\,(u_2+P_2 v) - \dot{m_1}\,(u_1+P_1 v) = Q - W$$

Since the boiler does no work *i.e.,* W= 0 and according to definition of enthalpy, enthalpy (H) is the sum of internal energy of the system and the product of volume and pressure of the working system. Therefore, the above equation can be further reduced to

$$m_2H_2 - m_1H_1 = Q$$

Where H_2 and H_1 are the values of enthalpy at outlet and inlet of the boiler respectively.

Since the mass flow rate at the inlet and outlet of the boiler is same, the above equation can be written as,

Heat absorbed by the working fluid, $Q_W = \dot{m}\,(H_2-H_1)$ .... (4)

Heat contained by the fuel (Q_f):

The heat contained by the fuel is the total energy emitted by complete combustion of coal. It is the product of total mass of fuel burnt to the higher heating value (HHV) of the fuel.

$$Q_f = m_f * HHV \qquad \text{......................} (5)$$

Higher heating value of coal ranges from 8000 Btu/lb to 12000 Btu/lb depending on the chemical composition of the coal. The Higher heating value of natural gas ranges from 18400 Btu/lb to 21800 Btu/lb depending on the chemical composition. (*Steam; Generation and its use; 41 edition pg. 10.9)*

3.3.2 Combustion efficiency

Combustion efficiency can be defined as the ratio of the actual heat energy released by the combustion process in the furnace to the total heat energy contained by the fuel.

$$\eta_{comb} = \frac{\text{Actual Heat energy released by combustion}}{\text{Heat energy that could be released by the fuel}}$$

$$= \frac{Q_{comb}}{Q_f} \text{..} (4).$$

Heat energy contained by the fuel is the value of energy that can be released when the chemical constituents of the fuel are burnt completely. The mass of the air required to completely burn the fuel is called theoretical air required and is derived from the chemical reaction during combustion and it depends on the composition of the fuel type. The theoretical air required for complete combustion of bituminous coal is 9.07 lb of air/lb of fuel and for that of natural gas, it is 15.74 lb of air/lb of fuel. *(Steam; Generation and its use; 41 edition pg. 10.9; Table 8)*

Actual heat energy contained by the fuel = Theor. Air *Higher heating value (5)

Actual heat energy released by the combustion of fuel is different than the theoretical heat energy contained by the fuel. It is due to the fact that actual air available for combustion is different from the theoretical air required for combustion. Actual energy released by the combustion can be given as the product of the actual air flow rate and higher heating value of fuel. Mathematically, it can be expressed as

Actual heat energy released = Act. air *Higher heating value............(6)

From the equation (5), actual heat energy can be calculated. This when divided by the total heat energy that could be released by the fuel gives the combustion efficiency.

3.3.3 Thermal efficiency

Thermal efficiency can be defined as the effectiveness of the boiler to convey heat from the combustion process to the working fluid which is water in the boiler in this case. It is the ratio of losses due to convection and radiation deducted from the total heat energy released by the combustion process in the boiler furnace to the total heat energy released by the combustion process itself. Mathematically, it can be represented as

$$\eta_{Therm} = \frac{\text{Heat energy released} - \text{Losses due to convection and radiation} * 100}{\text{Heat energy released by the combustion of the fuel}}$$

In order to be more precise in calculating the thermal efficiency, the heat energy released in the above equation should be the actual heat energy released by the combustion of fuel *i.e.*, by considering the combustion efficiency. Therefore, the above transforms into

$$\acute{\eta}_{Therm} = \frac{\text{Act. heat energy released - Losses due to convection and radiation} * 100}{\text{Act. heat energy released by the combustion of the fuel}}$$

Actual heat energy released is the product of the total heat energy that can be released by complete combustion and combustion efficiency. It can be expressed as

$$\text{Actual heat energy released} = \text{Total heat energy released} * \acute{\eta}_{comb}$$

Losses due to convection:

Convection heat transfer occurs between a hot surface and fluid flowing over it, through conduction of heat between the molecules of the fluid. If the fluid motion is caused by the natural phenomenon of flow due to difference in densities, then the type of heat transfer is called natural convection. On the other hand, if the fluid motion is caused by external sources like mechanical fan, then it is called forced convection. According to Newton's Law of Cooling, the rate of heat transfer through natural convection is directly proportional to the product of area of the hot surface and the temperature difference between the hot surface and the fluid. In the boiler furnace, the motion is due to the natural convection as the motion of the air is the result of differences in the densities of the air in the furnace and the ambient air.

Therefore, for calculating the losses due to convection, the equation for natural convection heat transfer holds good which can be stated as,

$$q_{cv} = h*A* (T_s - T_f)$$

where q_{cv} is the heat lost due to convection, BTU/hr

h is the heat transfer coefficient for air BTU/h ft^2 F,

A is the surface area of the grate ft^2,

T_s is the surface temperature ^0F,

T_f is the fluid temperature ^0F.

Losses due to radiation:

Transfer of heat between two bodies by electromagnetic waves is called radiation heat transfer. Since, electro magnetic waves doesn't require any medium to travel through, radiation doesn't need any intervening medium. According to Stefan-Boltzmann law, the energy radiated from a body is directly proportional to the product of surface area of the body and the fourth power of the absolute temperature of the body and the proportionality constant is called Stefan Boltzamann's constant(*Steam; Generation and its use; 41 edition pg. 4.4)*. Mathematically, it is represented by the following equation,

$$q_r = A\sigma T_s^4$$

Where q_r is the heat lost due to radiation, BTU/hr

A is the effective surface area, ft^2

σ is the Stefan-Boltzmann's constant, BTU/h $ft^2 R^4$

T_s^4 is the absolute temperature of the surface, ^0F.

3.3.4 Economic measures

Operating cost

Operating cost is defined as the costs incurred in generating one pound of steam. Operating cost is an important factor for consideration while selecting a boiler as it is the cost at which steam is generated. It is important to know the operating cost because it is the one which finally needs to be brought down. Operating cost with respect to the boiler can be given as the ratio of the product of the total fuel consumption per hour and the procurement cost per unit of the fuel to one pound of steam. Mathematically, it can be given as

$$\text{Operating cost, OC} = \frac{\text{Fuel consumption*cost of fuel/unit}}{\text{Total steam produced}}$$

Maintenance costs

Maintenance costs can be defined as the costs incurred in running the boiler. Typical costs which are included in the maintenance of natural gas boiler are costs incurred in re-tubing, replacement of components of the boiler line, regular inspection of the boiler and servicing the boiler. As these costs are not uniform and cannot be predicted accurately, the costs which were incurred in the fiscal year 2007-2008 for maintenance have been taken into account for comparison purposes.

Typical costs which are included in the maintenance of coal fired boiler are costs incurred in storage of coal, conveying coal to the boiler from storage, preheating the coal if necessary, ash handling, and fly ash control within the plant. As discussed earlier these costs are not uniform and cannot be predicted accurately, the costs which were incurred in the previous fiscal years for maintenance have been taken into account for comparison purposes.

Floor space required

Floor space required for the boiler can be defined as the floor space occupied by the boiler, elements of the boiler, accessories and floor space required for fuel storage. Since, the elements and accessories of the natural gas boiler and coal fired boiler are almost same and approximately occupy the same floor space, the floor space occupied by them can be neglected.

3.3.5 Environmental Measures

Combustion of fossil fuels is an exothermal reaction in which fossil fuels are burnt in the presence of atmospheric air and the by products of the reaction depends upon the type of fossil fuel and the chemical constituents of the fuel. Typical products of the combustion are carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide, particulate matter and mercury (Hg).

3.4 Objective -2: Boiler efficiency at Part-loads

The efficiency which was obtained earlier is the efficiency at certain load conditions on the boiler. This efficiency might not reflect the best of the boiler because of the fact that maximum efficiency is obtained at a certain load conditions. It is impractical and time consuming to interpret the maximum efficiency by calculating efficiency for each load value. The probable solution for this problem is to find out the efficiency values at certain load values and project a curve on the efficiency Vs load condition as it is seen in the case of evaluating the performance of an internal combustion engine This is a very effective way of finding the optimal load conditions, since the repetitive calculations are avoided. *(N. Stalin and H. J. Prabhu; ARPN Journal of Engineering and Applied Sciences).* Therefore, in order to determine the optimal load conditions for the boilers, four different load conditions that is ¼-load , ½ - load , ¾- load and full load are selected and the efficiency values thus obtained are plotted on the boiler efficiency Vs load conditions graph and the points and plot are joined together to obtain different efficiencies at different load conditions and thus coming up with the optimal load conditions for each boiler. In doing so, it is assumed that the operating temperatures and line pressures of the boiler are constant unless mentioned. In order to find out the boiler efficiency, equation (1) is used which is described earlier.

Chapter IV

Findings, Analysis & Conclusion

4.1 Calculations for natural gas boiler

4.1.1 Performance measures

Boiler efficiency:

Simplified data obtained from log sheets of MSU Power Plant: (Appendix C)

Mass flow rate of steam per hour (lbs) = 35541

Mass of natural gas consumed per hour (ft^3) = 1033

Average temperature of steam at outlet ($^\circ$ F) = 189.48

Average temperature of steam at inlet ($^\circ$ F) = 139.17

Steam pressure at outlet (Psi) = 40

Calorific value of natural gas (BTU/lb) = 21800

Density of natural gas (lbs/ft^3) = 0.156 (Appendix D)

Enthalpy of steam at a temperature of 189.48° F (BTU/lb) = 166.5 (Appendix C)

Enthalpy of steam at a temperature of 139.17° F (BTU/lb) = 97.99 (Appendix C)

Heat absorbed by the water, (BTU/hr) = 35541*(166.5-97.99) = 2434913.91

Heat released by the combustion, (BTU/hr) = 1033*0.156* 21800 = 3513026.4

By substituting the above values in equation 1, boiler efficiency of natural gas fired boiler is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 2434913.91/3513026.4 \qquad = 69.31\ \%$$

Combustion efficiency:

Density of air at 44.5° F (lb/ft^3) = 0.079 (Appendix D)

Air consumption (ft^3/hr) = 56.83 (Appendix C)

Mass flow rate of air (lb/hr) = 56.83*0.079 = 4.49

Theoretical air required for combustion (lb/hr) = 15.74

$$\eta_{comb} = \frac{\text{Actual Heat energy released by combustion}}{\text{Heat energy that could be released by the fuel}}$$

$$= \frac{4.49*21000}{15.74*21000}$$

$$= 28.5\ \%$$

Thermal efficiency:

Simplified data obtained from log sheets of MSU Power Plant: (Appendix C)

Effective cross sectional area (ft^2) = 1096

Length of the boiler (ft) = 25

Temperature at surface (F) = 308.17

Temperature of fluid (F) = 302.2

Convective heat transfer coefficient, h (BTU/h ft^2 F) = 5 (*Steam; Generation and its use; 41 edition pg. 4.3)*

Stefan Boltzman constant, σ (BTU/h $ft^2 R^4$) = $0.1713*10^{-8}$ (*Steam; Generation and its use; 41 edition pg. 4.4)*

Heat energy released by the combustion of fuel, Q = 3513026.4 BTU/hr (Section 3.2.1)

Losses due to convection $q_{cv} = h*A*(T_s - T_f)$

$$= 5*1096*25*(308.17-302.2)$$

$$= 817890 \text{ BTU/hr}$$

Losses due to radiation, $q_r = A\sigma T_s^4$

$$= 1096*25*0.1713*10^{-8}*308.17^4$$

$$= 423320.55 \text{ BTU/hr}$$

Thermal Efficiency,

$$\eta_{Therm} = \frac{\text{Heat energy released - Losses due to convection and radiation} * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= \frac{3513026.4-(817890+423320.55)}{3513026.4}$$

$$= 64.66\%$$

4.1.2 Economic measures

Operating cost:

Simplified data obtained from log sheets of MSU Power Plant: (Appendix C)

Total gas consumption (ft^3) = 1033

Cost of natural gas = \$ 14 /ft^3

Total steam generated (lbs) = 35541

Operating cost, OC = $\frac{\text{Fuel consumption*cost of fuel/unit}}{\text{Total steam produced}}$

$$= \frac{1033*14}{35541}$$

$$= 0.41 \text{ cents/lb of steam}$$

For 1000 lbs of steam, operating cost would be = 0.41*1000 = $410/1000 lbs of steam.

Maintenance costs:

According to Mr. John Mahanoy, Manager of Morehead State University Power Plant, the amount which was spent on maintenance of natural gas boiler for the fiscal year 2007-2008 was approximately $61,500 which when split is given as,

- $50,000 for re-tubing of the natural gas boiler
- $15,000 for purchase of control motor

Floor space required for natural gas boiler:

The floor area required by the natural gas boiler is measured at the site which is the Morehead State University Power Plant and is found out to be 22'5"*10'5" which gives the floor space required by the boiler as 236.25 ft^2. Since for the natural gas boiler, the fuel which is natural gas is obtained through a dedicated pipe line, there is no special need to dedicate an area for fuel storage.

4.1.3 Environmental measures

Natural gas being the cleanest of all the fossil fuels mainly comprises of methane and the products of combustion of natural gas include mainly carbon dioxide and water vapor and sulphur dioxide and nitrogen oxides in smaller quantities. Also, combustion of natural gas does not leave any fly ash or any other particulate matter. Because of this natural gas boilers have the advantage of reduced pollutants and also maintain a clean environment when compared to that of coal fired boiler. Typical values of combustion products of natural gas are given below:

Pollutant	Carbon dioxide	Carbon monoxide	Nitrogen oxide	Sulphur oxides	Particulates	Mercury
Emission Levels Pounds/ Billion Btu of Energy Input	117000	40	92	1	7	0.000

Source: EIA - Natural Gas Issues and Trends 1998 (www.naturalgas.org)

4.2 Calculations for coal-fired boiler

4.2.1 Performance measures

Boiler efficiency:

Simplified data obtained from check sheets of MSU Power Plant: (Appendix B)

Mass flow rate of steam per hour (lbs/hr) = 38260

Mass of coal consumed per hour (lbs/hr) = 2816.67

Average temperature of steam at outlet (^{o} F) = 188.43

Average temperature of steam at inlet (^{o} F) = 134.14

Steam pressure at outlet (Psi) = 40

Calorific value of coal (BTU/lb) = 12000

Enthalpy of steam at a temperature of 188.43° F (BTU/lb) = 166.5 (Appendix B)

Enthalpy of steam at a temperature of 133.14° F (BTU/lb) = 102.9 (Appendix B)

Heat absorbed by the water, (BTU/hr) = 38260*(166.5-102.9)) = 24333360

Heat released by the combustion, (BTU/hr) = 2816.67*12000 = 33800040

By substituting the above values in equation 1, boiler efficiency of coal fired boiler is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 24333360/33800040$$

$$= 71.99\ \%$$

Combustion efficiency:

Density of air at 44.5° F (lb/ft^3) = 0.079 (Appendix D)

Air consumption (ft^3/hr) = 56.83

Mass flow rate of air (lb/hr) = 56.83*0.079 = 4.49

Theoretical air required for combustion (lb/hr) = 9.07

$$\eta_{comb} = \frac{\text{Actual Heat energy released by combustion}}{\text{Heat energy that could be released by the fuel}}$$

$$= \frac{4.49*12000}{9.07*12000}$$

$$= 49.5\%$$

Thermal efficiency:

Simplified data obtained from log sheets of MSU Power Plant: (Appendix B)

Length of the boiler (ft) = 25

Width of the boiler (ft) = 11.5

Height of the boiler (ft) = 30

Temperature at surface (F) = 487.65

Temperature of fluid (F) = 44.9

Convective heat transfer coefficient, h (BTU/h ft^2 F) = 5 (*Steam; Generation and its use; 41 edition pg. 4.3)*

Stefan Boltzman constant, σ (BTU/h $ft^2 R^4$) = $0.1713*10^{-8}$ (*Steam; Generation and its use; 41 edition pg. 4.4)*

Heat energy released by the combustion of fuel, Q = 33800040 BTU/hr

Losses due to convection $q_{cv} = h*A*(T_s - T_f)$

$$= 5* 11.5*30*25*(487.65-44.9)$$

$$= 19093593.75 \text{ BTU/hr}$$

Losses due to radiation, $q_r = A\sigma T_s^4$

$$= 11.5*30*25* 0.1713*10^{-8}*487.65^4$$

$$= 835505.63 \text{ BTU/hr}$$

Thermal Efficiency,

$$\acute{\eta}_{Therm} = \frac{\text{Heat energy released - Losses due to convection and radiation * 100}}{\text{Heat energy released by the combustion of the fuel}}$$

$$= \frac{33800040-(19093593.75+835505.63)}{33800040} \quad = 41.04\%$$

4.2.2 Economical Measures

Operating cost:

Simplified data obtained from log sheets of MSU Power Plant: (Appendix B)

Total coal consumption (lbs) = 2816.67

Total coal consumption (tonne) = 1.267

Cost of coal = $ 115/tonne

Total steam generated (lbs) = 38260

$$\text{Operating cost, OC} = \frac{\text{Fuel consumption*cost of fuel/unit}}{\text{Total steam produced}}$$

$$= \frac{1.267*115}{38260}$$

$$= 3.8*10^{-3} \text{ cents/lb of steam}$$

For 1000 lbs of steam, operating cost = $3.8*10^{-3} * 1000$

= 3.8 cents/1000 lb of steam

Maintenance costs:

According to Mr. John Mahoney, Manager of Morehead State University Power Plant, the amount which was spent on maintenance of coal gas boiler for the fiscal year 2007-2008 was approximately $70,000 which when split is given as

- $60,000 for regular maintenance
- $10,000 for ash handling which includes transportation of ash to the dump area.

Floor space required:

The floor area required by the coal fired boiler is measured at the site which is the Morehead State University Power Plant and is found out to be 25'*12'6" which gives the floor space required by the boiler as 315 ft^2. A large open area is required in the case of coal fired boiler in order to store the coal and allow truck to enter in, in order to accommodate for easy unloading of the coal. Therefore, the total floor space required boiler for the coal fired boiler is the sum of the area required for the boiler and the area required for the storage of fuel which is more than 315 ft^2.

4.2.3 Environmental measures

Coal primarily consists of carbon, sulphur and nitrogen. Therefore, the combustion products include high nitrogen oxides and sulphur oxides. Also, fly ash and particulate matter are also produced while combustion. The major problem with coal fired boilers is the handling of fly ash. Fly ash is made of fine particles which are easily carried away by the flue gases and contaminate the surrounding areas with fly ash.

Typical values of combustion products of coal are given below:

Pollutants	Emission Levels Pounds/ Billion Btu of Energy Input
Carbon dioxide	208000
Carbon monoxide	208
Sulphur dioxide	457
Nitrogen oxides	2591
Particulate matter	2744
Mercury	0.016

Source: EIA - Natural Gas Issues and Trends 1998 (www.naturalgas.org)

4.3 Boiler efficiency at part load conditions

4.3.1 Natural gas fired boiler

At ¼ load conditions:

Capacity of the boiler (lbs) = 30000

Part load (¼) on the boiler (lbs) = 7500

Mass of natural gas consumed per hour (ft^3) = 1033

Average temperature of steam at outlet (^{o} F) = 189.48

Average temperature of steam at inlet (^{o} F) = 139.17

Steam pressure at outlet (Psi) = 40

Calorific value of natural gas (BTU/lb) = 21800

Density of natural gas (lbs/ft^3) = 0.156 (Appendix D)

Enthalpy of steam at a temperature of 189.48° F (BTU/lb) = 166.5 (Appendix C)

Enthalpy of steam at a temperature of 139.17° F (BTU/lb) = 97.99 (Appendix C)

Heat absorbed by the water, (BTU/hr) = 7500*(166.5-97.99) = 513825

Heat released by the combustion, (BTU/hr) = 1033*0.156* 21800 = 3513026.4

By substituting the above values in equation 1, boiler efficiency of natural gas fired boiler at ¼ load conditions is obtained *i.e.*,

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 513825/3513026.4$$

$$= 14.6 \%$$

<u>At ½ load conditions:</u>

Capacity of the boiler (lbs) = 30000

Part load (½) on the boiler (lbs) = 15000

Mass of natural gas consumed per hour (ft^3) = 1033

Average temperature of steam at outlet (° F) = 189.48

Average temperature of steam at inlet (° F) = 139.17

Steam pressure at outlet (Psi) = 40

Calorific value of natural gas (BTU/lb) = 21800

Density of natural gas (lbs/ft^3) = 0.156 (Appendix D)

Enthalpy of steam at a temperature of 189.48° F (BTU/lb) = 166.5 (Appendix C)

Enthalpy of steam at a temperature of 139.17° F (BTU/lb) = 97.99 (Appendix C)

Heat absorbed by the water, (BTU/hr) = 15000*(166.5-97.99) = 1027650

Heat released by the combustion, (BTU/hr) = 1033*0.156* 21800 = 3513026.4

By substituting the above values in equation 1, boiler efficiency of natural gas fired boiler at ½ load conditions is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 1027650/3513026.4$$

$$= 29.25\ \%$$

<u>At ¾ load conditions:</u>

Capacity of the boiler (lbs) = 30000

Part load (¾) on the boiler (lbs) = 21500

Mass of natural gas consumed per hour (ft^3) = 1033

Average temperature of steam at outlet (° F) = 189.48

Average temperature of steam at inlet (° F) = 139.17

Steam pressure at outlet (Psi) = 40

Calorific value of natural gas (BTU/lb) = 21800

Density of natural gas (lbs/ft^3) = 0.156 (Appendix D)

Enthalpy of steam at a temperature of 189.48° F (BTU/lb) = 166.5 (Appendix C)

Enthalpy of steam at a temperature of 139.17° F (BTU/lb) = 97.99 (Appendix C)

Heat absorbed by the water, (BTU/hr) = 21500*(166.5-97.99) = 1472965

Heat released by the combustion, (BTU/hr) = 1033*0.156* 21800 = 3513026.4

By substituting the above values in equation 1, boiler efficiency of natural gas fired boiler at ¾ load conditions is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$= 1472965/3513026.4$

$= 41.9\ \%$

<u>At full load conditions:</u>

Capacity of the boiler (lbs) = 30000

Full load (1) on the boiler (lbs) = 30000

Mass of natural gas consumed per hour (ft^3) = 1033

Average temperature of steam at outlet (^{o} F) = 189.48

Average temperature of steam at inlet (^{o} F) = 139.17

Steam pressure at outlet (Psi) = 40

Calorific value of natural gas (BTU/lb) = 21800

Density of natural gas (lbs/ft^3) = 0.156 (Appendix D)

Enthalpy of steam at a temperature of 189.48^o F (BTU/lb) = 166.5 (Appendix C)

Enthalpy of steam at a temperature of 139.17^o F (BTU/lb) = 97.99 (Appendix C)

Heat absorbed by the water, (BTU/hr) = 30000*(166.5-97.99) = 2055300

Heat released by the combustion, (BTU/hr) = 1033*0.156* 21800 = 3513026.4

By substituting the above values in equation 1, boiler efficiency of natural gas fired boiler at full load conditions is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 2055300/3513026.4$$

$$= 58.5\%$$

4.3.2 Coal-fired boiler

<u>At ¼ load conditions:</u>

Capacity of the boiler (lbs) = 60000

Part load (¼) on the boiler (lbs) = 15000

Mass of coal consumed per hour (lbs) = 2816.67

Average temperature of steam at outlet ($^\circ$ F) = 188.43

Average temperature of steam at inlet ($^\circ$ F) = 134.14

Steam pressure at outlet (Psi) = 40

Calorific value of coal (BTU/lb) = 12000

Enthalpy of steam at a temperature of 188.43° F (BTU/lb) = 166.5 (Appendix B)

Enthalpy of steam at a temperature of 133.14° F (BTU/lb) = 102.9 (Appendix B)

Heat absorbed by the water, (BTU/hr) = 15000*(166.5-102.9)) = 9540000

Heat released by the combustion, (BTU/hr) = 2816.67*12000 = 33800040

By substituting the above values in equation 1, boiler efficiency at ¼ load conditions of coal fired boiler is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 9540000/33800040$$

$$= 28.2\ \%$$

<u>At ½ load conditions:</u>

Capacity of the boiler (lbs) = 60000

Part load (½) on the boiler (lbs) = 30000

Mass of coal consumed per hour (lbs) = 2816.67

Average temperature of steam at outlet (^{o} F) = 188.43

Average temperature of steam at inlet (^{o} F) = 134.14

Steam pressure at outlet (Psi) = 40

Calorific value of coal (BTU/lb) = 12000

Enthalpy of steam at a temperature of 188.43^{o} F (BTU/lb) = 166.5 (Appendix B)

Enthalpy of steam at a temperature of 133.14^{o} F (BTU/lb) = 102.9 (Appendix B)

Heat absorbed by the water, (BTU/hr) = 30000*(166.5-102.9)) = 1908000

Heat released by the combustion, (BTU/hr) = 2816.67*12000 = 33800040

By substituting the above values in equation 1, boiler efficiency at ½ load conditions of coal fired boiler is obtained *i.e.,*

$$\acute{\eta}_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$= 1908000/33800040$

$= 56.4\ \%$

At ¾ load conditions:

Capacity of the boiler (lbs) = 60000

Part load (¾) on the boiler (lbs) = 45000

Mass of coal consumed per hour (lbs) = 3333.33

Average temperature of steam at outlet (^{o} F) = 188.43

Average temperature of steam at inlet (^{o} F) = 134.14

Steam pressure at outlet (Psi) = 40

Calorific value of coal (BTU/lb) = 12000

Enthalpy of steam at a temperature of 188.43^{o} F (BTU/lb) = 166.5 (Appendix B)

Enthalpy of steam at a temperature of 133.14^{o} F (BTU/lb) = 102.9 (Appendix B)

Heat absorbed by the water, (BTU/hr) = 45000*(166.5-102.9)) = 2862000

Heat released by the combustion, (BTU/hr) = 3333.33*12000 = 39999960

By substituting the above values in equation 1, boiler efficiency at ¾ load conditions of coal fired boiler is obtained *i.e.,*

$$\acute{\eta}_{boiler} = \frac{\text{Heat absorbed by the working fluid} \quad * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$= 2862000/39999960$

$= 71.5\%$

At full load conditions:

Capacity of the boiler (lbs) = 60000

Full load (1) on the boiler (lbs) = 60000

Mass of coal consumed per hour (lbs) = 4000

Average temperature of steam at outlet (^{o} F) = 188.43

Average temperature of steam at inlet (^{o} F) = 134.14

Steam pressure at outlet (Psi) = 40

Calorific value of coal (BTU/lb) = 12000

Enthalpy of steam at a temperature of 188.43^o F (BTU/lb) = 166.5 (Appendix B)

Enthalpy of steam at a temperature of 133.14^o F (BTU/lb) = 102.9 (Appendix B)

Heat absorbed by the water, (BTU/hr) = 60000*(166.5-102.9)) = 3816000

Heat released by the combustion, (BTU/hr) = 4000*12000 = 48000000

By substituting the above values in equation 1, boiler efficiency at full load conditions of coal fired boiler is obtained *i.e.,*

$$\eta_{boiler} = \frac{\text{Heat absorbed by the working fluid} * 100}{\text{Heat energy released by the combustion of the fuel}}$$

$$= 3816000/48000000$$

$$= 79.5\%$$

4.4 Results

The following results were obtained from the calculations above for the natural gas boiler and coal fired boiler which are tabulated below:

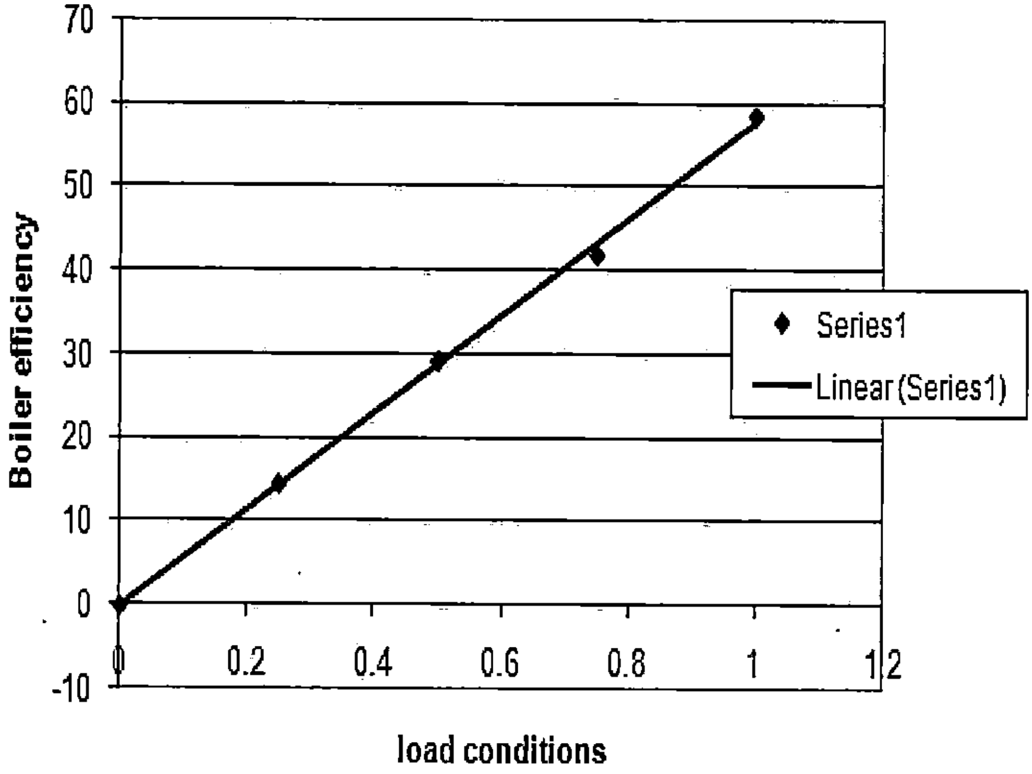
Table 4A Results obtained from the calculations

Aspect	Natural gas fired boiler	Coal fired boiler
	Performance measures	
Boiler efficiency, $\acute{\eta}_{boiler}$	69.31%	71.99%
Combustion efficiency,	28.50%	49.50%
Thermal efficiency	64.66%	41.04%
Economical measures		
Operating cost	$410/1000 lb of steam	3.8 cents/1000 lb of steam
Maintenance cost	$61,500	$70,000
Floor space required	236.25ft^2	315ft^2 + Area for coal storage

Table 4A Contd

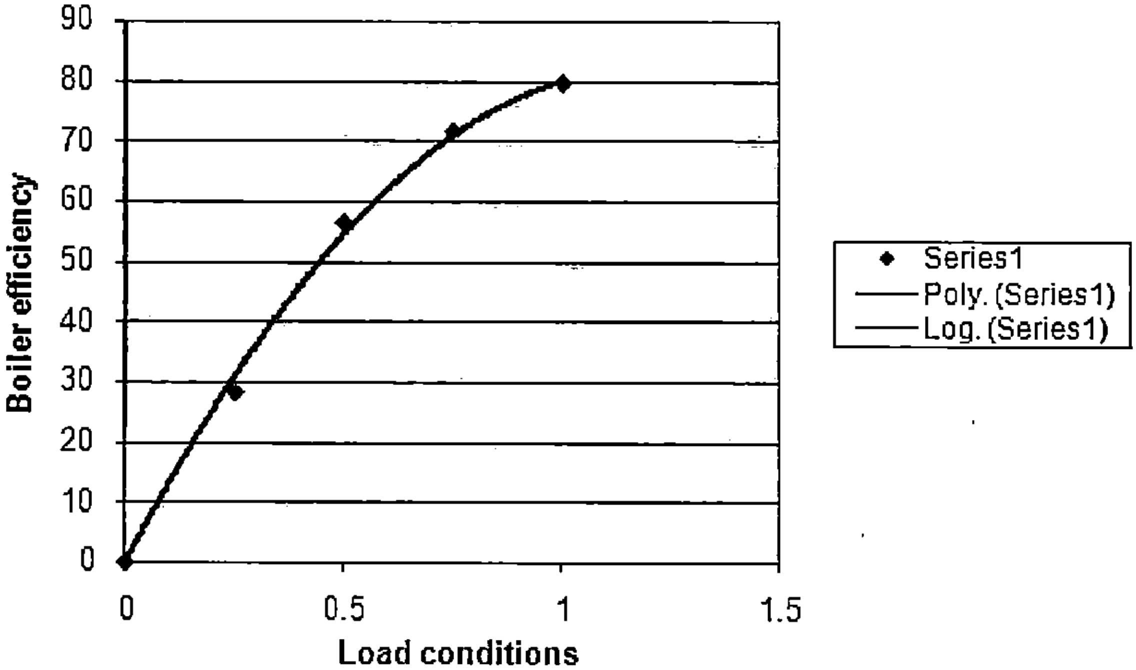
Environmental measures		
Pollutants	Emission Levels Pounds/ Billion Btu of Energy Input	
Carbon dioxide	117000	208000
Carbon monoxide	40	208
Sulphur dioxide	92	457
Nitrogen oxides	1	2591
Particulate matter	7	2744
Mercury	0	0.016
Boiler efficiency at part load conditions		
At ¼ load	14.60%	28.20%
At ½ load	59.25%	56.40%
At ¾ load	41.90%	71.50%
At full load	58.50%	79.50%

Boiler efficiency Vs Load conditions for natural gas boiler



Graph 4.1 Boiler efficiency vs. Load conditions for natural gas fired boiler

Graph for Boiler efficiency Vs Load conditions for coal fired boiler



Graph 4.2 Boiler efficiency Vs. Load conditions for Coal fired boiler

4.5 Analysis & Conclusions

From the table 4A above, it can be concluded that the natural gas fired boiler and coal fired boiler have their own benefits and limitations while selecting a boiler of the two. There are two main considerations while selecting a boiler. One of them is the operating cost and the other which is mainly considered with respect to EPA regulations is the environmental aspect. If one has to go with low operating cost, a coal fired boiler would be the best available option whereas if the environmental aspects are considered, then the natural gas fired boiler would be the best option available and it comes at a certain cost.

The following conclusions can be drawn from Graph 3.1 and 3.2 and Table A

- The Coal-fired boiler is more efficient in terms of boiler efficiency and combustion efficiency while its counterpart is efficient in terms of thermal efficiency.
- Steam generation is lot cheaper by employing a coal fired boiler but it is a bit expensive in terms of maintenance costs.
- For the same steam output, coal-fired boilers require more floor space than its counter part.
- At partial loads, the coal fired boiler is more efficient than its counterpart. The boiler efficiency is maximum when operated its full capacity.

Looking at the above statements, it can be concluded that coal fired boiler, when proper measures taken against the pollutants like fly ash, is much more effective than the natural gas boiler.

4.6 Future recommendations

One area where future research can be held is ways to improvise the overall efficiency and overall performance of the plant. As of March 2009, the Morehead State University Power Plant doesn't have any heat recovering equipment from the exhaust gases except for an economizer in the natural gas boiler circuit. The exhaust gases contains considerable amount of heat energy in them which is released into the atmosphere. Research could be done on developing techniques to capture the heat energy from the exhaust gases. This might include but not restricted to employing heat recovering equipment like feed water heater, air pre-heater and economizer.

A feasibility study of employing the heat recovering equipment at Morehead State University can also be made by researching on heat recovery equipments and their employability at Morehead State University Power Plant.

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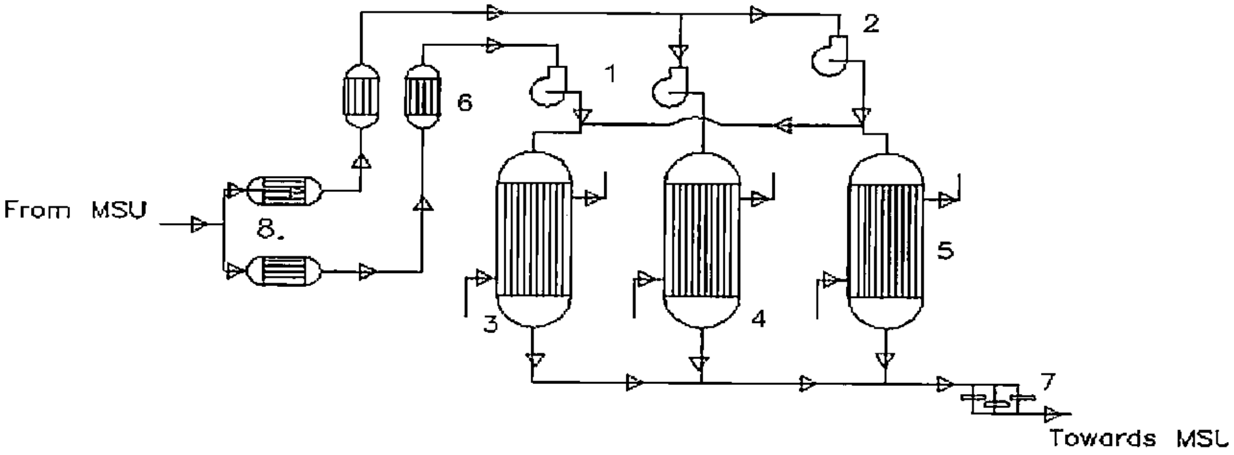
Appendix A

Layout of Morehead State University Power Plant



Equipment list:

1. Feed water pump
2. Standby feed water pump
3. Natural gas-fired boiler with 31,050 pounds of steam/hr capacity
4. Coal fired boiler with 60,000 pounds of steam/hr capacity
5. Coal fired boiler with 30,000 pounds of steam/hr capacity
6. Deaerator
7. Pressure regulator valve
8. Surge tank

Appendix B

Simplified data obtained from log sheets for the coal- fired boiler:

Average steam flow (lbs/hr)	38260
Average temperature of steam at outlet °F	188.43
Average temperature of steam at intlet °F	134.14
steam pressure (PSI)	40
Calorific Value (BTU/lb)	12000
Coal consumption/hr lbs/hr	2816.67
Length of the boiler (ft)	25
Width of the boiler (ft)	11.5
Height of the boiler (ft)	30
Temperature at surface (F)	487.65
Temperature of fluid (F)	44.9
Total coal consumption (lbs)	2816.67
Cost of coal $/tone	115
Total steam generated (lbs)	38260
Enthalpy of steam at 188.43 (BTU/lb)	166.5
Enthalpy of steam at 133.14 (BTU/lb)	102.9
Part load conditions	
1/4 load	15000
1/2 load	30000
3/4 load	45000
Full load	60000

Appendix C

Simplified data obtained from log sheets for the natural gas fired boiler:

Average steam flow (lbs/hr)	35541
Average temperature of steam at outlet °F	189.48
Average temperature of steam at intlet °F	139.17
steam pressure (PSI)	40
Calorific Value (BTU/lb)	21800
Mass of natural gas consumed, lbs/hr	1033
Air consumption (ft^3/hr)	56.83
Effective cross sectional area (ft^2)	1096
Length of the boiler (ft)	25
Temperature at surface (F)	308.17
Temperature of fluid (F)	302.2
Total gas consumption (ft^3)	1033
Cost of natural gas $ /ft3	14
Total steam generated (lbs)	35541
Density of nautral gas (lbs/ft	0.156
Enthalpy of steam at 189.48 (BTU/lb)	166.5
Enthalpy of steam at 139.17 (BTU/lb)	97.99
Part load conditions	
1/4 load	7500
1/2 load	15000
3/4 load	21500
Full load	30000

Appendix D

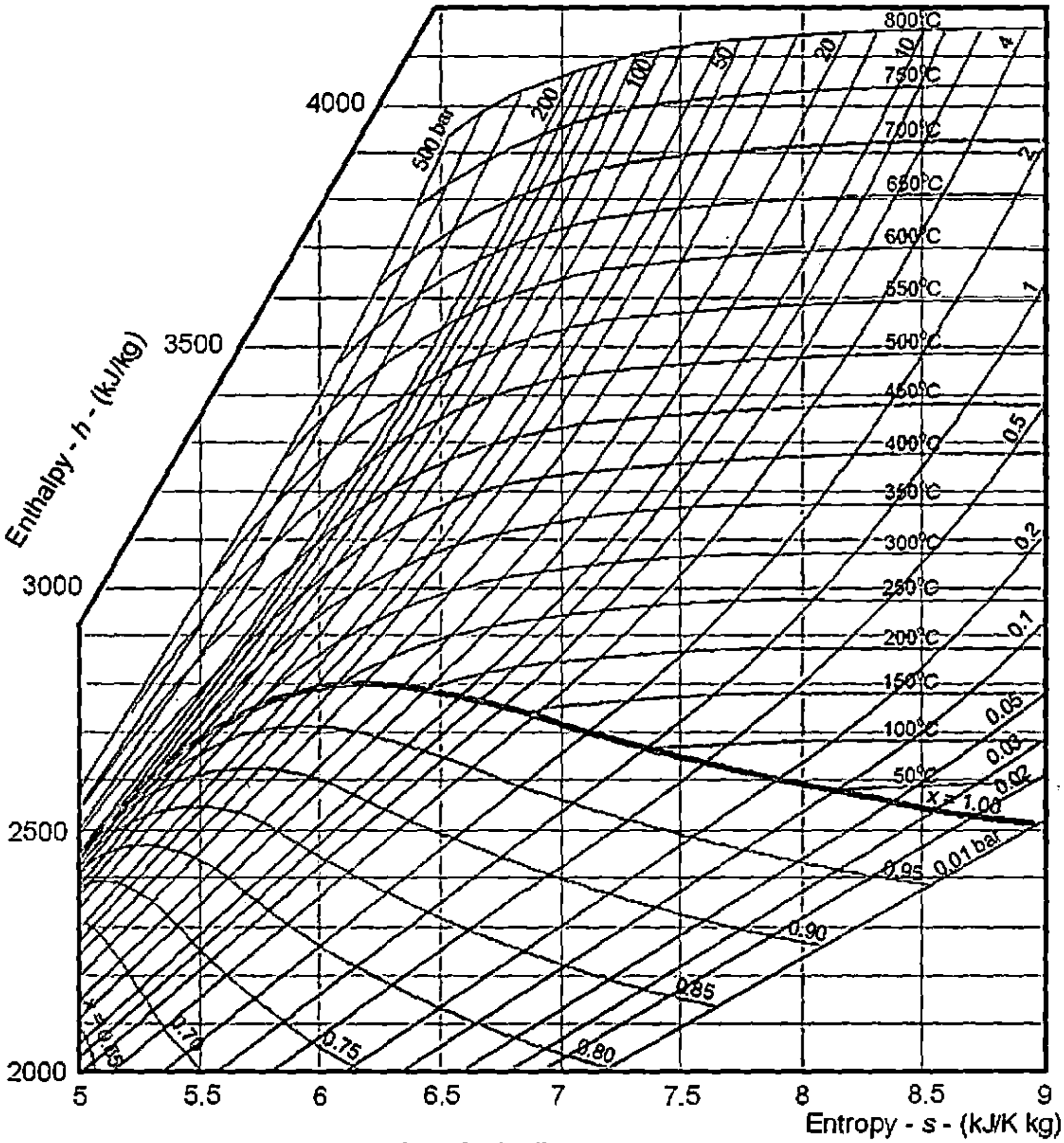
Density of air at different temperature and pressure

Density of air (lb/ft^3)												
Air temperature (°F)	Gauge Pressure (psi)											
	0	5	10	20	30	40	50	60	70	80	90	100
30	0.081	0.109	0.136	0.192	0.247	0.302	0.357	0.412	0.467	0.522	0.578	0.633
40	0.080	0.107	0.134	0.188	0.242	0.295	0.350	0.404	0.458	0.512	0.566	0.620
50	0.078	0.105	0.131	0.185	0.238	0.291	0.344	0.397	0.451	0.504	0.557	0.610
60	0.076	0.102	0.128	0.180	0.232	0.284	0.336	0.388	0.440	0.492	0.544	0.596
70	0.075	0.101	0.126	0.177	0.228	0.279	0.330	0.381	0.432	0.483	0.534	0.585
80	0.074	0.099	0.124	0.174	0.224	0.274	0.324	0.374	0.424	0.474	0.524	0.574
90	0.072	0.097	0.121	0.171	0.220	0.269	0.318	0.367	0.416	0.465	0.515	0.564
100	0.071	0.095	0.119	0.168	0.216	0.264	0.312	0.361	0.409	0.457	0.505	0.554
120	0.069	0.092	0.115	0.162	0.208	0.255	0.302	0.348	0.395	0.441	0.488	0.535
140	0.066	0.089	0.111	0.156	0.201	0.246	0.291	0.337	0.382	0.427	0.472	0.517
150	0.065	0.087	0.109	0.154	0.198	0.242	0.287	0.331	0.375	0.420	0.464	0.508
200	0.060	0.081	0.101	0.142	0.183	0.244	0.265	0.306	0.347	0.388	0.429	0.470
250	0.056	0.075	0.094	0.132	0.170	0.208	0.246	0.284	0.322	0.361	0.399	0.437
300	0.052	0.070	0.088	0.123	0.159	0.195	0.230	0.266	0.301	0.337	0.372	0.408
400	0.046	0.062	0.078	0.109	0.141	0.172	0.203	0.235	0.266	0.298	0.329	0.360
500	0.041	0.056	0.070	0.098	0.126	0.154	0.182	0.210	0.238	0.267	0.295	0.323
600	0.038	0.050	0.063	0.089	0.114	0.140	0.165	0.190	0.216	0.241	0.267	0.292

Souce: **www.engineeringtoolbox.com/air-temperature-pressure-density-d_771.html**

Appendix E

Mollier Diagram



Source:www.engineeringtoolbox.com/mollier-diagram.html