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DESIGN MODELING AND PERFORMANCE OPTIMIZATION OF A MARINE BOILER

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ABSTRACT

The design modeling and performance optimization of marine boiler using Excel and MATLAB is aimed at designing a boiler to improve the heat transfer performance and efficiency of the boiler. Theoretical models were used to optimize the performance of the boiler within design limit for a cargo vessel of 25,000 tonnes. MATLAB text code was used to analyze and optimize the parameters of the efficiency of the boiler by varying mass of fuel consumed, feed water temperature and calorific values of fuel. The design modeling shown that at 2170^{o}F furnace exit gas temperature and heat absorption rate of 79500Btu/ft hr, the performance of the boiler is optimum. The convective heat transfer coefficient and radiative heat coefficient show different trend with increase in Reynolds number. The result shows that the efficiency was optimized from 82% to 91%. That is the efficiency of a boiler is inversely proportional to the mass of fuel consumed per kWh. To optimize the boiler, design consideration was made to fuel consumption; furnace exit gas temperature, heat transfer capacity, heat absorption rate and steam parameters. Analysis has shown that at smaller calorific values, there is a significant change in the efficiency of the boiler, but as the value increased, the variation in the efficiency of the boiler reduces. Therefore, in the selection of boilers, adequate considerations should be given to boiler parameters that affect the performance of the boiler and they should be combined to ensure a maximum efficiency for boilers.

KEYWORDS: Boiler, performance, efficiency, design, furnace exit gas temperature, heat transfer.

1. INTRODUCTION

Onboard vessels, steam is required to power several automated and manual systems. There several means of generating steam. Steam is required for the heating of cargo and cabin, to generate distilled water and even to power the vessel when the prime mover is a steam turbine. The best used marine boiler in ships is the scotch marine boiler. The general layout is that of a squat horizontal cylinder. One or more large cylindrical furnaces are in the lower part of the boiler shell. Above this a large number of small-diameter fire tubes. Gases and smoke from the furnace pass to the back of the boiler, and then return through the small tubes and up and out of the chimney. The ends of these multiple tubes are capped by a smoke box, outside the boiler shell.

The scotch boiler is a fire-tube boiler, in that hot flue gases pass through tubes set within a tank of water. As such, it is a descendant of the earlier Lancashire boiler and like the Lancashire, it uses multiple separate furnaces to give greater heating area for a given furnace capacity. Several researches have been made on the optimization of the marine boiler. Others have been made on the design of these boilers which probably altered it physical configuration. In this study, optimization of the marine boiler will be centered on the process which will involve modeling, assisted by the use of the MATLAB software. This study will however not bring into consideration the fabrication of the marine boiler except for reference purposes.

The steam boiler technology is over 200years old and constitutes a complicated multivariable nonlinear process. Most marine steam boilers are controlled by proportional–integral–derivative (PID). This process exist either in single, double or triple element control mechanism, (Pederson et al., 2003). In single element control, the feedback comes from the water level only while in double element and triple element control; there is an addition of the feed forward action from the measured steam to the feedback law, and to the feedback in a separate loop. For small marine boiler both the water level and pressure can be controlled by hysteresis controller supplying an on/off control signal to the fuel valve or feed water pump rather than a continuous control signals. The tubing arrangement form heat exchangers. The performance of the heating element depends on the heat transfer rate and intensity (Nitonye and Ogbonnaya, 2015).

(Mortensen et al., 1998) presented a gain scheduled linear quadratic Gaussian (LQG) regulator, designed to improve load based capacity of a once through boiler. (Kim and Choi,

2005) developed a gain scheduled H_∞ controller for control steam pressure and temperature toward performance optimization. (Maciejowski, 2001) provide a generalized predictive control, which he applied for the super heater temperature modulation. (Lee et al., 2002) developed a constrained receding horizon algorithm which was applied to a nonlinear boiler-turbine model for performance improvement. (Kothare et al., 2000), applied similar algorithm to water level control in the steam generator in a nuclear power plant for optimum steam generation. (Adumene and Lebele-Alawa, 2015) presented a model for performance optimization of a waste heat recovery boiler (HRSG). Their analysis revealed that steam generation increased by about 19.29% when the waste heat flow increases by 80kg/s. It therefore proved that the rate of steam generation is dependence on the amount of heat in the waste gas.

1.1 Boiler Modeling and Design

(Lyung, 1999) developed a linear parametric model. This model entails a parametric lumped that reflect the plant dynamics, system behavior and measurements. The main challenges faced in modeling the boiler dynamics was caused by the distribution of steam below the water surface. This steam introduces a phenomenon called shrink-and-swell on the water level. This is seen as a non-minimum phase zero in the response from steam flow, feed water flow and fuel flow to the water level. (Kothare et al., 2000) also present a collection of linear models in which a non-minimum phase zero is easily inserted. (SØrensen et al., 2004) also developed a model for the waste heat recovery boiler for performance optimization.

1.2 Controller Design and Predictive Control Modeling

In marine boiler, multiple input and multiple output processes are utilized. The controllers in such boiler are often implemented in a control hierarchy differentiated by necessitating the frequency of the controller and the complexity of the tasks. The robust controller system addresses model uncertainty directly in the controller design and allows for designing controllers that stabilize a chosen plant. Tools such as linear matrix inequalities (Boyd and Barratt, 1991) and semi-definite programming allows for complex robust controller designs, and offers methods for multi objective analysis. (Aström and Wittenmark, 1989) present an auto –tuning controller and adaptive controller strategies for marine boiler plant.

Predictive control model is control algorithms that explicitly make use of a process model to predict future response. At each controller update, the predictions are based on current measurements gathered from the plant. These models are used to evaluate the performance function and an optimization problem in the plant. The optimization problem arising in linear predictive control model using a quadratic performance function is a convex quadratic programming problem. It is possible to exploit the structure of the predictive control model to setup efficient solutions to the optimization problem. Predictive control model are multi-parametric programming model, and it is necessary to reduce the complexity involved. This is done by introducing input blocking (Cagienard, et al., 2007), which refers to the approach of constraining the input sequence to change at certain time throughout the prediction horizon. They also suggested another method for reducing the online computational load. A multiplexed predictive control model scheme is introduced to analyze each subsystem sequentially.

In this research we will analyse a predictive performance model using linear based tools, and special kind of nonlinear models to evaluate the boiler performance, efficiency and heat transfer characteristic. We will analyse the model in MATLAB environment and ascertain performance optimization of the plant.

2. MATERIAL AND METHODS

Boiler efficiency may be indicated by combustion efficiency which is the burner's ability to burn fuel measured by unburned fuel and excess air in the exhaust; thermal efficiency which indicates the heat exchangers effectiveness to transfer heat from the combustion process to the water or steam in the boiler, exclusive radiation and convection losses, and fuel to fluid efficiency which indicate the overall efficiency of the boiler inclusive thermal efficiency of the heat exchanger, radiation and convection losses-output divided by input. The performance of a steam boiler is also measured in terms of its "evaporated capacity". Evaporative capacity of a boiler is the amount of water evaporated or steam produced in kg/h. It may also be expressed in kg/kg of fuel burnt (Rajput, 2011).

2.1 Theoretical Formulations

2.1.1 Equivalent Evaporation (E)

It is the amount of water evaporated from feed water at 100°C and formed into dry and saturated steam of 100°C at normal atmospheric pressure.

$$E = \frac{\text{Total heat required to evaporate feed water}}{2257} \qquad 2.1\,a$$

$$E = \frac{m_e(h - h_{f1})}{2257} \left(\frac{KJ}{kg}\right) \qquad 2.1b$$

where

m_e = Mass of water actually evaporated or steam produced in kg/h or kg/kg of fuel burnt.

h = Enthalpy or total heat of steam in (KJ/kg) of steam correspond to a working pressure (from steam table)

h_{f1} = Enthalpy or sensible heat of feed water in KJ/kg of steam correspond to t_1°C (from steam table).

t_1 = Temperature of feed water in °C

2.1.2 Boiler Efficiency

It is defined as ratio of heat actually used in producing the steam to the heat supplied by the fuel.

$$\eta\ \eta_b = \frac{\text{Heat actually used in producing steam}}{\text{Heat supplied by fuel}} \qquad 2.2a$$

$$\eta\ \eta_b = \frac{m_e(h - h_{f1})}{C} = \frac{m_s(h - h_{f1})}{m_f \times C} \qquad 2.2b$$

where C = Calorific value of fuel in $\frac{KJ}{kg}$ of fuel, $m_e = \frac{m_s}{m_f}$

m_s = Total mass of water evaporated to steam in kg.

m_f = Mass of fuel used in kg.

2.1.3 Combustion Heat Q_C

$$Q_C = 1713 S_C F_E F_A \left\{ \left(\frac{T_E}{1000}\right)^4 - \left(\frac{T_C}{1000}\right)^4 \right\} + U S_w (T_E - T_C) \qquad 2.3$$

where

U = Convection heat transfer coefficient, T_C = Furnace surface temperature,

T_E = Furnace exit temperature, T_F = Effective flame radiating temperature

S_W = Convection surface area, S_C = Radiant heat absorbing surface

F_A = Arrangement factor, F_E = Emissivity factor

2.1.4 Furnace Heat Absorption Rate

$$\left[\frac{Q_C}{S_C}\right]_1 = 1713 F_E F_A \left\{ \left(\frac{T_E}{1000}\right)^2 \times \left(\frac{T_C}{1000}\right)^2 - 1 \right\} \qquad 2.4a$$

$$\left[\frac{Q_C}{S_C}\right]_2 = \frac{M_f(R-1)}{S_C}\ (q_{TA} - q_{TE}) \qquad 2.4b$$

2.1.5 Adiabatic Sensible Heat Content q_{TA}

$$q_{TA} = \frac{LHV + Q_f + (t_a - t_o)C_pR}{R+1} \qquad 2.5$$

where

LHV = Lower heating value of fuel, t_a = Air temperature to burner

t_o = Ambient temperature, C_p = Average gas constant of the gas,

R = air to fuel ratio

3. RESULTS AND DISCUSSION

In this research data were obtained from a boiler design manual and operational log sheet. The design and operational parameters considered for analysis and optimization are the adiabatic sensible heat, furnace exit gas temperature, surface effectiveness and the efficiency. Simulation of the models was done in MATLAB environment. The optimization in this sense will be based on improving the performance and efficiency of the boiler.

The results shown in Tables 3.2- 3.5 and Figures 3.1- 3.3, described the design parameters of the boiler. The furnace gas exit temperatures, furnace heat absorption rate, combustion heat content, heat transfer coefficient, and heating elements formed the major design parameters considered in this research. The steam is produced due to the activity of the boiler in the turbine’s schematic network. The result of the design heat transfer capacity, furnace heat absorb rate, combustion heat content are also presented.

Table 3.1 Boiler information (Jackeh, 2013).

Parameter	Estimated Value
Used Steam by the turbine	5.4kg/kWh
Operating Pressure	50bar
Operating Temperature	350^{o}C
Temperature of feed water	150^{o}C
Calorific value of coal	28100kJ/kg
Cost of coal/tone	$280

Table 3.2 Furnace Design Particulars.

	Project Area	Tube Diameter	3.5	Number of rows	Surface effectiveness
Real Wall	153	2	3.5	1	0.95
Front Wall	162	2		1	0.85
Root	140	2	3.5	2	1
Floor	126	2	3.5	2	1
Water Screen	252	2	3.5	2	1
Side Wall	252	2	3.5	2	1

Table 3.3 Heat Content at Various Furnace Exit Gas Temperatures.

Assumed T_E (^oF)	2100	2200	2300	2400	2500
q_{TA} (Btu/Ib)	1069	1069	1069	1069	1069
q_{TE} (Btu/Ib)	590	620	650	680	710
$q_{TA} - q_{TA}$	479	449	419	389	359

Table 3.4 Furnace Heat Absorption Rate at Different Furnace Exit Temperature.

Assumed T_E (^oF)	$[Q_C/S_C]_1$ (Btu/ft hr)	$[Q_C/S_C]_2$ (Btu/ft hr)
2100	75,000	84,000
2200	81,000	78,000
2300	87,000	73,000
2400	94,000	68,000
2500	100,000	63,000

Table 3.5 Result of Heat Transfer Analysis.

Reynolds Number	Convective heat Transfer coefficient h_f (Btu/hr.Ft.F)	Radiative Conductive Coefficient h_r (Btu/hr.Ft.F)
3.326×10^3	5.1827	2.370
3.652×10^3	8.3890	1.178
3.955×10^3	10.4550	1.027
4.139×10^3	16.4269	0.780

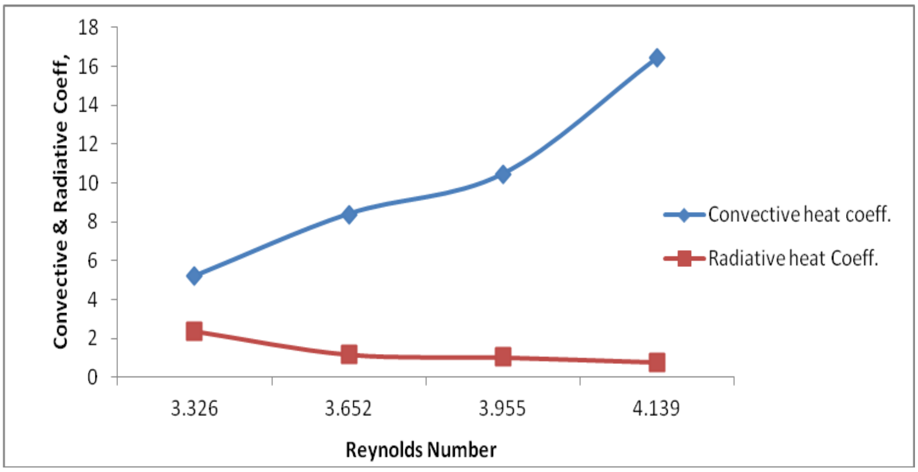

Figure 3.1: Effects of Reynolds Number on Heat Transfer Coefficients

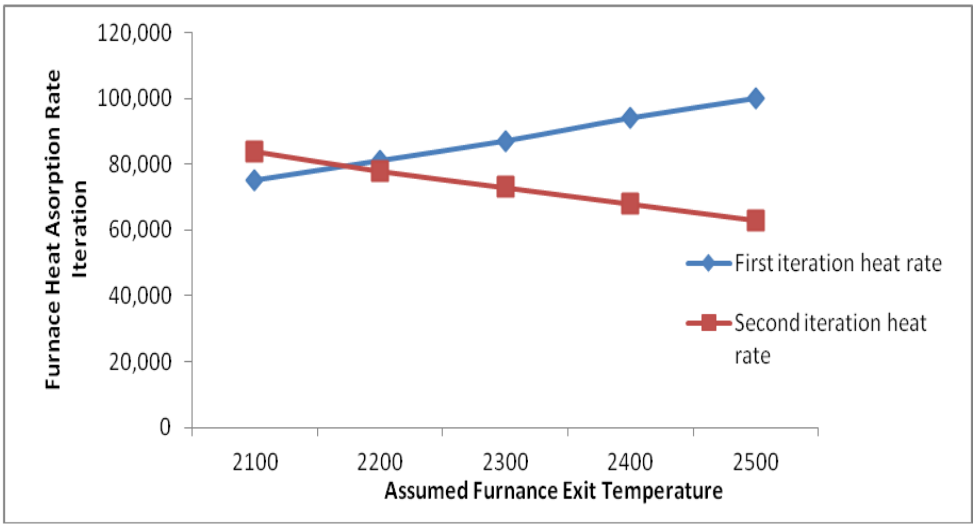

Figure 3.2: Furnace Heat Absorption against Furnace Exit Gas Temperature.

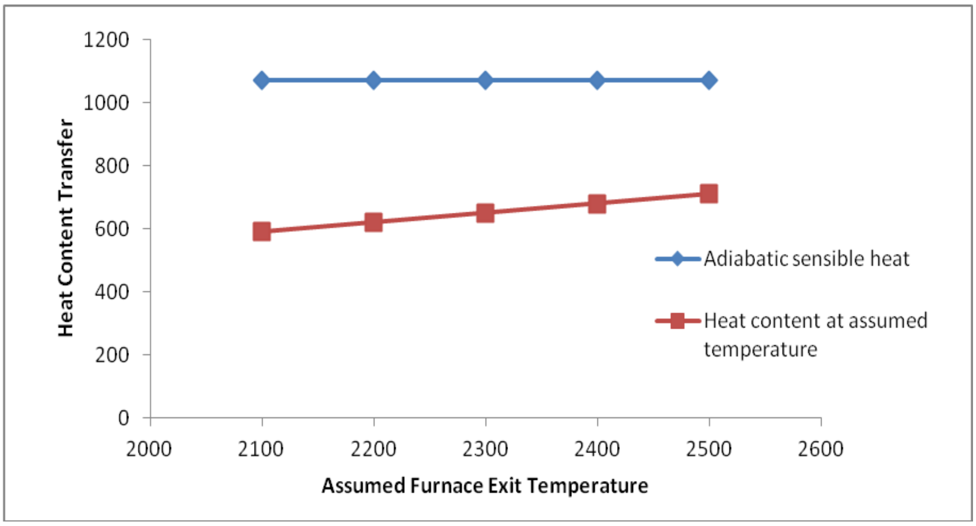

Figure 3.3: Effect of Heat Transfer on Furnace Exit Gas Temperature

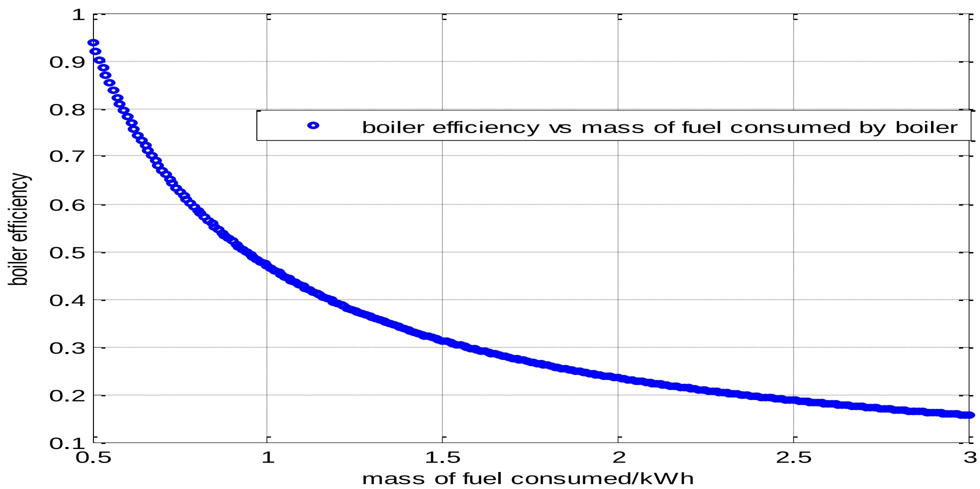

Figure 3.4 Relationship between boiler efficiency and mass of fuel consumption by boiler

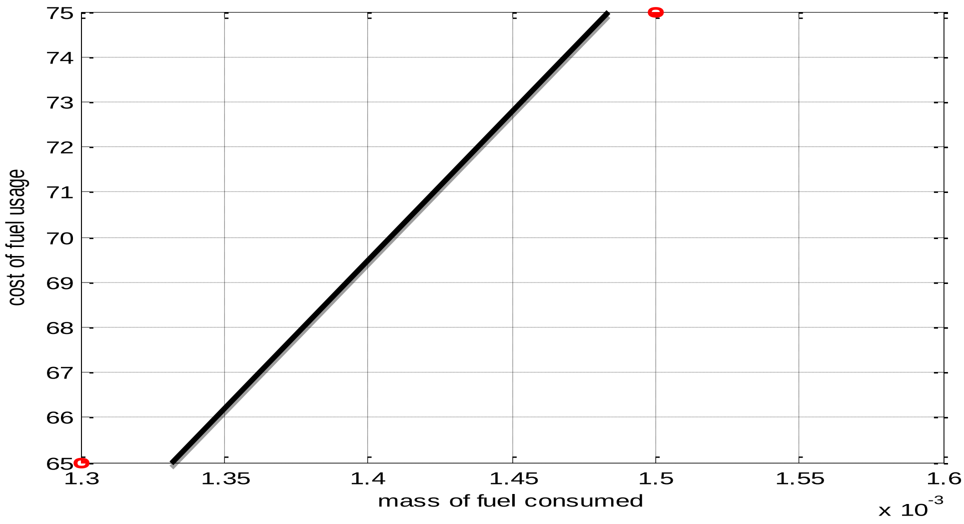

Figure 3.5 Effect of increased mass of fuel consumption on cost of fuel required.

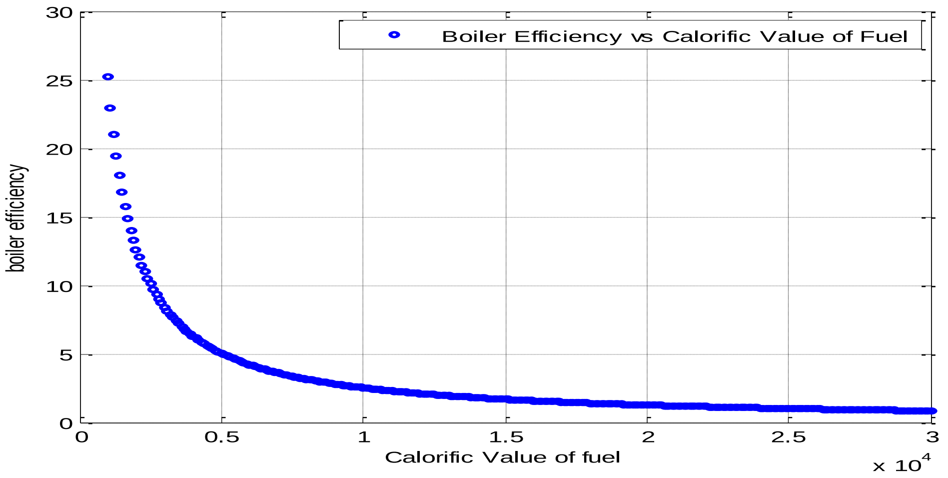

Figure 3.6 Effect of the calorific fuel value on the efficiency of the boiler

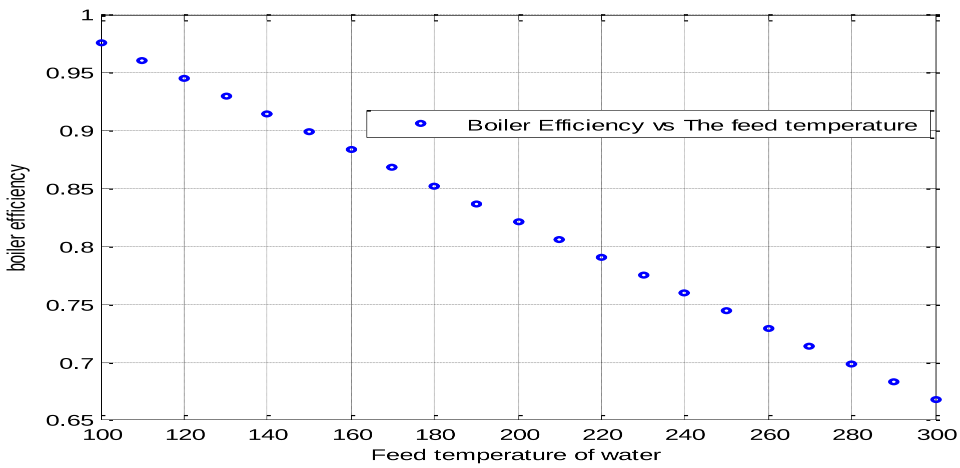

Figure 3.7 Variation of the boiler efficiency with the feed water temperature.

Figure 3.1 shows that for every 1 x 10^3 drop in the Reynolds number, the convective heat transfer coefficients increase by 13.80% and the radiative heat coefficient decreases by 1.96%. Figure 3.2 shows that the point of interception of the two furnace heat absorption rate, gives the actual operating furnace exit gas temperature. This gives the actual design temperature that will optimize the heat transfer to the feed water for steam generation. The lower the exit gas temperature, the greater the heat transfer, and steam generation. Figure 3.3 show the trend of the heat supplied (content) at different furnace exit gas temperature. The result shows that the heat supplied increase due to increase in fuel flow. Although the sensible heating remains constants across the temperatures, there is a gradual increase in the heat content due to temperature rise. For optimum design, the furnace exit gas temperature is maintain at 2170^{o}F at the heat absorption rate of 79500Btu/Ft.hr.

Coal is used as fuel in the boiler to heat up the feed water for intake into the turbine. How much coal is consumed per kWh worked by the turbine is not known from the information presented above. However, this can be calculated using the general formula for boiler efficiency. Result shows that the amount of coal fuel consumed per KWh is about 0.522kg. Figure 3.4 shows an inverse relationship between the boiler efficiency and the mass of fuel consumed per kWh. This implies that a boiler system that consumes much fuel is termed to be inefficient. Therefore to optimize the boiler, it was considered from the design stage on how fuel consumption can be minimized. Apart from the fact that it makes the process inefficient, using more fuel for less work will be expensive. Figure 3.5 shows the effect of excessive fuel mass consumption on the cost of fuel purchase for the plant operation. It is clear that a boiler system that consumes much fuel is definitely not economically viable for ship operation.

Analyses have shown that the boiler efficiency is a function of the Calorific value of the fuel used. The calorific value of fuel differs, however for this analysis, coal is considered as the only source of fuel for the boiler. The Figure 3.6 shows that at smaller values of the calorific fuel value, there is a significant change in the efficiency of the boiler, but as the value increased, the variation in the efficiency of the boiler became lesser. It is also clear that the boiler efficiency is inversely proportional to the calorific fuel value; this implies that, a fuel with a lower calorific fuel value will produce a greater efficiency of the boiler.

It is also important to determine how the optimization of the boiler efficiency can be achieved by controlling the temperature of the feed water, furnace exit gas temperature and the combustion heat generated. It is important to understand this because the temperature of the system is an important parameter. The feed water temperature affects the enthalpy of the water and this can have a tremendous effect on the efficiency of the boiler. Also the temperature gradient between the feed water and the heat source determine the effectiveness of the heat transfer. Heat energy as a result of combustion gases is a function the fuel quality and flow, as well as the calorific value of the fuel.

Figure 3.7 shows the relationship between the boiler efficiency and the temperature of the feed water. This shows an inverse relationship between the boiler efficiency and the feed temperature of the water. This is true because, the efficiency of a boiler is measured by the amount of heat energy it can impact to the feed water to produce a superheated steam. When the feed water is already at high temperature, it means that the energy from the boiler to the water is lesser to produce the required steam. A boiler is said to be efficient when it can impact as much energy to produce a steam of the required quality. Therefore to optimize or boost the efficiency of a system, feed water with a lower temperature should be used, minimum furnace exit gas temperature, and high steam flow and temperature at constant operating conditions. Considering the data presented above, the efficiency of the system is about 82%. But with a reduction in the feed water temperature from 150^{o}C to 100^{o}C, the efficiency of the boiler increased from 82% to about 91%.

4. CONCLUSION

The design modeling and optimization of a boiler was carried out in this research. It was revealed that for the optimum design, the furnace exit gas temperature should be maintained at 2170^{o}F with the absorption rate of 79,500Btu/ft hr. The performance analysis show the boiler's efficiency can be optimized from 81% to 92% at minimum feed water temperature and furnace exit gas temperature. This simultaneously increased steam flow and heat transfer capacity. It further revealed that the performance depends on the fuel flow and consumption, calorific value of the fuel and feed water enthalpy

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APPENDIX A

```
%A PROGRAM TO DETERMINE THE MASS CONSUMPTION OF A FUEL BY A BOILER IN A
%TURBINE SCHEMMATIC
% To achieve this it is important to determine the enthalpies using the
% process conditions:
Tsup=350;
Tw=150;
%Using the steam table, at P=50bars and T=350oC:
hsup=3068.4;
hf1=1*4.18*(Tw-0);
% The Calorific value of coal,C has a value:
C=28100;
% The observed boiler efficiency, meu, is given as:
meu=0.82; % In others words 81%.
% The mass os steam used in kJ/kg, ms ,has a value of:
ms=5.4;
% from the efficiency model, the mass of fuel consumption can be written as:
mf=ms*(hsup-hf1)/(meu*C)
```

```
%A PROGRAM TO DETERMINE THE RELATIONSHIP BETWEEN BOILER EFFCIENCY AND MASS
%OF FUEL CONSUMPTION
% To achieve this it is important to determine the enthalpies using the
% process conditions:
Tsup=350;
Tw=150;
%Using the steam table, at P=50bars and T=350oC:
hsup=3068.4;
hf1=1*4.18*(Tw-0);
% The Calorific value of coal,C has a value:
C=28100;
% The observed boiler efficiency, meu, is given as:
ms=5.4;
```

```
for mf=0.5:0.01:3
% The efficiency is given as:
meu=(ms*(hsup-hf1))/(mf*C)
plot(mf,meu,'bo','linewidth',2,'markersize',4)
grid
xlabel('mass of fuel consumed/kWh')
ylabel('boiler efficiency')
legend('boiler efficiency vs mass of fuel consumed by boiler')
holdon
end
holdof

% COST ANALYSIS OF CONSUMED MASS OF FUEL
% To achieve this it is important to know the cost of the fuel involved.
% here we are considering coal.
%Cost of coal/tonne is given as, costc
costc1=50000;
% The mass consumption is required for this analysis, mcon1
mcon1=1.3;%kg/kWh
%Intonne/kWh
mcon1=(1.3/1000); %1000kg=1tonne
% The cost of fuel, cof, is given as:
cof1= mcon1*costc1
plot(mcon1,cof1,'ro--','linewidth',2,'markersize',5)
grid
xlabel('mass of fuel consumed')
ylabel('cost of fuel usage')
holdon
%Using a different mfuel mass consumption
mcon2=1.5;%kg/kWh
mcon2=(1.5/1000); %1000kg=1tonne
% The cost of fuel for the new mass consumption
cof2=mcon2*costc1
plot(mcon2,cof2,'ro--','linewidth',2,'markersize',5)
```

```
holdoff

%A PROGRAM TO DETERMINE THE RELATIONSHIP BETWEEN BOILER
EFFCIENCY AND
%FEED WATER TEMPERATURE
% To achieve this it is important to determine the enthalpies using the
% process conditions:
Tsup=350;
%Using the steam table, at P=50bars and T=350oC:
hsup=3068.4;
% The amount of steam used per kWh, ms
ms=5.4;
% The estimated fuel consumption value per kWh
mf=0.522;
% The calorific fuel value of the coal is given as, C
C=28100;
% For different values of the fed water temperature, what will be the
% corresponding efficiency recorded by the system. We can use the for
% statement to actualize this.
for Tw=100:10:300
% The water enthalpy is calculated from
hf1=1*4.18*(Tw-0);
% The efficiency is given as:
meu=(ms*(hsup-hf1))/(mf*C)
plot(Tw,meu,'bo','linewidth',2,'markersize',4)
grid
xlabel('Feed temperature of water')
ylabel('boiler efficiency')
legend('Boiler Efficiency vs The feed temperature')
holdon
end
holdoff
```