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PERFORMANCE EVALUATION OF KADUNA REFINING AND PETROCHEMICAL COMPANY BOILER FURNACE USING EXERGY ANALYSIS

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Abstract
This study investigated the causes of operational inefficiencies and losses resulting in the decline of the expected output of the KRPC steam boiler furnace 1. The Exergy analysis was used to investigate the causes and locations of irresistibility and losses in the steam boiler furnace 1 which was experiencing frequent failures leading to the decline of expected output of the boiler facility. The data for the analysis were both base parameters and measured values kept in the control room operational log book for one year and inputted in the Aspen Hysys 8.4 software. The furnace operating parameters collected were, temperature, pressure, and mass flow rate from the input and output streams. The input streams were preheated water, air, and fuel, while the output streams were steam and flue gases. The identified values of the parameters temperature, pressure, and mass flow rate, and their streams were inputted into the Aspen Hysys model for simulation. The Aspen Hysys spreadsheet was used to compute the effects of; flue gasses temperature on exergy destruction and exergy efficiency, fuel oil pressure on exergy destruction and exergy efficiency, fuel oil sulfur content on exergy destruction and exergy efficiency, nitrogen content on, exergy destruction and exergy efficiency and the oxygen content on exergy destruction and exergy efficiency respectively. These processes showed high exergy destruction, of 445.4 kJ/kg in the boiler finance 1 which could be due to age, inadequate maintenance, or refractory breakdown. Other results showed that the energy and exergy efficiencies were 71.54% and 6.396% respectively. Physically, this discrepancy implies that although 71.54% of the input energy is transferred to the generated steam, the energy is degraded as it is transferred. The results of this study are one of the reasons for the poor performance of the KRPC PPU. It serves as a guide for formulation of maintenance policy of KRPC which can help to improve the equipment performance.

Keywords: Performance Evaluation; Refining; Petrochemical; Boiler furnace; Exergy Analysis; Flue gases.

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1.0 Introduction

Exergy analysis according to Celenk *et al*, (2013) is, a thermodynamic tool for assessing and improving the efficiency of processes, equipment and increasing environmental and economic performance. Exergy is a measure of the quality of energy and is defined as the maximum theoretical work that can be obtained from a quantity of energy or matter by bringing this energy or matter into equilibrium with a reference environment (Craig, 2014). Exergy serves a powerful technique used for, the assessment and for improvement of the performance of energy systems through the laws of thermodynamics.

The main purpose of exergy analysis is to identify where energy is destroyed. This destruction of energy in a process is proportional to the entropy generation in it which, accounts for the inefficiencies due to irreversibility. The first law of thermodynamics deals with the amount of energy of various forms transferred between the system and its surroundings and with the changes in the energy stored in the system. It treats work and heat interactions as equivalent forms of energy in transit and offers no indication about possibility of a spontaneous process proceeding in a certain direction. The first law does not restrict the direction of a process, but satisfying the first law does not ensure that the process can actually occur. This inadequacy of the first law to identify whether a process can take place is remedied by the second law of thermodynamics (Pal *et al.*, 2012). The submissions of the scholars above explain in clear terms the reason for the adoption of the second law of thermodynamics as a critical technique to determine the performance of the KRPC steam furnace which at a point seems not to have been performing up to its optimum installed capacity in the assessment of this researcher. The use of exergy analysis is actually to help identify the optimum capacity at which the furnace can perform.

Exergy analysis helps in identifying the process of irreversibility leading to losses in useful work potential and thus pinpointing the areas where improvement can be sought. Exergy analysis provides a method of evaluating the maximum work extractable from a substance relative to a reference state- a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure, P_o and a temperature, $T_{o.}$(i.e., dead state) (Mahamud *et al*, 2013). To quantify and pinpoint the origins of the irreversibilities produced in the boiler, Gulhane and Thakur (2013) conducted an analysis of a cogeneration system. Exergy study showed that for the 1.1 MW load, the boiler's exergy destruction rate was almost 83.35 percent compared to the system as a whole. The irreversibilities produced by a 30 MW boiler were demonstrated by Hada and Shah (2012). The boiler was found to have the highest exergy destruction, and its exergy efficiency was found to be 33.73%.A 500 MW coal-fired boiler's energy and efficiency analysis was provided by Pattanayak and Ayyagari (2014). The locations and levels of exergy destruction were determined for the boiler and the findings revealed that exergy destruction is highest at the combustor followed by the heat exchanger. The boiler's energy efficiency was 85.54% for design circumstances, while for exergy it was 41.81%. Yuehong et al, (2010) performed work on exergetic efficiency optimization for an irreversible heat pump working on reversed Brayton cycle. The authors stated that the expression of the exegetic efficiency was deduced based on the theoretical model of the heat pump. Nkoi et al (2023) analyzed energy and exergy of the steam generation unit with capacity of 120 tonnes per hour of Petrochemical Olefins Plant located in the Niger Delta area of Nigeria. Energy and exergy efficiencies and losses were evaluated by equations. The results showed that highest energy loss and exergy destruction in the combustion chamber were 10.734MW and 17.256MW representing 60.40% and 63.52% of total energy loss and exergy destruction in the plant respectively.

Additionally, efficiencies of the energy and exergy of the combustion chamber were found to be 89.64% and 66.77% respectively.

One of the vital requirements for refining and petrochemical plants is the energy or 'Internal-fuel' requiredfor carrying out the various operations such as distillations, extractions, reactions, absorptions and steam generation etc. In these operations energy is consumed as direct fuel in process heaters and as in-direct fuel in process equipment, steam generation, electric power generation and in utilities such as compressed air, cooling and service water. However, in Nigerian refineries, due to unreliability of public power and utilities, refining and petrochemical plants are designed to generate on-site all their energy requirements to guarantee continuous supply. This requirement, calls for energy efficient conversion system. The Power Plant and Utilities (PPU) Department of the Kaduna Refining and Petrochemical Company Limited (KRPC) for instance, generates steam and electric power and other utilities required for continuous operation of the process plants and other facilities in the refining and petrochemical plants. Particularly for its energy needs, the KRPC uses steam boilers to produce steam for power generation and for its process units. But in recent times the steam and electric power generating facilities have not been operating optimally due to frequent failures. This has led to interruptions in smooth and sustainable operation of the process plants causing petroleum products scarcity and subsequent long queues in towns and cities of the country. Ideally, the performance requirement of a typical industrial steam boiler is to produce steam at the right pressure and temperature, right quantity and quality for the process and power generation in the most cost-effective manner. But with the poor performance of PPU, the facilities have failed to meet the need for which they were established. This situation therefore, needs to be addressed to improve the performance of the facilities. To do this, it is necessary to determine the cause(s) of the equipment/components failures and locations where they occur.

Against the backdrop of the above, the question that may readily come to mind is what is the cause of the degradation of the energy quality of the KRPC steam boiler plant? What is the exergetic efficiency of the KRPC boiler? These and others are the pertinent questions that this study intends to investigate.

2.0 Plant Description

The Kaduna Refining and Petrochemical Company Limited (KRPC), Kaduna was commissioned in 1980 to meet the rising and growing demand for refined petroleum products. The refinery like other process industries uses energy in various forms for its operations. However, in Nigeria all refinery and petrochemical plants by design generate on-site, all their energy requirements in the form of fuel gas, fuel oil, steam, electricity and the utilities they consume for their normal operations. It is on this basis that the steam power plant of KRPC was established. The KRPC which comprises of a refinery and petrochemical plants was established as the third refinery in Nigeria coming after Port Harcourt and Warri refineries.

The Refinery consists of a Fuels Plant and a Lubes Plant. While the Fuels Plant processes 60,000 barrels per stream day (BPSD) of a mixture of local Chevron Escravos Light crude oil and Ughelli Quality Control (UGCC) crude oil in the ratio of 50:50 into different distillates-Naphtha, Kerosene, Light Gas Oil (LGO) and Heavy Gas Oil (HGO), the Lubes Plant processes 50,000 barrels per stream day (BPSD) of imported crude oil (Arabian light crude). In December 1986, the design capacity of the fuels plant of the refinery was increased from 50,000 BPSD to 60, 000 BPSD after de-bottlenecking, bringing the total refinery installed capacity to 110, 000 BPSD of crude oils with a stream factor of 330 days per year.

The 330 stream days is used to establish unit capacities and refinery materials balance except for some specific units such as Asphalt Blowing Unit (ABU). In March 1988, the 30, 000 metric tons per year Linear Alkyl Benzene Plant (LAB) was commissioned. The Linear Alkyl Benzene Plant and Refinery was subsequently merged to form the Kaduna Refining and Petrochemical Company Limited (KRPC). The Linear Alkyl Benzene plant takes intermediates by-products from the two plants of the refinery to produce Linear Alkyl Benzene (LAB), mono aromatics (BTX), and Raffinates-like de-paraffinated Kerosene, Benzene drag, and heavy alkylates. Chiyoda Engineering Company Ltd of Japan built KRPC.

The steam and power generating facilities of KRPC have five boilers and four turbo generators. Each boiler has a design capacity of 120 tons/hr. The total installed capacity is 600 tons/hr with the operating pressure and temperature of 46kg/cm^{2}G and 412^{0}C.

The steam produced is used to generate 56MW of electricity (14MW each from the four turbo-generators). Part of the steam produced is let down into three pressure levels of high (46kg/cm^2 and 412^{0}C), medium (16.5kg/cm^{2}and 275^{0}C) and low (3.1kg/cm^{2}and 54.3^{0}C) respectively to drive steam turbine driven pumps, compressor, blowers, fans, mixers etc., and for process units operation. The steam and power generating system consists of the following equipment:

- Furnace or wind box to combust/burn the fuel
- Steam generator or boiler to contain/hold water. The heat of combustion in the furnace is used to convert water in the boiler drum into steam at suitable pressure and temperature.
- Superheaters (primary and secondary) to superheat and dry the steam before admitting it into the steam turbine.
- Economizer to utilize heat from flue gases exiting or leaving the superheaters to pre-heat the boiler feed water before it goes to the boiler drum.
- Soot blowers to clean the boiler heating surfaces of deposits (carbonsoot, scales, etc) that might adhere to them.
- Ljungstrom air heater to pre-heat combustion air before it goes to the furnace burners for combustion. The Ljungstrom is a piece of equipment which improves the efficient operation of the boiler. It removes a large portion of heat contained in the combustion products (smokes) and passes it into the comb rent air. In this way, the thermal yield of the boiler is increased. The Ljungstrom is constructed in such a way that it does not lower excessively the temperature of the smokes which go up the chimney. If the temperature of the smoke in the chimney were too low, the conservation of the materials in contact with the smoke flow could be endangered. The smoke of anhydrides could condense, and sulfur dioxide and the highly corrosive sulphuric acid could be formed.
- The main steam turbine uses the heat energy of steam to do work
- Piping system to convey water and steam.

The different Systems and components of the KRPC steam boiler plant

The different systems and components of KRPC steam boiler plant are:

- Feed water purification/treatment plant
- High-pressure boiler
- De-aerator, high-pressure heaters, economizer, super-heater, soot blowers and air pre-heater
- Draught system

- Fuel oil and gas system
- Condenser and cooling tower
- Pumping system
- Steam turbine and turbo-generator

3.0 Materials and Methods

The materials used for this study were: -

1. Process Flow Diagrams for KRPC Steam Boiler.
2. Operating data.
3. Aspen Hysys: Version One -8.4

3.1 Method of data collection

The data used are base parameters of the steam generating facilities which were collected from log books, and data banks in the data files kept in the PPU department control room for one year. The operating parameters retrieved were: -

- Temperatures
- Pressures
- Mass Flow rates

3.1.1 Experimental proceeding

The process parameters of KRPC steam boiler furnace 1 of temperature, pressure, mass flow rate, and composition of the fuel entering furnace 1 were collected and tabulated as shown in Table 1 below. These parameters were needed to simulate the KRPC boiler furnace 1, and determine the exergetic destruction efficiency and energy efficiencies of the KRPC boiler furnace 1. The process flow diagram in Figure 1depicts the process inputs analyzed. Relevant graphs showing the effects of operating parameters on exergy efficiency and exergy destruction were plotted.

The following assumptions were made.

- The process flow was in a steady state
- Kinetic and potential energy effects were negligible
- Pressure drops in the pipelines were negligible
- Components such as fuel oil and gas pumps, boiler stop valves, forced and

  Induced draught fans and cooling water were neglected in the analysis.

- The average surrounding temperature was 35^0

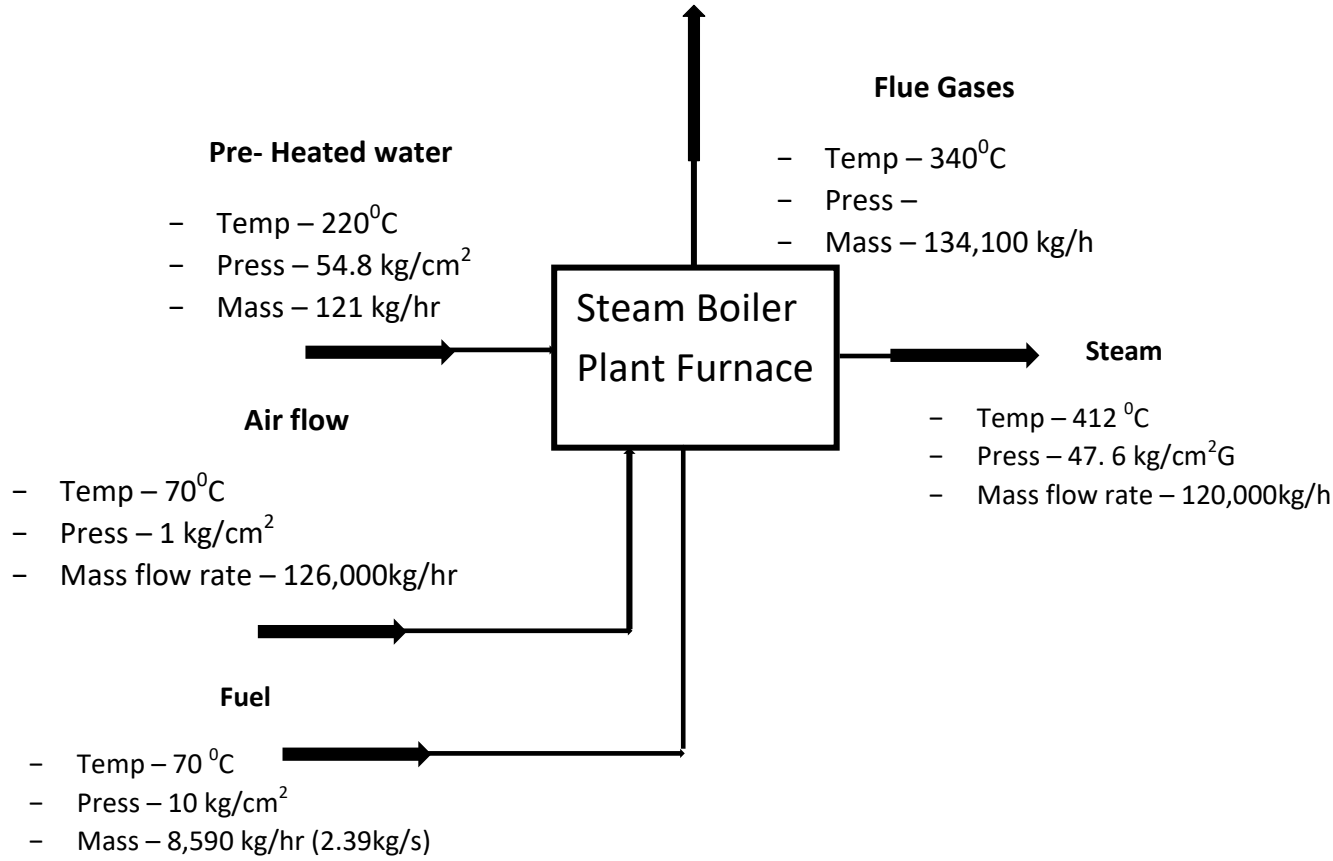


Figure 1: Process Flow Diagram of KRPC Steam Boiler Furnace used in Aspen Hysys

Table 1: Inlet operating parameters of the KRPC Steam Boiler Furnace collected from KRPC Power Plant Utilities and Offsite unit

Process Parameters	**Air**	**Fuel**	**Pre-heated Water**
Temperature (^{o}C)	31	70	220
Pressure (kg/cm^2)	1	14	
Flowrate (kg/hr)	138000	8590	
Compositions			
Water	0	0	0.98
Oxygen	0.21	0	0.02
Nitrogen	0.79	0	0
Propane	0	0.1	0
Propene	0	0.11	0
Cyclobutane	0	0.24	0
i-butane	0	0.32	0
n-butane	0	0.13	0
C5+	0	0.10	0

3. 1.2 Simulation procedure of KRPC steam boiler furnace 1

The simulation of the KRPC boiler furnace was carried out in Aspen Hysys. The following steps were carried out in the simulation of KRPC boiler furnace 1 in the Aspen Hysys 8.4 environment:

3.2.1Aspen Hysys operating environment (figure 2)

3.2.2Component Selection in Aspen Hysys 8.4 Environment (figure 3)

3.2.3Aspen Hysys thermodynamic properties selection (figure 4)

3.2.4Data collected from the KRPC operating log book and inputted in operating condition of Aspen Hysys Boiler Furnace Model (figure 5)

3.2.5Connection of KRPC steam boiler furnace (figure 6)

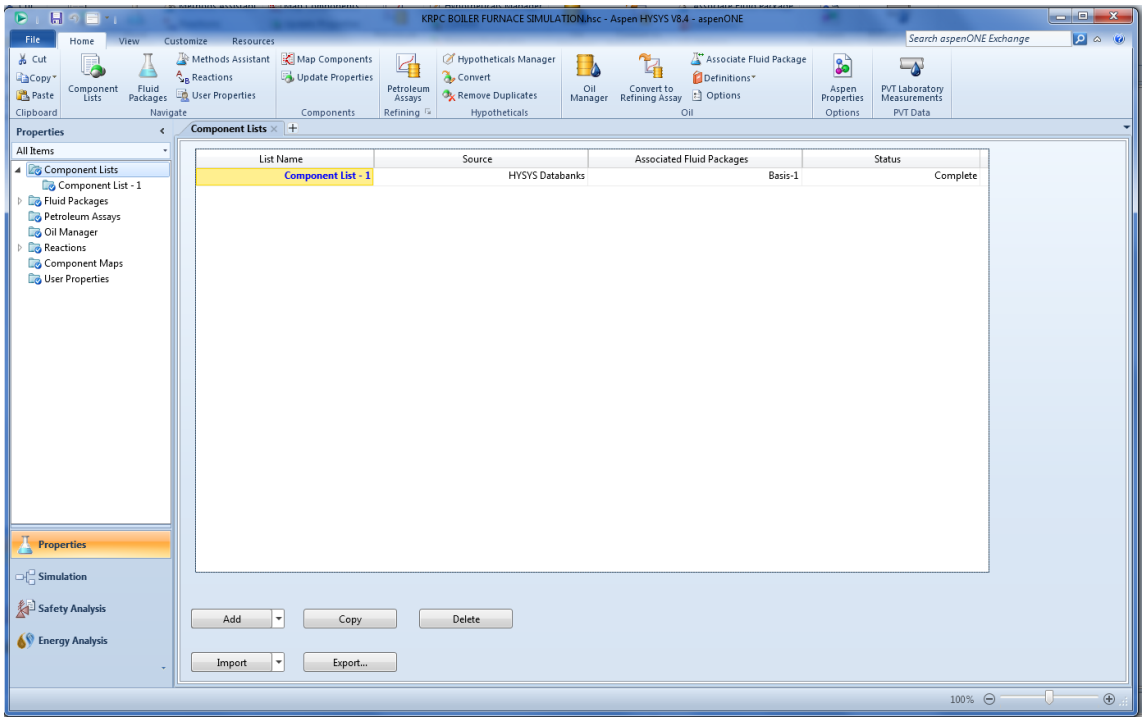


Figure 2: Aspen Hysys simulation environment

3.1.3 Aspen Hysys component selection

This was followed by inputting of the process fluid into the component selection environment of the Aspen Hysys 8.4 software as shown in Figure 3.

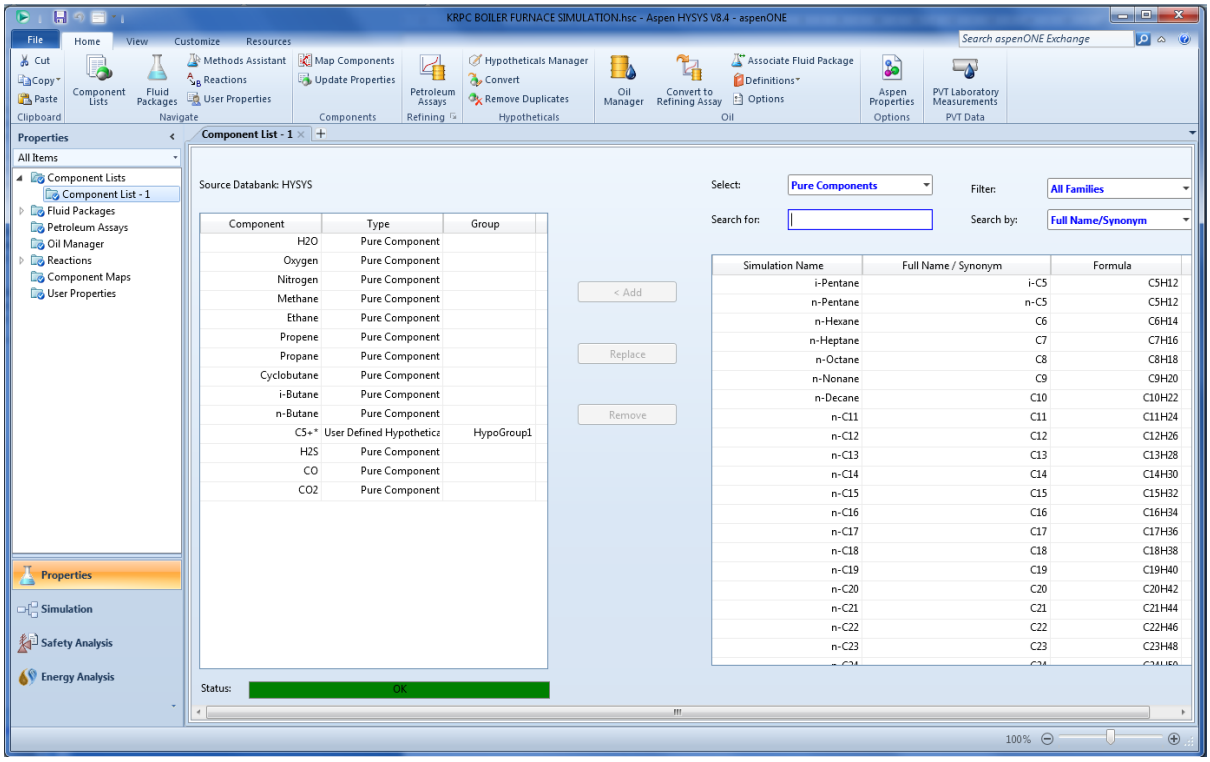


Figure 3: Component Selection in Aspen Hysys 8.4 Environment

3.1.4 Aspen Hysys Thermodynamic Properties Selection

The next step carried out was the selection of Peng Robinson as a suitable thermodynamic fluid for handling of hydrocarbon component of air, water used for steam generation, and oxygen and nitrogen components of air.

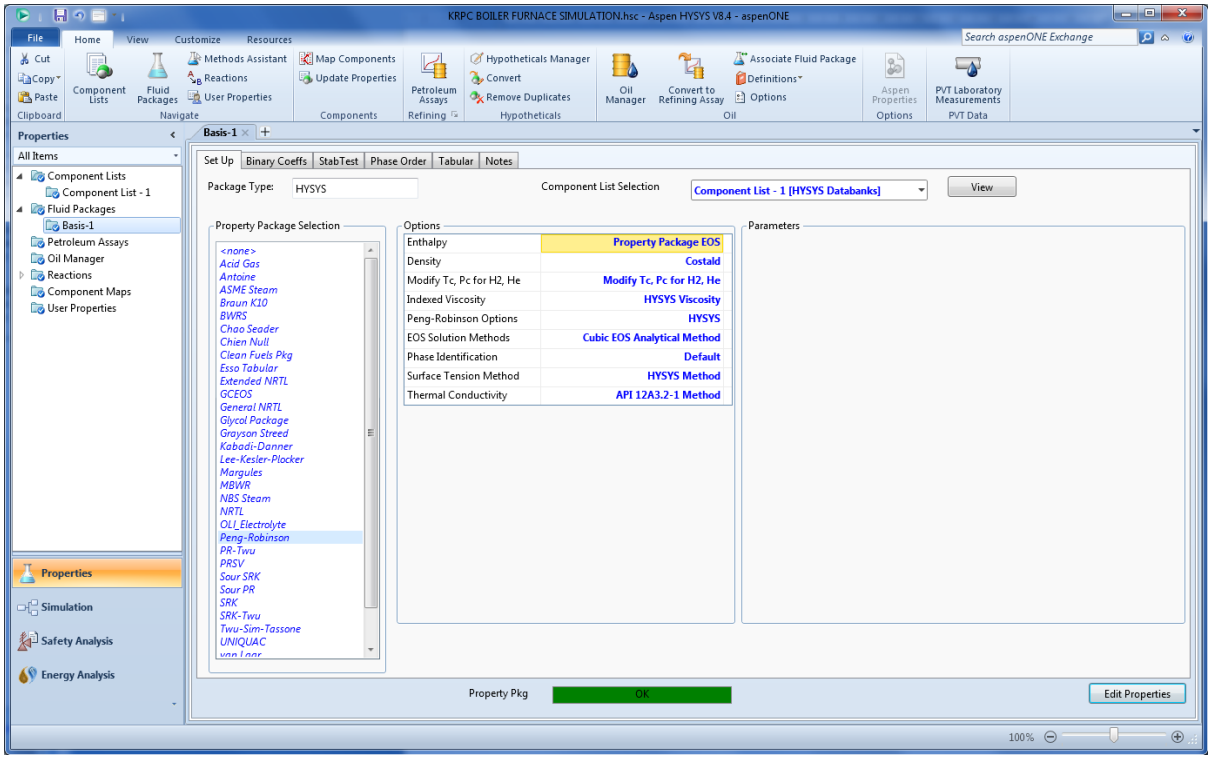


Figure 4: Thermodynamic property Selection in aspen hysys environment

3.1.5 Data collected from the KRPC operating log book and inputted in operating condition of Aspen Hysys boiler furnace 1 model

The following inlet operating parameters of the streams; pre-heated water, pre-heated air, and fuel of the KRPC steam boiler furnace 1 were collected and modeled in Aspen Hysys as show in figure 5 below.

Flowsheet Main - Solver Active | Workbook

Material Streams | Compositions | Energy Streams | Unit Ops

Name	Air	Fuel	Steam	Flue Gases	Pre-Heated W...	** New **
Vapour Fraction	1.0000	1.0000	0.4254	1.0000	0.0654	
Temperature [C]	25.00	45.00	98.61	452.5	90.00	
Pressure [kPa]	101.3	395.5	101.3	101.3	101.3	
Molar Flow [kgmole/h]	100.0	110.0	100.0	225.8	100.0	
Mass Flow [kg/h]	2885	4465	1825	7350	1825	
Liquid Volume Flow [m3/h]	3.335	8.879	1.832	12.32	1.832	
Heat Flow [kJ/h]	-818.3	-7.510e+006	-2.582e+007	-9.055e+006	-2.736e+007	

Figure 5a: Aspen Hysys worksheet showing the inlet parameters of preheated water, pre heated air and fuel.

Flowsheet Main - Solver Active | Workbook

Material Streams | Compositions | Energy Streams | Unit Ops

Name	Air	Fuel	Steam	Flue Gases	Pre-Heated W...
Comp Mole Frac (H2O)	0.0000	-0.0000	0.9800	0.0930	0.9800
Comp Mole Frac (Oxygen)	0.2100	-0.0000	0.0100	0.0000	0.0100
Comp Mole Frac (Nitrogen)	0.7900	-0.0000	0.0100	0.3499	0.0100
Comp Mole Frac (Methane)	0.0000	0.2530	0.0000	0.1233	0.0000
Comp Mole Frac (Ethane)	0.0000	0.1350	0.0000	0.0658	0.0000
Comp Mole Frac (Propene)	0.0000	0.0965	0.0000	0.0470	0.0000
Comp Mole Frac (Propane)	0.0000	0.1841	0.0000	0.0897	0.0000
Comp Mole Frac (Cyclobutane)	0.0000	0.1447	0.0000	0.0472	0.0000
Comp Mole Frac (i-Butane)	0.0000	0.0698	0.0000	0.0340	0.0000
Comp Mole Frac (n-Butane)	0.0000	0.0698	0.0000	0.0340	0.0000
Comp Mole Frac (C5+*)	0.0000	0.0471	0.0000	0.0229	0.0000
Comp Mole Frac (H2S)	0.0000	-0.0000	0.0000	0.0000	0.0000
Comp Mole Frac (CO)	0.0000	-0.0000	0.0000	0.0930	0.0000
Comp Mole Frac (CO2)	0.0000	-0.0000	0.0000	0.0000	0.0000

Figure 5b: Aspen Hysys worksheet showing the inputted compositions of preheated water, Preheated air, and fuel.

3.1.6 Connection of KRPC steam boiler furnace

The next step carried out in Aspen Hysys was dropping of Furnace model in the Aspen Hysys 8.4 PFD environment and connecting of the inlet and outlet streams to the furnace model as shown in Figure 6.

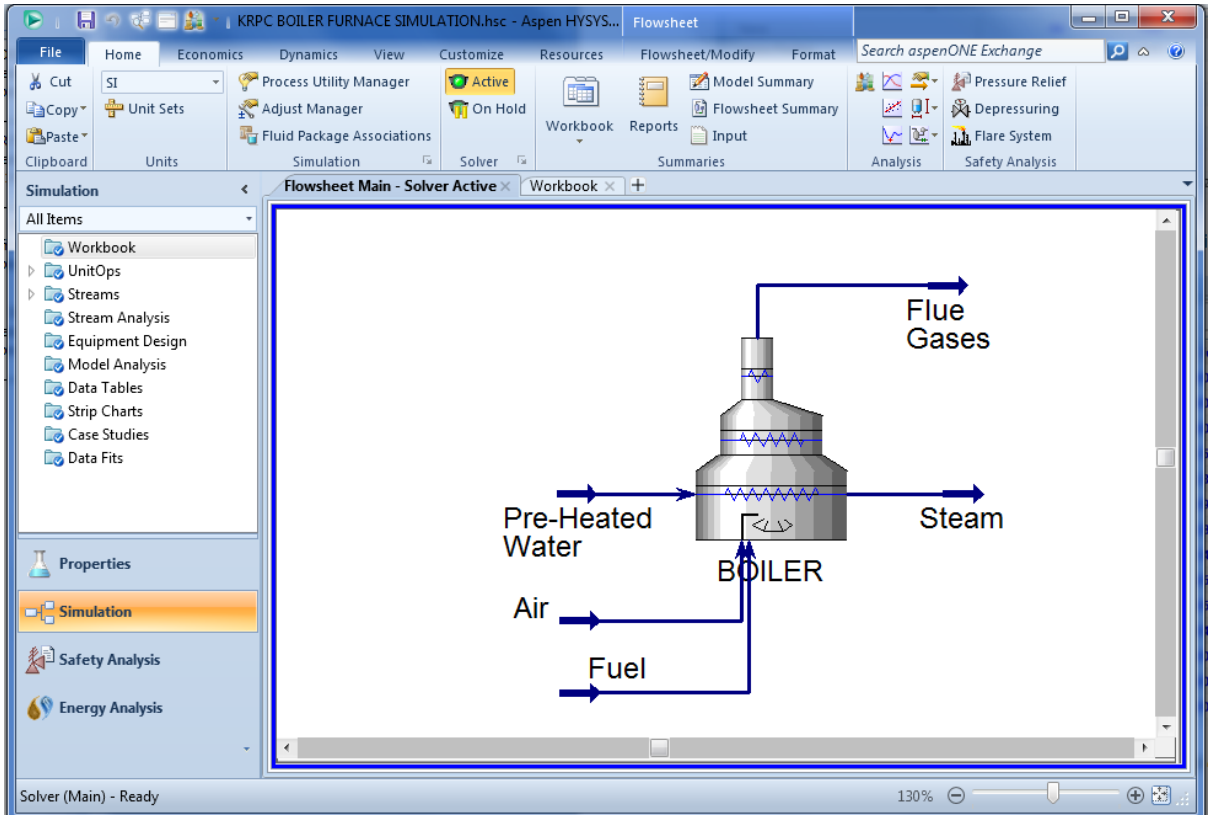


Figure 6: Furnace PFD in aspen hysys 8.4 environment.

3.1.7 Exergy analysis of KRPC boiler furnace1

The exergy balance for the KRPC steam boiler Furnace1 was carried out using the following equations

$$Irreversibility = \left(Ex_f + Ex_a + Ex_{pw}\right) - \left(Ex_{fg} + Ex_s\right) \quad 69$$

Here, Ex_f, $E\dot{x}_a, Ex_{pw}$, Ex_{fg} , Ex_s, i_{cc} and Ex_{Heat} are exergy flow rate of fuel, exergy flow of preheated air, exergy flow of preheated water, exergy flow rate of flue gases, exergy flow rate of steam, and irreversibility rate of combustion chamber. The values of,Ex_f ,$E\dot{x}_a, Ex_{pw}$, Ex_{fg} , Ex_s, i_{cc} and Ex_{Heat} are determined from simulated KRPC Boiler Furnace1 (Furnace Model in Aspen Hysys).

4.0 RESULTS

The results obtained from the simulation processes are represented in the following tables and graphs below. The results presented variations of fuel oil temperature, fuel oil pressure, flue gas outlet temperature, fuel oil Sulphur content, nitrogen content, and oxygen content on exergetic destruction and efficiency of KRPC boiler furnace 1.

4.1 Exergy analysis of KRPC boiler Furnace 1

The results of the exergy analysis of KRPC boiler finance 1 are presented in Table 2 used in Aspen Hysys 8.4 and Table 3.

Table 2: Energy Efficiency, Exergy Efficiency, and Total Revamp Potential of KRPC Boiler Furnace 1

Parameters	Values
Exergy Destruction (kJ/kg)	445.4
Energy Efficiency (%)	71.54
Exergy Efficiency (%)	6.396
Total Revamp Potential (%)	93.604

Table 3. Variation of Exergy Destruction and Exergy Efficiency of Boiler Furnace Fuel Temperature for Boiler Furnace 1

Fuel Oil Temperature (^{o}C)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
70	419.2325887	6.020089345
71	419.4082103	6.03783799
72	419.5807197	6.055359696
73	419.7501145	6.072650161
74	419.9163924	6.089705103
75	420.0795512	6.10652026
76	420.2395887	6.123091396
77	420.3965024	6.139414301
78	420.5502904	6.155484792
79	420.7009502	6.17129872
80	420.8484799	6.186851967
81	420.9928771	6.202140453

3.2 Effect of boiler furnace fuel oil temperature on, boiler furnace 1 Exergy destruction and exergetic efficiency

The result of the effect of boiler furnace fuel oil temperature on the boiler furnace 1 exergy destruction and exergy efficiency is presented is presented on Table 4 and Figure 7.

Table 4: Variation of Exergy Destruction and Exergy Efficiency of Boiler Furnace Fuel Temperature for Boiler Furnace 1

Fuel Oil Temperature (^{o}C)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
70	419.2325887	6.020089345
71	419.4082103	6.03783799
72	419.5807197	6.055359696
73	419.7501145	6.072650161
74	419.9163924	6.089705103
75	420.0795512	6.10652026
76	420.2395887	6.123091396
77	420.3965024	6.139414301
78	420.5502904	6.155484792
79	420.7009502	6.17129872
80	420.8484799	6.186851967
81	420.9928771	6.202140453

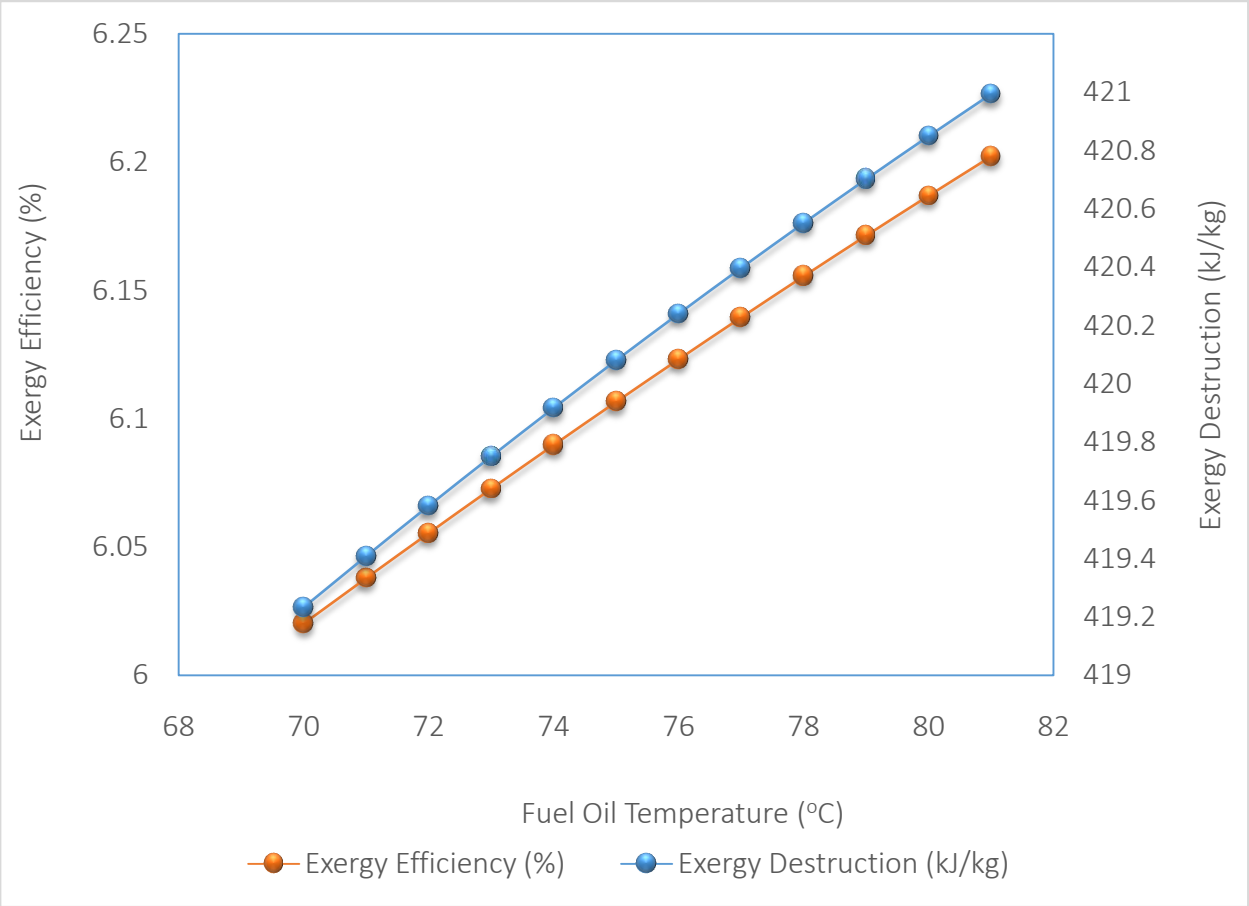


Figure 7: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Temperature for KRPC boiler furnace 1.

3.3 Effect of boiler furnace fuel oil pressure on boiler furnace 1 exergy destruction and exergy efficiency.

The effect of boiler furnace fuel oil pressure on boiler furnace 1 exergy destruction and exergy efficiency is presented on Table 7 which shows the variations of exergy destruction and exergy and exergy efficiency with boiler furnace 1 and oil pressure for KRPC boiler furnace 1 is presented on Table 5 and figure 8.

Table 5: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Pressure for KRPC boiler furnace 1.

Fuel Oil Pressure (kg/cm^2)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
1078.731725	419.2325887	6.020089345
1176.798246	420.7797627	6.179599102
1274.864766	422.4410882	6.359150113
1372.931287	424.2348583	6.56337823
1470.997807	426.1841491	6.798564727

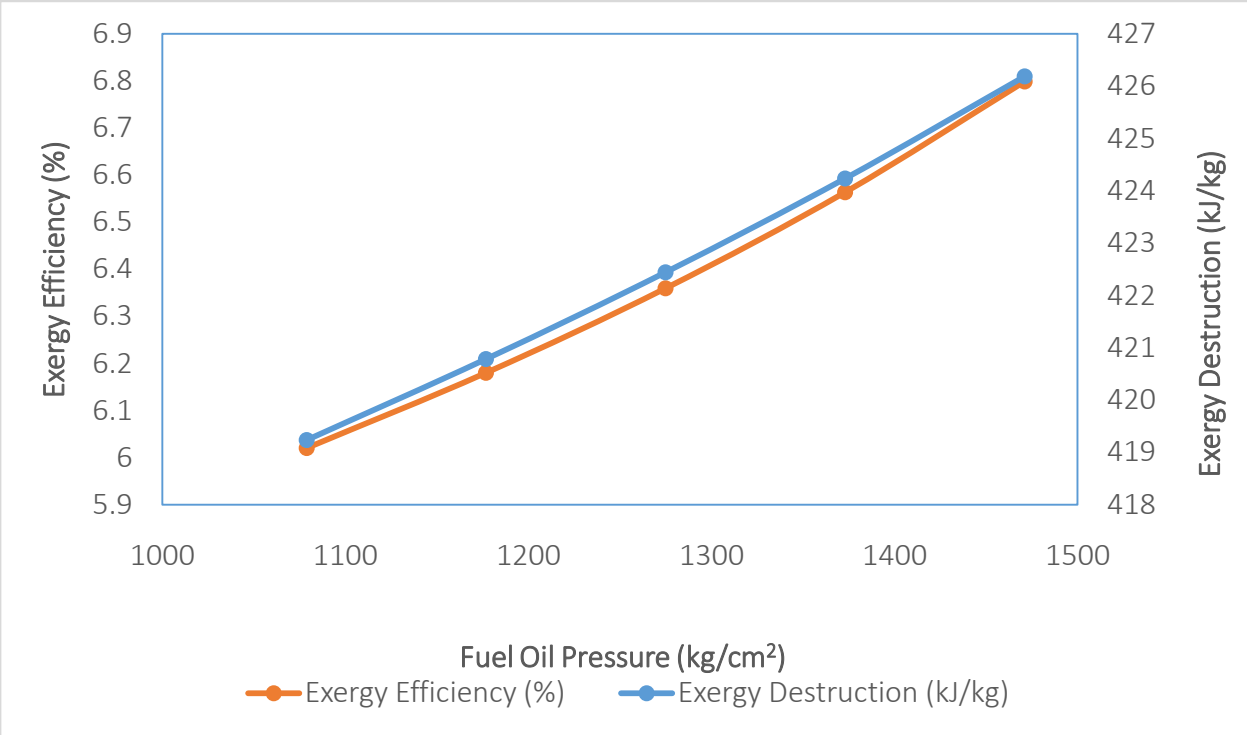


Figure 8: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Pressure for KRPC boiler furnace 1.

3.4 Effect of boiler furnace flue gas temperature on the furnace 1 exergy destruction and efficiency

The effect of boiler furnace flue gas temperature on the boiler furnace 1 exergy destruction and efficiency is presented in Table 6 and Figure 9.

Table 6: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Flue Gas Temperature for KRPC Boiler Furnace 1.

Flue Gas Temperature (^{o}C)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
340	419.2325887	6.020089345
345	422.0494768	6.060539249
350	424.8909866	6.101342716
355	427.7568232	6.14249551
360	430.6466986	6.183993496
365	433.5603316	6.225832635
370	436.4974472	6.268008981
375	439.4577771	6.310518679
1380	442.4410588	6.353357959
385	445.4470358	6.396523139

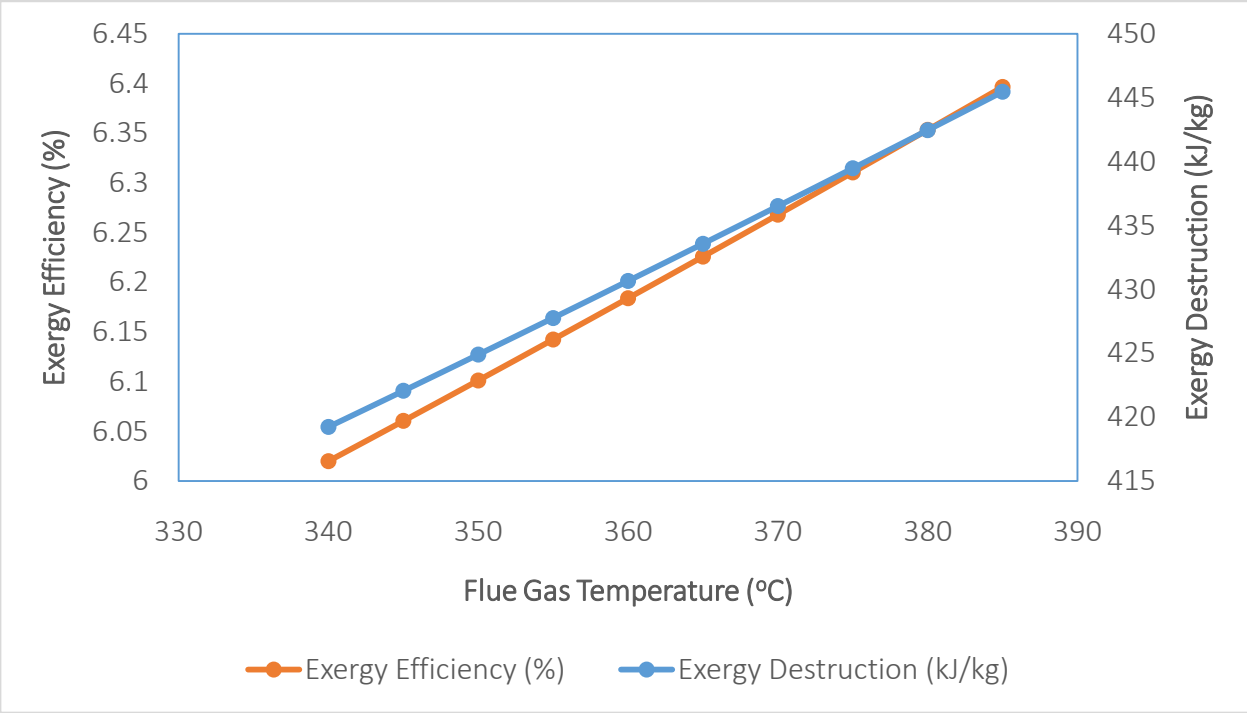


Figure 9: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Flue Gas Temperature for KRPC Boiler Furnace 1.

3.5 Effect of boiler furnace fuel oil sulfur content on the furnace1 exergy destruction and the exergy efficiency.

The results of the effect of boiler furnace fuel oil sulfur content on the boiler furnace1 exergy destruction and the exergy efficiency are presented inTable7, figure 10.

Table 7: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Sulphur Content for KRPC Boiler Furnace 1.

Fuel Oil Sulphur Content (wt %)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
0	421.7760609	4.514096203
1	430.0932073	5.055512593
2	437.9725006	5.676670484
3	445.4476452	6.396588837
4	452.548961	7.240855615
5	459.3038099	8.24473402

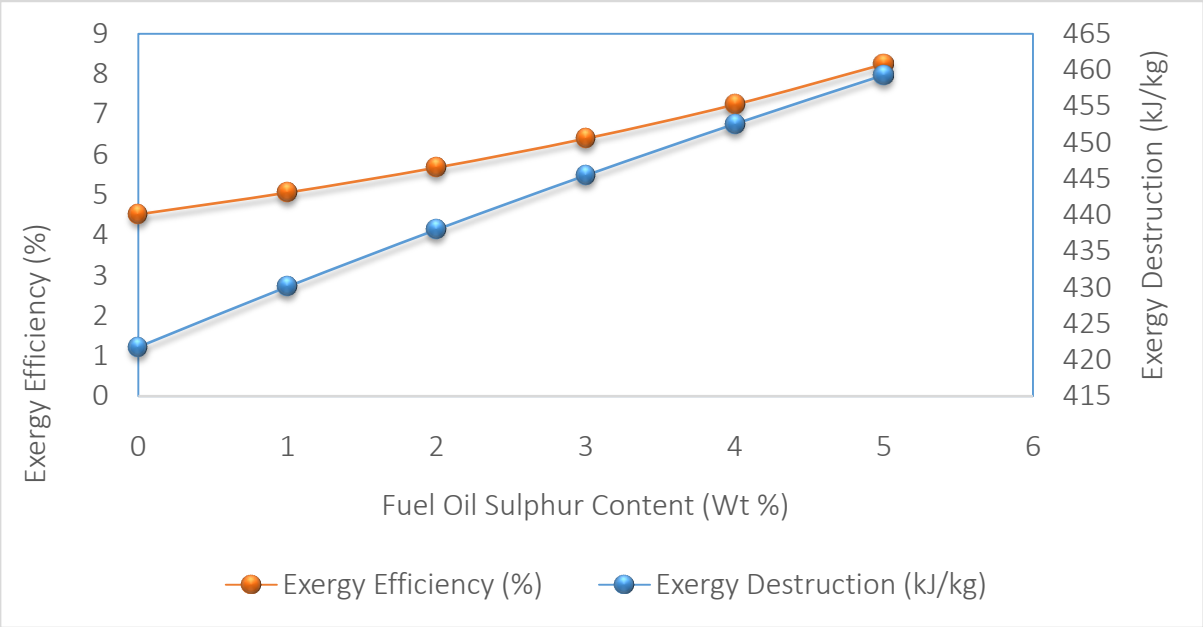


Figure 10: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Sulphur Content for KRPC boiler furnace 1.

3.6 Effect of boiler furnace fuel oil nitrogen content on the furnace1 exergy destruction and the exergy efficiency.

The result of the effect of boiler furnace fuel oil nitrogen content on the boiler furnace1 exergy destruction and the exergy efficiency is presented in Table 8 and on Figure 11

Table 8: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Nitrogen Content for KRPC Boiler Furnace 1.

Fuel Oil Nitrogen Content (wt %)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
0	445.2415146	6.373344036
0.03	445.2813721	6.377837061
0.06	445.3217102	6.382386769
0.09	445.3620506	6.38694207
0.12	445.4023447	6.391497781
0.15	445.4425879	6.396053375

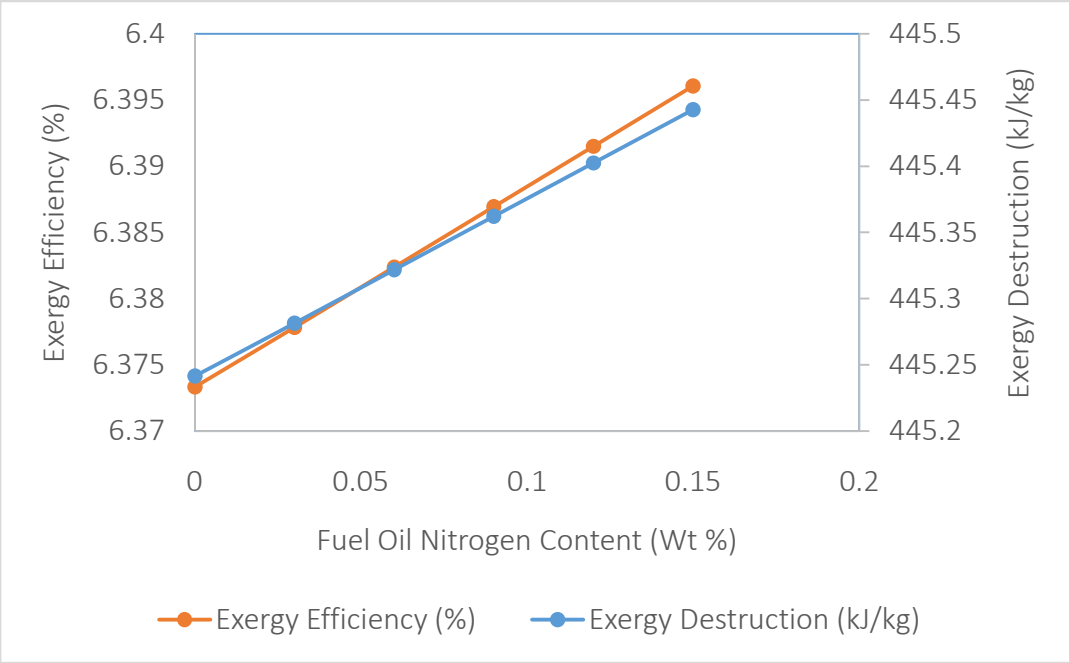


Figure 11: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Nitrogen Content for KRPC boiler furnace 1.

3.7 Effect of boiler furnace fuel oil oxygen content on the boiler furnace1 exergy destruction and the exergy efficiency

The result of the effect of the boiler furnace fuel oil oxygen content on the boiler furnace1 exergy destruction and the exergy efficiency is presented on table 9 and on figure 12

Table: 9: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Oxygen Content for KRPC Boiler Furnace1.

Fuel Oil Oxygen Content (wt %)	Exergy Destruction (kJ/kg)	Exergy Efficiency (%)
0	444.8216803	6.326277008
0.1	444.9793337	6.343858359
0.2	445.1362121	6.361437824
0.3	445.2923215	6.379015431
0.4	445.4476677	6.396591209
0.5	445.6022566	6.414165185

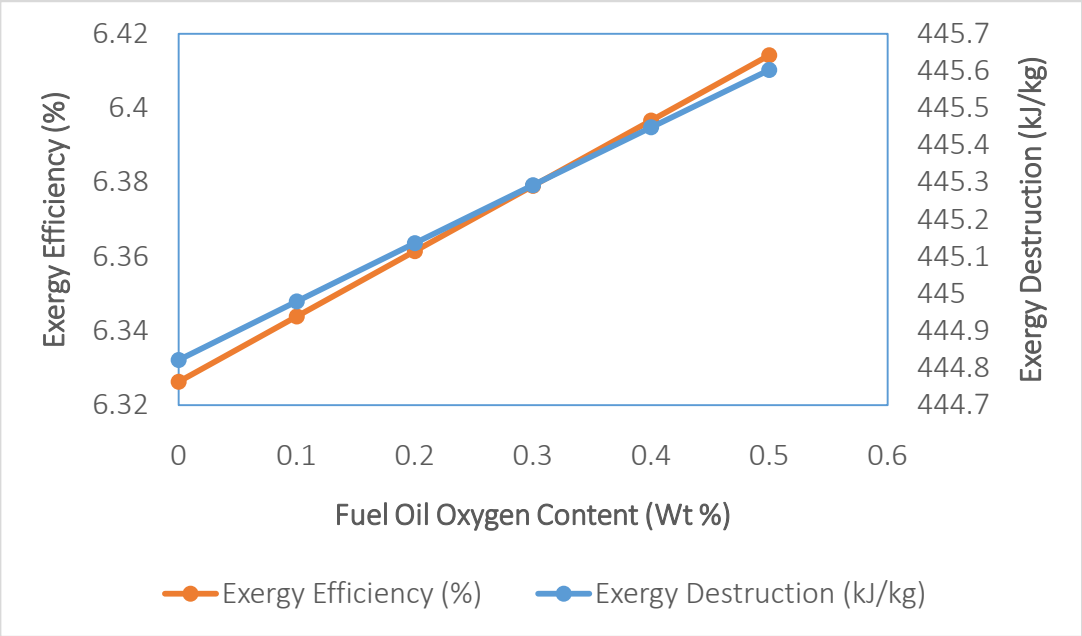


Figure 12: Variation of Exergy Destruction and Exergy Efficiency with Boiler Furnace Fuel Oil Oxygen Content for KRPC Power Plant.

3.8 Comparison of Efficiency Values with those of other Researchers

A comparison of the calculated exergy efficiency of the boiler furnace 1 of the KRPC with those of other researchers is shown in Table 10.

Table 10: Comparison of Efficiency Values with those of other Researchers

Researcher	Energetic Efficiency %	Exergetic Efficiency %
Utlu and Hepbasli (2007)	63.45-70.11	29.72-33.23
Oladiran and Meyez (2007)	83	16
Saidut et al (2009)	72.46	24.84
Hada and Shah (2012)		33.73
Pattanayak and Ayyagari (2014)	85.54	41.81
Nkoi et al (2023)	89.64	66.77
Current work	71.54	6.316

5.0 Discussions

The furnace 1 was examined using energy and exergy analyses with variable values of fuel oil temperature, fuel oil pressure, flue gas outlet temperature, fuel oil Sulphur content, nitrogen content, and oxygen content to study the effects on exergetic destruction and efficiency of KRPC boiler furnace 1 respectively to:(i) improve understanding the behavior and performance of boiler furnace1 (ii) Provide a base-case reference for efficiency improvement investigations. Table 2 shows that the energy and exergy efficiency of the boiler are 71.54% and 6.396% respectively. The low energy and exergetic efficiency (Table 2) obtained in the boiler furnace1 could have been as a result of failure of the equipment due to aging or inadequate maintenance or other operational problems (equipment obsolescence, chemical attacks leading to corrosion, poor boiler feed water quality, poor operation of equipment etc).

The implications of these discrepancies are that, although 71.54% of the input energy is transferred to generate steam, the energy is degraded as it is transferred. Exergy analysis highlights this degradation. These are expected as Dincer and Rosen (2008) reported that furnace or steam generator have the highest energy degradation. They further reported that steam generator is thus the most inefficient plant device, with combustion in that device accounting for nearly 44% of the plant exergy consumption and heat transfer nearly 40%. As a result, significant potential exists for improving boiler furnace1 efficiency by reducing steam-generator irreversibility, by modifying the combustion and/or heat-transfer processes occurring within it (Dincer and Rosen, 2008).

5.1 Effect of boiler furnace fuel oil temperature on the furnace 1 Exergy destruction and exergy efficiency

In Figure 7, the exergy destruction and exergy efficiency are plotted against boiler furnace fuel oil temperature for values between 70 ^{o}C and 80 ^{o}C. The variation of boiler furnace fuel oil temperature was obtained from KRPC boiler plant data. The exergy destruction profiles increase almost linearly with the boiler furnace fuel oil temperature and the exergy destruction varies from 419.23 kJ/kg to 420.99 kJ/kg. Also, the exergy efficiency profiles increase almost linearly with the boiler fuel oil temperature and the exergy efficiency vary from 6.02% to 6.20%. The trend of the exergy efficiency profiles appears similar to that for the exergy destruction profile. This shows that irreversibility in the boiler furnace 1 can be minimized by operating the furnace at low boiler furnace fuel oil temperature.

5.2 Effect of boiler furnace fuel oil pressure on the furnace 1 exergy destruction and exergy efficiency

In Figure 8, the exergy destruction and exergy efficiency are plotted against boiler furnace fuel oil pressure for values between 1078 kPa and 1470 kPa. The variation of boiler furnace fuel oil pressure was obtained from KRPC boiler plant data from 2009 to 2013. The exergy destruction profiles increase almost linearly with the boiler furnace fuel oil pressure and the exergy destruction varies from 419.23 kJ/kg to 426.18 kJ/kg. Also, the exergy efficiency profiles increase almost linearly with the boiler fuel oil pressure and the exergy efficiency varies from 6.02% to 6.80%. The trend of the exergy efficiency profiles appears similar to that of the exergy destruction profile. This shows that irreversibility in the boiler furnace 1 can be minimized by operating the furnace at low boiler furnace fuel oil pressure. It is also observed that exergy destruction is higher in pressure variation than temperature variation as shown in Figure 7 and Figure 8 respectively.

5.3 Effect of Boiler Furnace Flue Gas Temperature on Furnace Exergy Destruction and Exergy Efficiency

In Figure 9, the exergy destruction and exergy efficiency are plotted against boiler furnace flue gas temperature for values between 340 ^{o}C and 385^{o}C. The variation of boiler furnace fuel oil temperature was obtained from KRPC boiler plant data from 2009 to 2013. The exergy destruction profiles increase almost linearly with the boiler furnace flue gas temperature and the exergy destruction vary from 419.23 kJ/kg to 445.44 kJ/kg.

Also, the exergy efficiency profiles increase almost linearly with the boiler flue gas temperature and the exergy efficiency vary from 6.02% to 6.40%. The trend of the exergy efficiency profiles appears similar to that of the exergy destruction profile. This shows that irreversibilities in the boiler furnace can be minimized by operating the furnace at low boiler furnace flue gas temperature. This linear increase in exergy efficiency against variation in flue gas temperature is similar to that obtained by Dincer and Rosen (2008).

5.4 Effect of Boiler Furnace Fuel Oil Sulphur Content on Furnace Exergy Destruction and Exergy Efficiency

In Figure 10, the exergy destruction and exergy efficiency are plotted against boiler furnace fuel oil sulfur content for values between 1% and 5%. The variation in boiler furnace fuel oil sulphur content was obtained from KRPC boiler plant data from 2009 to 2013. The exergy destruction profiles increase almost linearly with the boiler furnace fuel oil sulphur content and the exergy destruction varies from 421.77 kJ/kg to 459.30 kJ/kg.

Also, the exergy efficiency profiles increase almost linearly with the boiler fuel oil Sulphur content and the exergy efficiency varies from 4.51% to 8.24%. The trend of the exergy efficiency profiles appears similar to that of the exergy destruction profile. The increase in exergy destruction and efficiency could be a result of sulfur present in the fuel oil corroding the boiler furnace tubes at high temperatures, thereby reducing its efficiency to transfer heat to the steam and destroying the energy that could be transfer to steam as depicted in exergy result of Figure 16. This shows that irreversibility in the boiler furnace can be minimized by using a fuel oil of low sulfur content.

5.5 Effect of Boiler Furnace Fuel Oil Nitrogen Content on the Furnace Exergy Destruction and Exergy Efficiency

In Figure 11, the exergy destruction and exergy efficiency are plotted against boiler furnace fuel oil nitrogen content for values between 0% and 0.15%. The variation of boiler furnace fuel oil nitrogen content was obtained from KRPC boiler plant data from 2009 to 2013. The exergy destruction profiles increase almost linearly with the fuel oil nitrogen content and the exergy destruction varies from 445.24 kJ/kg to 445.44 kJ/kg. Also, the exergy efficiency profiles increase almost linearly with the boiler fuel oil oxygen content and the exergy efficiency varies from 6.37% to 6.40%. The trend of the exergy efficiency profiles appears similar to that of the exergy destruction profile. The increase in exergy destruction and efficiency could be as a result of nitrogen present in the fuel oil increasing the boiler furnace tube corrosion rate at high temperatures, thereby reducing its efficiency to transfer heat to the steam and destroying the energy that could be transfer to steam as depicted in exergy result of Figure 17. This shows that irreversibility in the boiler furnace can be minimized by using a fuel oil of low sulfur content.

5.6 Effect of Boiler Furnace Fuel Oil Oxygen Content on the Furnace Exergy Destruction and Exergy Efficiency

In Figure 12, the exergy destruction and exergy efficiency are plotted against boiler furnace fuel oil oxygen content for values between 0% and 0.5%. The variation of boiler furnace fuel oil oxygen content was obtained from KRPC boiler plant data from 2009 to 2013. The exergy destruction profiles increase almost linearly with the boiler furnace flue gas temperature and the exergy destruction varies from 444.82 kJ/kg to 445.60 kJ/kg. Also, the exergy efficiency profiles increase almost linearly with the boiler fuel oil oxygen content and the exergy efficiency varies from 6.33% to 6.41%. The trend of the exergy efficiency profiles appears similar to that of the exergy destruction profile. The increase in exergy destruction and low exergy efficiency could be as a result of excess oxygen present in the fuel oil increasing the boiler furnace tube-corrosion rate at high temperature, thereby reducing its efficiency to transfer heat to the steam and destroying the energy that could be transferred to steam as depicted in exergy result of Figure 20. This shows that irreversibility in the boiler furnace can be minimized by using a fuel oil of low oxygen content.

5.7 Comparison of efficiency values of this research with those obtained by other researchers.

The table 10 shows the results of other studies carried out by scholars in the past. When compared with the result of this work, it can be seen that the exergy efficiency of 6.316% of the KRPC boiler furnace1 is quite low when compared to the work of previous scholars. This low exergy efficiency implies that a major portion of exergy of the fuel is either wasted, destroyed, lost or and not transferred to the products.

Comparing the above results this study shows that the energy input of 71.54% and low exergy efficiency of 6.316% indicate high irreversibility. This may be due to;

- Tubes fouling (scaling, silting etc.)
- Defective burners /refractory materials
- Poor fuel quality,
- Inefficient soot blowers,
- Valves leakage
- Defective steam traps,
- Air heater fouling
- Poor equipment maintenance
- Moisture in the air
- Poor equipment operation,
- Impulse lines blockage.
- Poor blow- down systems etc.

6.0 Conclusion

The following conclusions were drawn from the work:

- The energy and exergy efficiency of the KRPC boiler furnace is 71.54% and 6.396% respectively. These results are expected as Dincer and Rosen (2008) reported that furnaces or steam generators have the highest energy degradation.
- The exergy destruction of KRPC boiler furnace1 is 445.4 kJ/kg.
- The exergy efficiency of KRPC boiler furnace1 increased linearly from 6.02% to 6.20% as the boiler furnace fuel oil temperature increased from70 ^{o}C to 80 ^{o}C.
- The exergy efficiency of KRPC boiler furnace1 increased linearly from 6.02% to 6.8% as the boiler furnace fuel oil pressure increased from1078 kPa to 1470 kPa.
- The exergy efficiency of KRPC boiler furnace1 increased linearly from 6.02% to 8.24% as the boiler furnace flue gas temperature increased from340 ^{o}C to 385^{o}C.
- The exergy efficiency of KRPC boiler furnac1e increased linearly from 4.51% to 6.41% as the boiler furnace fuel oil sulphur content increased from 0% to 5%.
- The exergy efficiency of KRPC boiler furnace1 increased linearly from 6.37% to 6.40% as the boiler furnace fuel oil nitrogen content increased from 0% to 0.15%.
- The exergy efficiency of KRPC boiler furnace1 increased linearly from 6.33% to 6.41% as the boiler furnace fuel oil oxygen content increased from 0% to 0.5%.

5.1 Recommendations:

- Design change,
- Retrofitting-modification
- Replacement of refractory materials
- Upgrading of the tube materials etc
- Effective maintenance (routine, preventive, TAM, etc)
- Regular inspections (visual and non-destructive tests)

- Regular soot-blowing
- Effective fuel oil filtering system
- Effective boiler water treatment plants
- Ensuring frequent water purity test
- Ensure proper sealing of joints and flanges etc

Further studies should also be carried out in the following areas.

- Application of exergy analysis to the entire KRPC boiler equipment should be carried out to determine the equipment that has the highest and least irreversibility.
- To study the effect of water composition on the exergetic efficiency of the KRPC boiler furnaces.

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