POTENTIAL OF EXERGY EFFICIENCY IMPROVEMENT OPPORTUNITIES OF COAL POWER PLANTS IN SRILANKA: A CASE STUDY

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Degree of Master of Engineering

Department of Mechanical Engineering

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Dissertation submitted in partial fulfillment of the requirements for the degree Master of Engineering

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ABSTRACT

When considering global as well as local energy scenarios, it is required to consume energy in proper way and also required to harvest maximum possible output from the available energy source. Therefore analysis, monitoring and optimization of available power plants are major requirement in the sector. Generally the performance of power plant is evaluated by energy performance criteria based on 1st law of thermodynamics. However, as recent developments in thermodynamic studies exergy analysis was identified as a useful method to design, evaluation, optimization and improvement of power plants. It is based on 2nd law of thermodynamics.

Therefore in this thesis, it is tried to find out potential of exergy efficiency improvement opportunities in coal power plants through exergy flow analysis. A methodology was developed to calculate exergy values in major thermodynamics state in coal power plant and efficiency of major equipment in power plant. That was done according to general equations which are used in thermodynamics. As a result, set of thermodynamic equations were derived to analyze exergy flow in coal power plants.

The methodology which mentioned in above was applied to unit 01 of Lak Vijaya power station (LVPS) in Sri Lanka to validate it. In this calculation, thermodynamic properties of water-steam cycle of LVPS unit 01 under both design and actual calculation were used to evaluate exergy values of critical states of the cycle as well as exergy efficiencies of major equipment. The obtained results were used for the analysis of exergy of power plant. Then the exergy destruction, exergy efficiency of major equipment as well as the overall exergy efficiency of LVPS unit 01 was figured out under both design and operational conditions.

Boiler was identified as the major exergy destruction equipment in power plant and it has less exergy efficiency also. It is around 49% in design condition and 45% in actual operation condition. Also energy balance calculation was done for the boiler to identify the difference of exergy and energy efficiency of equipment. The boiler exergy destruction value is contributing extra percentage of total exergy destruction of power plant. Therefore the changes of boiler exergy destruction are directly affected to overall exergy efficiency of the power plant.

Hence boiler sub system was analyzed to identify potential of exergy efficiency improvement in coal power plants. The main variable parameters of boiler were used to identify the exergy flow behaviors of the boiler. The main steam pressure, main steam temperature, Feed water temperature, Gross Calorific Value of Coal and Load variation of power plant were considered as major variable parameters of the boiler. The above variables were taken individually to identify exergy destruction and exergy efficiency of boiler in LVPS unit 01. Then potential of exergy efficiency improvement in coal power plant was discussed using obtained results.

As per the results which were obtained from case study of LVPS unit 01, Coal power plant should run in full load (300MW) conditions as much as possible to improve its overall exergy efficiency. Also boiler main steam pressure should be kept in high pressure condition at least above 16.0MPa.Above working conditions were identified as better working conditions which will improve the exergy efficiency of overall power plant.

Also economic analysis was done for the boiler to identify the benefits of doing this kind of thesis. The steam generating cost was calculated in the thesis according to past actual operational data in LVPS unit 01. The cost saving due to the improvement of exergy efficiency also determined here. Not only steam generating cost saving in power plant but also reduction of hazardous CO_2 emission calculation was done here.

Key words: Exergy, Energy, Exergy destruction, Exergy efficiency, 1st law of Thermodynamics, 2nd law of Thermodynamics and Gross calorific value.

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LIST OF ABBRIVATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
CFC	Chlorofluorocarbon
LVPS	Lak Vijaya Power Station
NOx	Nitrogen Oxide
FGD	Flue Gas Desulphurization
SOx	Sulphur Oxide
N_2	Nitrogen
CO_2	Carbon Dioxide
H_2O	Water
PM	Particulate Matter
ESP	Electrostatic Precipitator
PW	Present Worth
CRF	Capital Recovery Factor
PEC	Purchase Equipment Cost
HP	High Pressure
LP	Low Pressure
IP	Intermediate Pressure
CP	Condensate Pump
BFP	Boiler Feed Pump
HTR	Heater
EIA	Environmental Impact Assessment
USD	United State Dollars
SH	Super Heater

RH	Re Heater
TMCR	Turbine Maximum Continuous Rating
FRP	Fiber Reinforced Plastic
CWS	Cooling Water System
VWO	Valve Wide Open
BMCR	Boiler Maximum Continues Rating
GCV	Gross Calorific Value
HHV	High Heating Value

Symbols	**Description**
E^{PH}	Physical exergy
E^{KN}	kinetic exergy
E^{PT}	Potential exergy
E^{CH}	Chemical exergy
e^{T}	Thermal exergy
e^{M}	Mechanical exergy
x^{n}	Mole Fraction of n^{th} gas mixture
$\bar{R}$	Universal Gas Constant
E_i	Exergy input
E_o	Exergy Output
E_D	Exergy destruction
C	Cost value
c	Unitary (specific) cost value
e	Product output
i	Feed input

k	Number of component
q	Heat
W	Work
E	Exergy
Z	Investment cost
$\dot{C}$	Exergy Cost
$\dot{E}$	Exergy Rate
c	Exergy Unit Cost
$\dot{Z}^{CI}$	Capital Investment Cost
$\dot{Z}^{OM}$	Operation and Maintenance Cost
i	Interest Rate
n	Life Time of Plant
j	Salvage Value Ratio
τ	Total annual operating hours
h	Enthalpy
s	Entropy
C_p	Specific heat
h_0	Reference environmental enthalpy
s_0	Reference environmental entropy
T_0	Reference environmental temperature

LIST OF APPENDICES

CHAPTER 01

1.0 Introduction

1.1 World energy scenario

The energy supply to demand narrowing down day by day around the world, the growing demand of power has made the power plants of scientific interest. The total energy requirement in world supply by different sources, the world primary energy consumption in 2012 as follows.

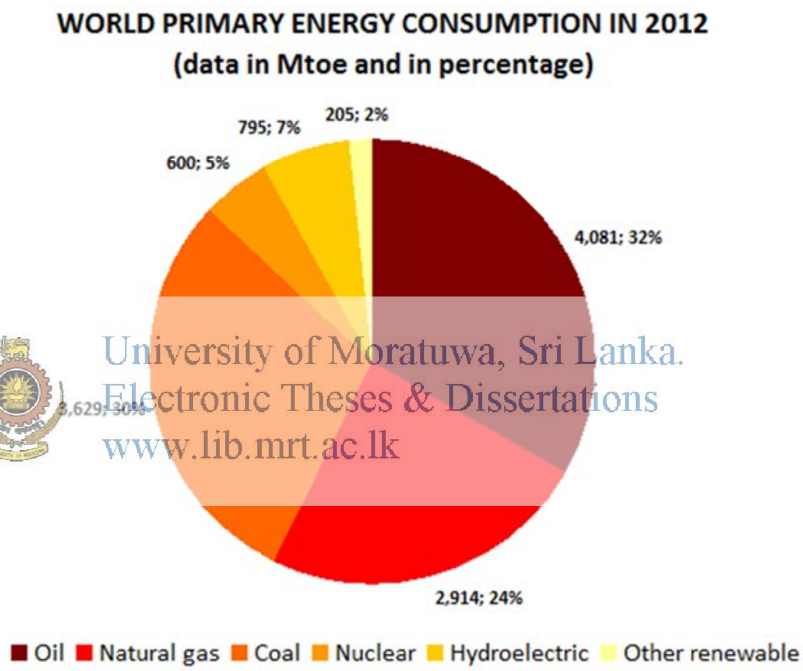


Figure 1.1: World Primary Energy Consumption in 2012 [21]

These numbers will be changed soon as the world's population grows, energy demand rises, inexpensive oil and gas deplete, global warming effects continue to rise and urban pollution worsens the living conditions. The development of alternative energy sources and devices will emerge more rapidly to address the world's energy and environmental situation. The Figure 1.2 shows the world net electricity generation by fuel.

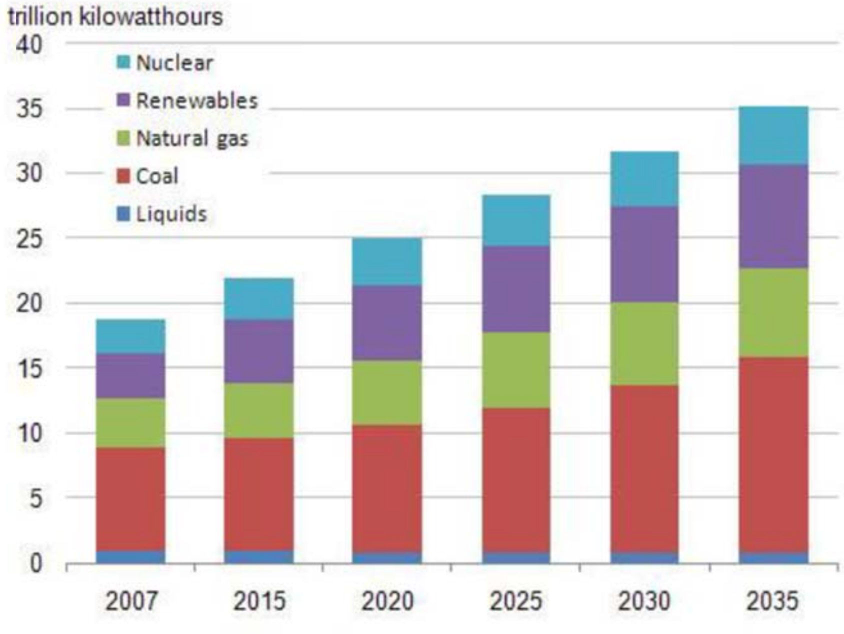


Figure 1.2: World net Electricity generation by fuel [22]

When consider above data it could be observed that major energy supply sources are coal, natural gas & oils. According to the energy surveys those recourses are depleting rapidly. Therefore it is required to utilize those limited resources in proper manner in order to make sure the sustainability of future generation. Therefore the maximum power plant efficiency obtains together with minimum investment costs should be the main target of power industry. Also the highest reliability should obtain from the overall design targets of power plants. To save primary energy resources i.e. to reduce fuel consumption, and to reduce emissions, maximum power plant efficiency is a crucial parameter. Therefore, optimizing the working conditions of existing power plant to an economically reasonable extent is the challenge.

1.2 World energy related CO_2 emissions

Until the last decade the primary concern about energy impacts on the environment was of a local nature, focused on the negative consequences of mining the fuels and of producing power. Global warming due to CO_2 and other emissions is now widely considered to be the real phenomenon, and has already resulted in the international ban on CFCs, and evolving agreements to control and limit CO_2 emissions. The latter would have a very significant impact on the ways we would convert fuels and produce power, and is a powerful motivator for scientific and engineering progress in these areas.

Therefore when we are using energy we have to think about emission more than earlier as most of countries used energy only considering the power or electricity demand without thinking of environmental. Therefore it is necessary to figure out real thermodynamic losses and address the issues which will result to reduce the hazardous emissions from power plants. The Figure 1.3 shows the world energy related CO_2 emissions by fuels. It also shows that, emission rate of CO_2 increases due to rapid growth in coal usage.

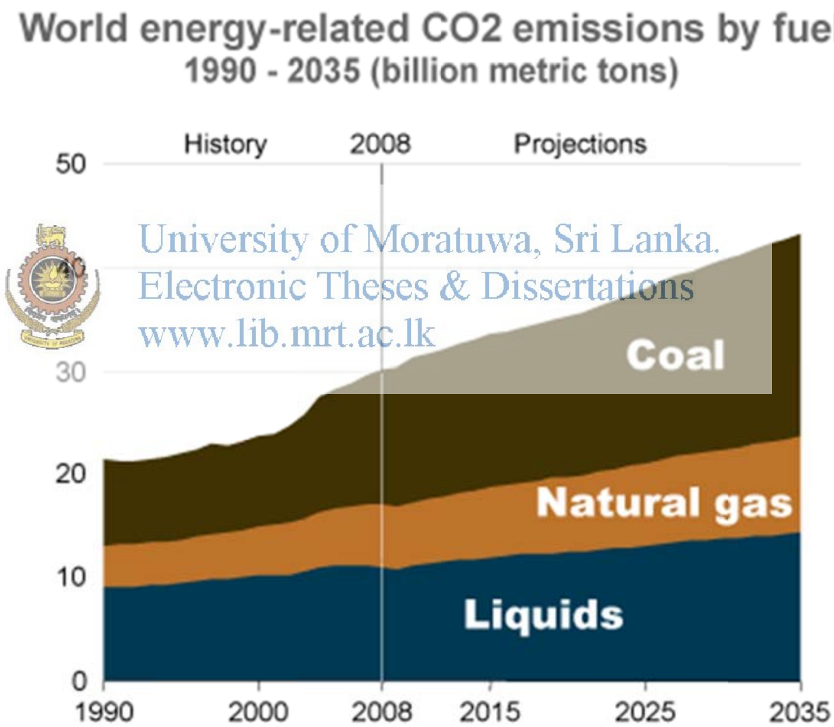


Figure 1.3: World energy related CO_2 emission by fuel [23]

1.3 Sri Lankan energy scenario

The early years in Sri Lanka, almost all of the electricity requirements were met by hydro power plants. By 2008, the required capacity had increased to 2000 MW while the total number of required electricity units had increased to 10,000 GWh [1]. According to the assessment of the CEB, the demand for electricity will increase by 7-10% per annum over the next twenty years [1]. Accordingly, demand shall double every ten years. It is interpreted as the responsibility of the government to be able to meet this demand at affordable prices. In order to address this issue, the CEB prepared a plan but this only focused attention on the generation of electricity through coal, petroleum and hydro power. Therefore Sri Lankan power sector is trend to generate more power using coal. So we have to give more concern about it due to these reasons.

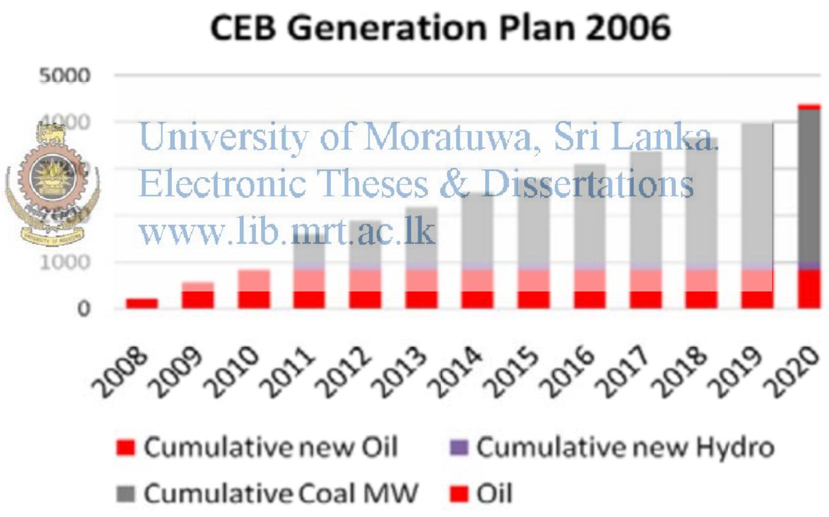


Figure 1.4: CEB Generation Plan 2006 [1]

According to the above generation plan CEB already moved to coal power generation in Sri Lanka. They have already built one coal power plant which has the capacity of 900MW. It consists of three numbers of identical units of 300MW each. (300MW×3). The total power complex is called as Lak Vijaya coal power station (LVPS). Lak Vijaya Coal Power station is the only coal power plant in Sri Lanka, Also now a days it generates 600MW (300MW×2) and it gives around 33% of daily power requirement of Sri Lanka [2].

Energy		Percentage %
CEB Thermal (Coal)	8.502 GWh	33.01
CEB Thermal (Oil)	5.906 GWh	22.93
IPP Thermal (Oil)	0.861 GWh	3.34
Laxapana Complex Hydro	4.726 GWh	18.35
Mahaweli Complex Hydro	3.344 GWh	12.98
Samanala Wewa	0.415 GWh	1.61
Kukule Ganga	1.593 GWh	6.18
CEB (Small Hydro)	0 GWh	0.00
Wind	0.41 GWh	1.59

Figure 1.5: Daily power supply by power plants in Sri Lanka [2]

The trend of the power generation sector in Sri Lanka also moves to Coal Power generation. Therefore it is needed to do thermal analysis of existing power plant and get idea about improve efficiency of existing and incoming power plants.

When considering global as well as local energy scenarios, it is required to consume energy in proper way and also required to harvest maximum possible output from the available energy source. Therefore analysis, monitoring and optimization of available power plants have become a major requirement in the sector. Generally the performance of power plant is evaluated by energy performance criteria based on 1st law of thermodynamics. However, as recent developments in thermodynamic studies exergy analysis was identified as a useful method to design, evaluation, optimization and improvement of power plants. It is based on 2nd law of thermodynamics. That is used to analyze thermodynamic processes. It is the concept of exergy or a substance's availability to do useful work. This method can improve resource utilization by determining inefficient, wasteful processes within thermodynamic systems. Exergy is an extensive property of a substance like energy, but differs in that in a given process, it can be destroyed due to irreversibility inherent to the process. While a First Law analysis might suggest that the amount of energy is conserved during a given process, it fails to identify the decline in the quality of the energy, or the reduced availability of the substance to do work, in its final state. Therefore it is useful to perform an exergy analysis for the same process to determine the location, cause and magnitude of losses, so that opportunities to improve resource utilization in the process are identified.

The Rankin power cycle which converts the thermal energy into mechanical energy, does not differ between critical, sub-critical, supercritical, ultra supercritical and advanced ultra-supercritical cycles. Energy can neither be created nor destroyed. It just changes forms such as potential, chemical, electrical, heat and work. Energy analysis based on the first law of thermodynamics embodies of conservation of energy and is the traditional method used to assess the performance and efficiency of the energy systems and processes.

Also most of the power plants are designed by the energy performance criteria based on first law of thermodynamics only. The real useful energy loss cannot be justified by the fist law of thermodynamics, because it does not differentiate between the quality and quantity of energy.

Therefore 2nd low of thermodynamic is used to measure the quality of energy of thermodynamic systems. It is useful to identify the energy losses in systems in a proper way. The word ‘Exergy’ was derived from Greek words ex (meaning out) and erg on (meaning work) [3]. Exergy is the useful work potential of the energy. Exergy could not be conserved. Once the exergy is wasted, it can never be recovered. When we use energy we never destroy any; we are simply converting it into a less useful form, a form of less exergy. The useful work potential of a system is the amount of energy we extract as useful work. The useful work potential of a system at the specified state is called exergy (also called as availability). Exergy is a property and is associated with the state of the system and the environment. Exergy losses are additive (i.e. the total exergy loss for the plant is the sum of all the component losses). Exergy is always destroyed when a process involves a temperature change.

This destruction is proportional to the entropy increase of the system together with its surroundings. Second law analysis is about understanding irreversibility in systems. It focuses on changes in the quality of energy. The quality of energy is measured by exergy. As energy is used in a process it loses quality and its exergy. The exergy analysis is a tool to identify losses and destructions so that appropriate measures can be implemented to reduce the losses and destructions. An exergy analysis is a very powerful way of optimize complex thermodynamic systems.

Exergy analysis helps in improving plant efficiency by determining the origin of exergy losses. Exergy helps in identifying components where high inefficiencies occur, and where improvements are merited. The thermodynamic cycle can often be optimized by minimizing the irreversibility.

Therefore the result of Exergy Analysis (2^{nd} low thermodynamic analysis) of coal power plant can indicate the real thermodynamic loss in power generation process and it is assisted to find out the improvement required area to improve the efficiency of system.

1.4 The intentions of the study

1.4.1 Aim of the study:

To develop an approach to identify potential of exergy efficiency improvement opportunities of coal power plants in Sri Lanka.

1.4.2 Objectives of the study:

- To Study the Exergy Balance related to Coal power Plants.
- To develop methodology to identify and characterize of real thermodynamic losses in coal power plants through exergy analysis.
- To apply the developed methodology to Lak Vijaya coal power plant unit 01.
- To identify the potential of efficiency improvement opportunities in coal power plants in Sri Lanka by analyzing the obtained results from the case study.

1.4.3 Methodology of the study:

Objective 01

- Study on Exergy analysis of coal power plant using text books, journals, research papers etc. as literature review.

Objective 02

- Create methodology (model) to formulate Exergy analysis for coal power plants.

Objective 03

- Collect relevant thermodynamics data from Lak Vijaya coal power plant unit 01 (To do the case study).
- Do the necessary calculations using existent data and design parameters of power plant.
- Evaluate the obtained results to find out location, magnitude, and sources of real thermodynamic losses through analysis.

Objective 04

- Analysis the results and find out maximum exergy destruction component of the coal power plant.
- Discuss the exergy efficiency improvement opportunities of that area.

The Chapter No.01 of this thesis discusses the current situation of energy scenarios in both Global and Local. Also tendency of power generation sector in Sri Lanka is discussed in furthermore. The energy systems evaluation processes using thermodynamic approach is conversed and give an idea about exergy and energy analysis. After concern above factors express objective of this thesis. That part includes aim of thesis, objective of thesis and methodology of it.

Power generation from coal is discussed in Chapter No.02 of this thesis. The topics under natural coal formation process, existing type of coal in world and working process of typical coal power plant are explained here.

The Exergy analysis of coal power plant is one of the objectives in this thesis. To achieve this target it is needed to understand theoretical background of exergy analysis of energy systems. Therefore Chapter No.03 is reserved for theoretical approach part of this thesis. Basics laws of thermodynamics are deeply discussed here. Also a methodology for exergy analysis of coal power plant was developed using general equation of thermodynamics. That exergy destruction and exergy efficiency of major equipment in coal power plants can easily identify using that set of equations. The cost calculation of steam generated in boiler sub system of coal power plant is also discussed here.

LVPS unit 01 was used as case study in this thesis. Chapter No.04 was used to discuss introduction of LVPS unit 01. The specific data of major equipment in power plant also expressed here. The major equipment which include Boiler, Turbines, Feed water system, condenser cooling water system, feed water heaters and pumps etc.

The collected data from LVPS unit 01 are applied to calculate exergy values in Chapter No. 05. In this calculation, thermodynamic properties of water-steam cycle of LVPS unit 01 under both design and actual conditions were used to evaluate exergy values of critical states of the cycles as well as exergy efficiencies of major equipment. The energy analysis of boiler is also done in this chapter. Furthermore the cost calculation of steam generated in boiler is discussed here using actual economical data in the power plant.

The result which was obtained from calculations of Chapter No.05 is discussed in Chapter No. 06. The exergy values in each and every critical state in the power plant, exergy destruction in major equipment and exergy efficiency of major equipment are included here. Exergy improvement opportunities in coal power plant also discussed in this chapter. This discussion is based on case study of LVPS unit 01. The benefits which are obtained due to improvement of exergy efficiency also mentioned in this chapter.

After summarize all results which obtained from this thesis is concluded in the last Chapter of this thesis.

CHAPTER 02

2.0 Power Generation from Coal

Schematic diagram of typical coal power generation process is illustrated in Figure No 2.1.

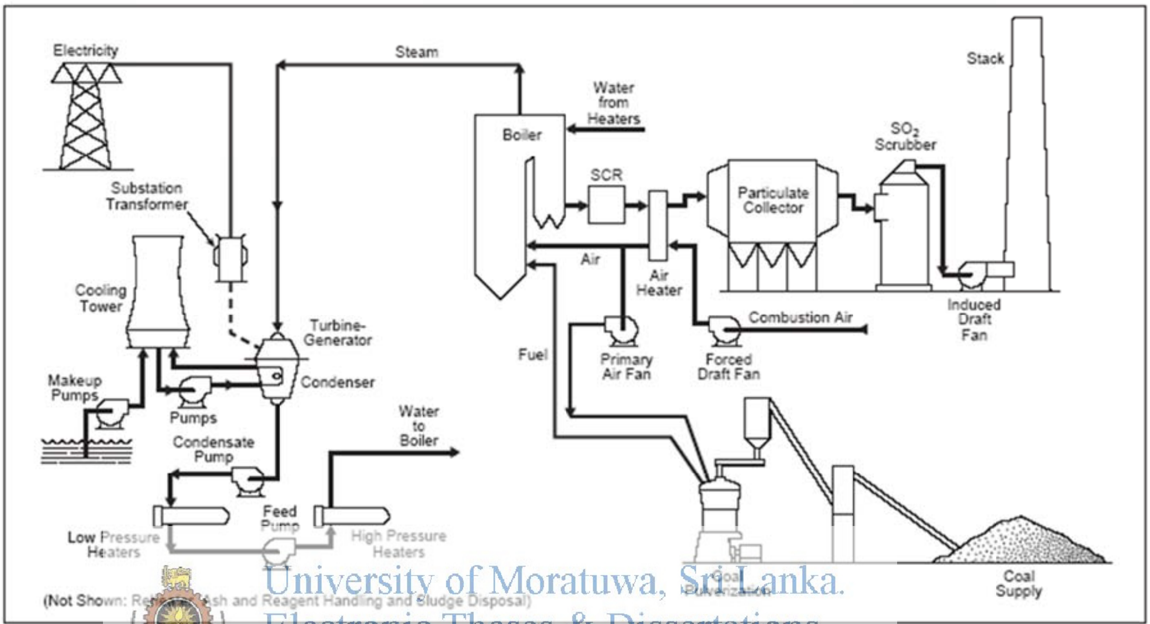


Figure 2.1: Schematic diagram of Typical Coal power generation process [24]

2.1 Natural coal formation process

Coal is a rock that burns (a solid hydrocarbon), formed from partially decayed plant matter that collected in a stagnant swamp and later was subjected to heat over time [4]. It is called a “fossil fuel” because all this happened millions of years ago. Oil and natural gas are the other fossil fuels. Coal is the world’s most abundant and widely distributed fossil fuel with reserves for all types of coal estimated to be about 990 billion tones [5], enough for 150 years at current consumption [5]. Coal is thought to consist of a large polymeric matrix of aromatic structures, commonly called the coal macromolecule. This macromolecule network consists of clusters of aromatic carbon that are linked to other aromatic structures by bridges.

There are different types of coal depending on the degree of coalification (amount of heat and time). Such as peat, Lignite, Subbituminous, Bituminous and Anthracite coal.

2.2 Existing types of coal

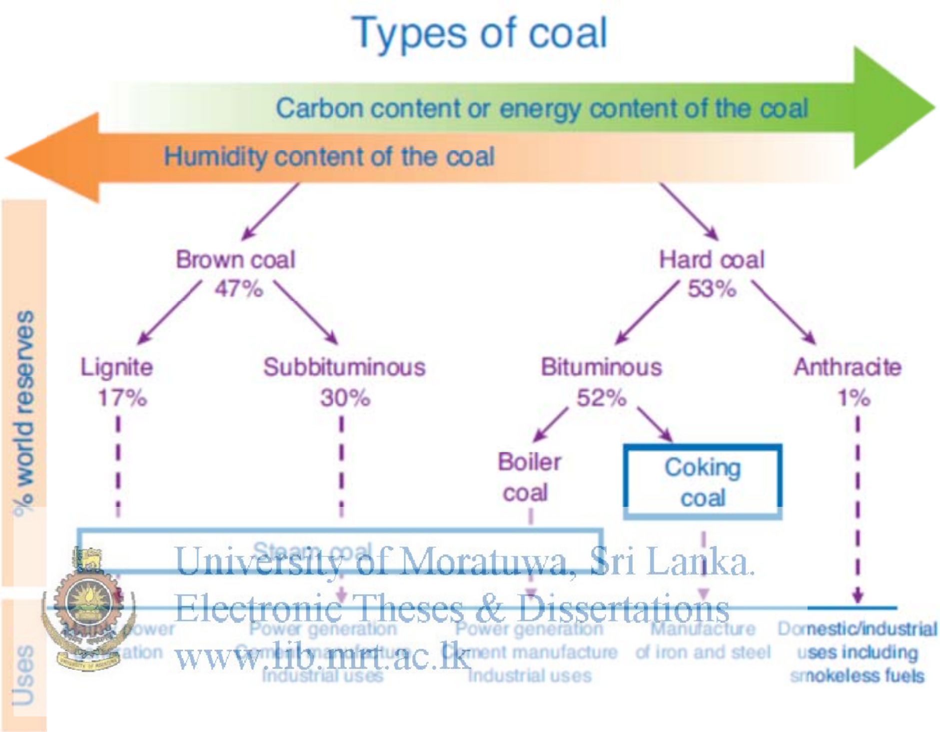


Figure 2.2: World coal classification [25]

The above mentioned coal could be used as power generating primary source. Such as coal power plants use coal as raw material to generate power from it. The coal power plants can classify into several ways. This is divided according to operating pressure, boiler type, emission treatment methods, etc. Normally main classification is done according to the operating pressure. Sub critical, super critical and ultra-super critical power plants are now available in power industry to generate electricity.

2.3 Process of typical coal power plant

In a coal-fired plant, raw coal supply from coal mine to coal stock yard by several ways. There are pulverizes to grind the coal into a fine powder for burning in the furnace of the boiler. That stock coal transferred to mills to produce powder forms.

According to the grinding mechanism pulverizes also can be classified in several ways. Such as Bowel mill, Ball mill etc. The heat produced from the burning of the coal generates steam at high temperature and high pressure. The high-pressure steam from the boiler impinges on a number of sets of blades in the turbine.

Another major component of coal power plant is the boiler. Normally water tube boilers are used in power generation industry and that boiler can be classified in several ways. The main classification is depended on the steam pressure. According to that, it could be classified as subcritical, super critical and ultra-super critical boilers. The pulverized coal from mills directly or indirectly supplies to the boiler to combustion and produce heat. The Air preheater, Furnace, economizer, super-heater panel, reheater panels are the major components of typical power boilers. Also air and flue gas system is provided to supply required air for the combustion and transfer pulverized coal to the furnace. This system consists of forced draft fans, induced draft fans, primary air fan and seal air fans.

A typical coal plant consists of turbo- generator unit. Normally steam turbines used in coal power plants consists of several stages. Such as High pressure, Intermediate pressure and low pressure turbines. The generated high pressure, high temperature steam from the boiler is admitted to the high pressure turbine initially. Then the steam is expanded through high pressure turbine and exhaust steam is directed to reheater part of the boiler. At the reheater, steam is heated to higher temperature and then admitted to intermediate pressure turbine. This reheating process increases the power output from the turbine. Finally exhaust steam from intermediate turbine admitted to low pressure turbine and exhaust steam is condensed into water in the condenser. Steam is extracted from different stages of the turbine which have adequate pressure for pre-hating of boiler feed water in feed water heaters. This is called as regenerative feed water heating, generally known as regeneration.

The generator is coupled with the turbine where mechanical energy in rotating shaft of the turbine is converted into electrical energy and supplied to the power distribution grid through a transformer. The purpose of the transformer is to step up the voltage of the generated power to a suitable level for long distance transmission.

The steam leaving the turbine is condensed in the condenser as shown in the above figure using cooling water which discharges low temperature heat to the environment. The condensate produced is pumped back to the boiler through series of the feed water heaters.

There are three major factors that determine the nature and extent of the flue gas treatment process. The properties of coal used, the environmental legislation and environment policy of a plant are those three factors. In some countries, due to stringent environmental regulation, coal-fired power plants needed to be equipped with denitrification plants (DeNOx) for Nitrogen Oxide (NOx) and flue gas desulphurization plants (FGD) for Sulphur Oxide (SOx) removal.

The burning of coal in the boiler of a power plant produces flue gas. The main constituents of the flue gas are Nitrogen (N_2), Carbon Dioxide (CO_2) and water (H_2O). It carries particulate matter (PM) and other pollutants. There are traces of some oxides such as Oxides of Sulphur (SO_x) and Oxides of Nitrogen (NO_x) depending on the combustion technology and fuel used. The flue gas clean-up unit comprises all the equipment needed for treating the flue gas. The power plant shown in the above figure includes a $DeNO_x$ plant for NO_x removal, followed by Electrostatic Precipitator (ESP) to remove particulate matter (PM), and wet flue gas desulfurization (FGD) to remove SO_x from the flue gas.

CHAPTER 03

3.0 Theoretical Approach

3.1 First law of thermodynamics

The law of conservation of energy states that the total energy of an isolated system is constant; energy can be transformed from one into another, but cannot be created or destroyed. The first law is often formulated by stating that the change in the internal energy of a closed system is equal to the amount of heat supplied to the system minus the amount of work done by the system on its surroundings [6].

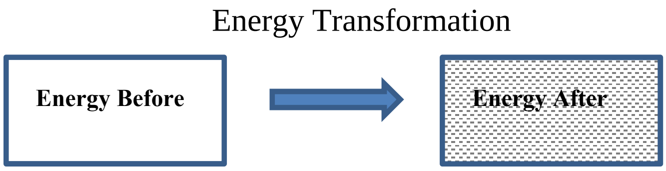


Figure 3.1: Sketch of Energy Conversion according to 1^{st} Law

$$\Delta U = Q - W$$

ΔU = Change in internal Energy

Q = Heate added **to** the system

W = Work done **by** the system

3.2 Second law of thermodynamics

The second law of thermodynamics states that in a natural thermodynamic process, there is an increase in the sum of the entropies of the participating systems [7].

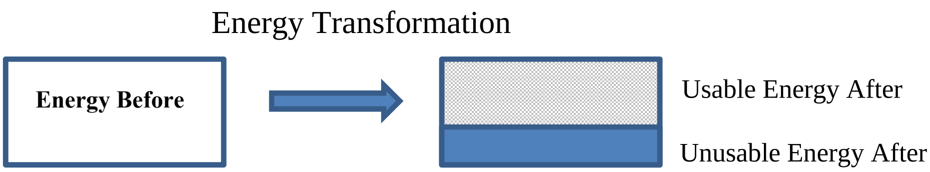


Figure 3.2: Sketch of energy conversion according to 2^{nd} Law

There are many alternative statements of the second law. Two of them are frequently used in engineering thermodynamics which are called as Clausius statement and Kelvin–Planck statement.

3.3 Clausius statement of the second law

The Clausius statement of the second law asserts that, it is impossible for any system to operate in such a way that the sole result would be an energy transfer by heat from a cooler to a hotter body [8].

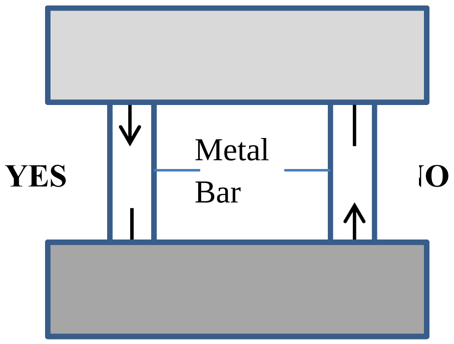


Figure 3.3: Sketch about Clausis statement

3.4 Kelvin–Planck statement of the second law

The Kelvin–Planck statement of the second law states, it is impossible for any system to operate in a thermodynamic cycle and deliver a net amount of energy by work to its surroundings while receiving energy by heat transfer from a single thermal reservoir [8].

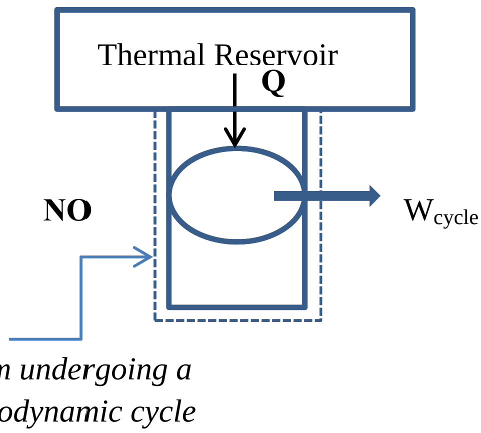


Figure 3.4: Sketch about Kelvin-Plant statement

3.5 What is exergy?

In thermodynamics, the exergy of a system is the **maximum useful work** possible during a process that brings the system into equilibrium with a heat reservoir [3]. When the surroundings are the reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. Exergy is the energy that is available to be used. The Exergy becomes zero after the system and surroundings reach equilibrium.

The following terms should be identified clearly before doing the exergy analysis of any energy system.

3.5.1 Theoretical definition of environment in exergy analysis

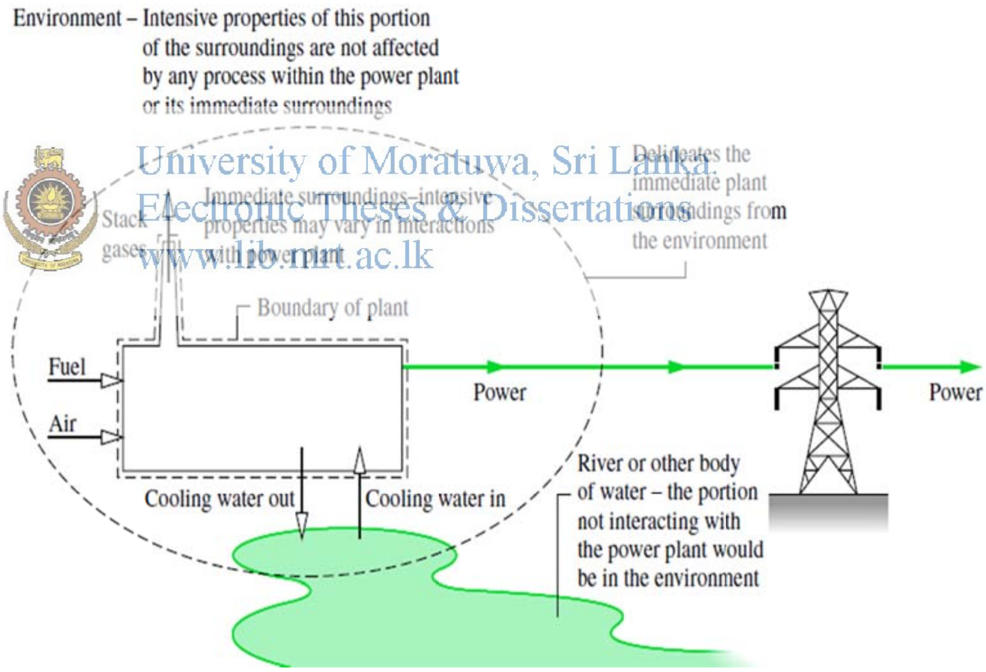


Figure 3.5: Schematic of a power plant and its surroundings [11]

3.5.2 Theoretical definition of dead state in exergy analysis

System exchanges work, heat and mass with its surroundings during a process. If the system reaches a state which is in equilibrium with its surroundings, then the system cannot exchange work, heat and mass with its surroundings. This state is called a dead state and its properties are denoted by subscript 0, such as pressure P_0 and temperature T_0. At the dead state: [9]

- A system is at the same temperature and pressure of its surroundings.
- It has no kinetic or potential energy relative to its surroundings.
- It does not react with the surroundings.
- There are no unbalanced magnetic, electrical and surface tension effects between the system and its surroundings.

3.5.3 Theoretical definition of reversible work

Reversible work is defined as the maximum amount of useful work that can be produced (or the minimum work consumed) as a system undergoes a process between the specified initial and final states.

3.5.4 Theoretical definition of exergy destruction

Unlike energy, exergy is not conserved but destroyed by irreversibility within a system. This phenomenon could be classified as internal and external irreversibility. Main reasons of internal irreversibility are friction, unrestrained expansion, mixing and chemical reaction. External irreversibility arises due to heat transfer through a finite temperature difference.

3.6 Definition of exergy analysis

Exergy analysis is a method that uses the conservation of mass and energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy systems. The exergy method is a useful tool for furthering the goal of more efficient energy-resource use, as it enables the locations, types, and true magnitudes of wastes and losses to be determined.

3.7 Difference of energy and exergy concept

Table 3.1: Deference of Exergy and Energy

Energy	Exergy
1. Independent from environmental properties, and depends only on the properties of matter or energy flow	1. Depends both on the environmental conditions (i.e. reference conditions) and a matter or energy flow
2. Not zero when in equilibrium with the environment	2. Equal to zero when in complete equilibrium with the environment
3. Conserved for all processes (first law of thermodynamics)	3. Conserved for reversible processes, and not conserved for real processes where part of it is destroyed due to irreversibilities
4. Cannot be destroyed or produced	4. Cannot be destroyed nor produced in a reversible process, always destroyed or consumed in an irreversible process
5. Appears in many forms (e.g., kinetic energy, potential energy, work, heat) and is measured in that form	5. Appears in many forms (e.g., kinetic exergy, potential exergy, work, thermal exergy) and is measured on the basis of work or ability to produce work
6. A measure of quantity only	6. Measure of quantity and quality

3.8 Identification of exergy components

In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system E can be divided into four components: physical exergy E^{PH}, kinetic exergy E^{KN}, potential exergy E^{PT} and chemical exergy E^{CH} [10].

$$E = E^{KN} + E^{PT} + E^{PH} + E^{CH} \qquad (01)$$

If we consider above equation as unit mass basis

$$e = e^{KN} + e^{PT} + e^{PH} + e^{CH} \qquad (02)$$

Control volume exergy rate balance is; [11]

$$\frac{dEcv}{dt} = \sum_j (1 - T_0/T_j)\,\dot{Q}_j - (\dot{W}_{cv} - \frac{P_0 dVcv}{dt}) + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe} - E_d \qquad (03)$$

Where

e = exit flow exergy

i = input flow exergy

The equation No.03 represent the;

Rate of exergy change $= \frac{dEcv}{dt}$

Rate of exergy transfer $= \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j - \left(\dot{W}_{cv} - \frac{P_0 dVcv}{dt}\right) + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe}$

Rate of exergy destruction $= E_d$

For the Steady state form [11];

$$\frac{dEcv}{dt} = 0 \qquad (04)$$

$$\frac{dVcv}{dt} = 0 \qquad (05)$$

Therefore considering the No: 05 & 06 equations, equation No 03 could be modified as;

$$\sum_j (1 - T_0/T_j)\, \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i e_{fi} - \sum_e \dot{m}_e e_{fe} - E_d = 0 \qquad (06)$$

Also

$$\sum_j E_{qj} - W_{cv} + \sum_i E_{fi} - \sum_e E_{fe} - E_d = 0$$

Where

$$\dot{E}_{qj} = (1 - T_0/T_j)\dot{Q}_j$$

$$E_{fi} = m_i e_{fi}$$

$$E_{fe} = m_e e_{fe}$$

The above No.06 equation can express as;

$$\sum_j (1 - T_0/T_j)\, \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i (e_{fi} - e_{fe}) - E_d = 0 \qquad (07)$$

$(e_{fi} - e_{fe})$;

When considering the power plant analysis, it has to be considered about flow exergy, when mass flow across the boundary of control volume, there is an exergy transfer accompanying flow.

Specific flow exergy is

$$e_f = h - h_0 - T_0(S - S_0) + v^2/2 + gz \qquad (08)$$

If we considering single inlet and exit, it can be expressed as

$$ef_1 - ef_2 = (h_1 - h_2) - T_0 (S_1 - S_2) + \frac{V_1^2}{2} - \frac{V_2^2}{2} + g (Z_1 - Z_2) \qquad (09)$$

Where the above kinetic and potential exergy can be represented as follows

$$e^{KE} = \frac{V^2}{2} \qquad (10)$$

$$e^{PE} = gz \qquad (11)$$

Physical flow exergy for simple compressible pure substances is given as

$$e^{PH} = e^{T} + e^{M} \quad (12)$$

Where;

e^{T} = Thermal Exergy depend on the system temprature

e^{M} = Mechanical Exergy depend on the system Pressure

Also physical exergy of liquid system can express as;

$$e^{PH} = (h - h_0) - T_0 (S - S_0) \quad (13)$$

Also it can be expressed for gases forms as

$$e^{PH} = C_p (T - T_0) - C_p T_0 \ln(T/T_0) \quad (14)$$

Chemical exergy is the exergy component associated with the departure of the chemical composition of a system from that of environment. Standard molar chemical exergy tables are available in literature. For a hydrocarbon fuel, C_aH_b, standard chemical exergy tables may be used to calculate the chemical exergy values. Following equation could be used to find out the chemical energy of the gaseous form of fuel.

$$\bar{e}_{ch} = \sum x_n (\bar{e}_{ch})_n + \bar{R} T_0 \sum x_n \ln x_n \quad (15)$$

Where

x_n = Mole Fraction of nth gas mixture

$\bar{R}$ = Universal Gas Constant

But according to the references [12] the chemical exergy value of fuel is nearly equal to the HHV of that fuel

So;

$$e^{ch} \approx \text{HHV of that fuel} \quad (16)$$

Therefore by considering the exergy components explained earlier, the exergy balance could be easily expressed as;

$$\sum_{i=1}^{i} E_i = \sum_{e=1}^{e} E_o + E_D \qquad (17)$$

Where;

E_i –Exergy input (kJ/s)

E_o –Exergy Output (kJ/s)

E_D –Exergy destruction (kJ/s)

3.9 Definition of exergy efficiency in power plant

In defining the exergy efficiency, it is necessary to identify both a product and a fuel for the thermodynamic system being analyzed. The product represents the desired result produced by the system. Accordingly, the definition of the product must be consistent with the purpose of purchasing and using the system. The fuel represents the resources expended to generate the product and is not necessarily restricted to being an actual fuel such as natural gas, oil or coal. Both the product and the fuel are expressed in terms of exergy [10]. This efficiency can be represented as follows;

3.9.1 Boiler sub system

$$\text{Exergy Efficency} = \frac{\text{Useful Exergy}}{\text{Exergy Supplied}}$$

$$\text{Exergy Efficency} = \frac{\sum E_{Product}}{\sum E_{Fuel}}$$

Also it can be expressed as;

$$\text{Exergy Efficency} = 1 - (E_D + E_L)/\sum E_{Fuel} \qquad (18)$$

3.9.2 Turbines sub system

$$\text{Exergy Efficency} = \frac{\text{Useful Exergy}}{\text{Exergy Supplied}}$$

$$\text{Exergy Efficency} = \frac{\text{Work of Turbine}}{\text{Exergy}_{\text{in}} - \sum \text{Exergy}_{\text{out}}} \qquad (19)$$

3.9.3 Pump sub system

$$\text{Exergy Efficency} = \frac{\text{Exergy}_{\text{out}} - \text{Exergy}_{\text{in}}}{W_{\text{pump}}} \qquad (20)$$

3.9.4 Feed water heat exchanges

$$\text{Exergy Efficency} = \frac{\sum \text{Exergy}_{\text{Product}}}{\sum \text{Exergy}_{\text{Source}}}$$

Also it can express as;

$$\text{Exergy Efficency} = 1 - E_D / \Delta \text{Exergy}_{\text{source}} \qquad (21)$$

Where;

$$\Delta \text{Exergy}_{\text{source}} = \text{Ex. Source}_{\text{in}} - \text{Ex. Source}_{\text{out}}$$

3.10 Definition of exergy cost

The exergy analysis yields the desired information for a complete evaluation of the design and performance of an energy system from the thermodynamic viewpoint. However, it is required to know how much the exergy destruction in a plant component costs the plant operator. Knowledge of this cost is very useful in improving the cost effectiveness of the plant. The cost which includes in product and fuel of energy system is called as exergy cost of that component.

3.11 Exergy cost balance of system

A cost balance expresses that the total cost of the output streams in an energy-conversion system (process) equals the total cost of the input streams plus the appropriate charges due to capital investment and operating and maintenance expenses (Z). For the following cost balance can be formulated into the energy systems [13].

$$\sum_e (C_e \dot{E}_e)_k + C_{w,k}\dot{W}_k = C_{q,k}\dot{E}_{q,k} + \sum_i (C_i \dot{E}_i)_k + \dot{Z}_k \quad (22)$$

Where:

C = Cost value [LKR]

c = Unitary (specific) cost value [LKR/kWh];

e = Product output

i = Feed input

k = Number of component

q = Heat

W = Work

w = Work or power

E = Exergy [kW or kJ/s]; and

Z = Investment cost [LKR]

Also with exergy costing, each of the cost rates is evaluated in terms of the associate rate of exergy transfer and a unit cost. Thus, for an entering or exiting stream, it can be expressed as,

$$\dot{C} = c \times \dot{E} \quad (23)$$

$\dot{C}$ = exergy cost (LKR/h)

$\dot{E}$ = exergy rate (kJ/s or kW)

c = exergy unit cost (LKR/kWh)

When considering the capital investment, operation and maintenance cost of power plant, it is required to convert the values to present states. Hourly leveled method could be adopted for the said conversion. The following equations are used to convert values into its present state [14].

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM} \quad (24)$$

$\dot{Z}^{CI}$ = Capital Investmant Cost(LKR/hrs)

$\dot{Z}^{OM}$ = Operation and Maintance Cost(LKR/hrs)

$$PW = C_{plant} - S_{plant} \times PWF(i, n) \quad (25)$$

PW = present worth of power plant

S_{plant} = Salvage value of plant

$$S_{plant} = C_{plant} \times j \quad (26)$$

j = Salvage value ratio

$$PWF = 1/(1+i)^{n} \quad (27)$$

i = interest rate

n = life time of plant

Annual Capital cost

$$CA_{plant} = PW_{plant} \times CRF(i, n) \quad (28)$$

CRF = Capital recovery Factor

$$CRF = \frac{i \times (i+1)^{n}}{(i+1)^{n} - 1} \quad (29)$$

$$\dot{Z}^{CI} = CA_{plant} / \tau \quad (30)$$

τ = Total anual operating hours

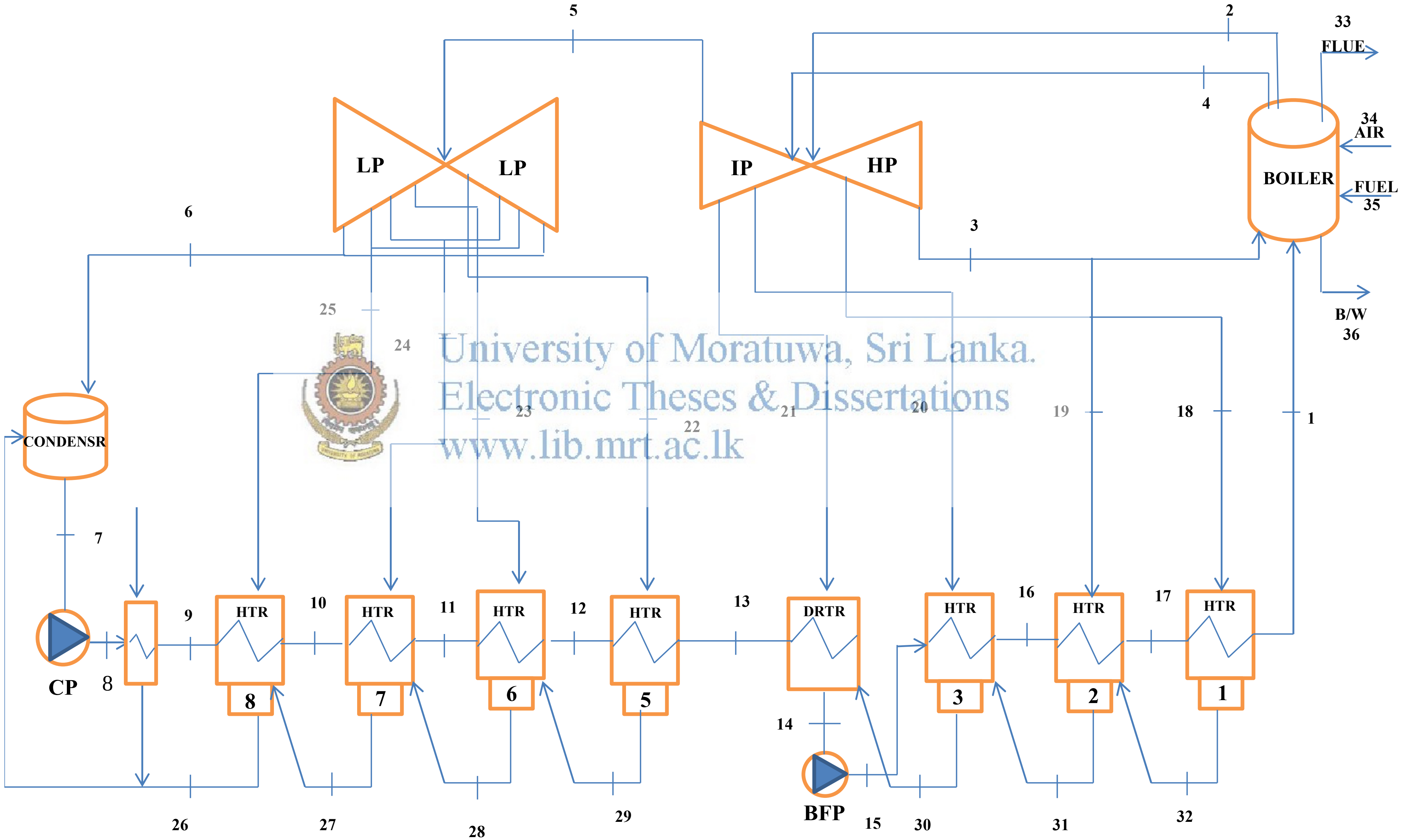
If we consider individual component in power plant;

$$\dot{Z}_K^{CI} = Z_{Plant}^{CI} \times \ PEC_k / \sum_{plant} PEC \qquad (31)$$

$PEC = \text{purchase equipment cost}$

Levelised Operation and maintenance cost of power plant

$$\dot{Z}_K^{OM} = Z_{Plant}^{OM} \times \ PEC_k / \sum_{plant} PEC \qquad (32)$$


LP
LP
IP
HP
BOILER
FLUE
33
AIR
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FUEL
35
B/W
36
CONDENSR
CP
BFP
HTR
DRTR
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3.12 Develop equation to find out exergy destruction and exergy efficiency of major equipment in coal power plant

3.12.1 Boiler

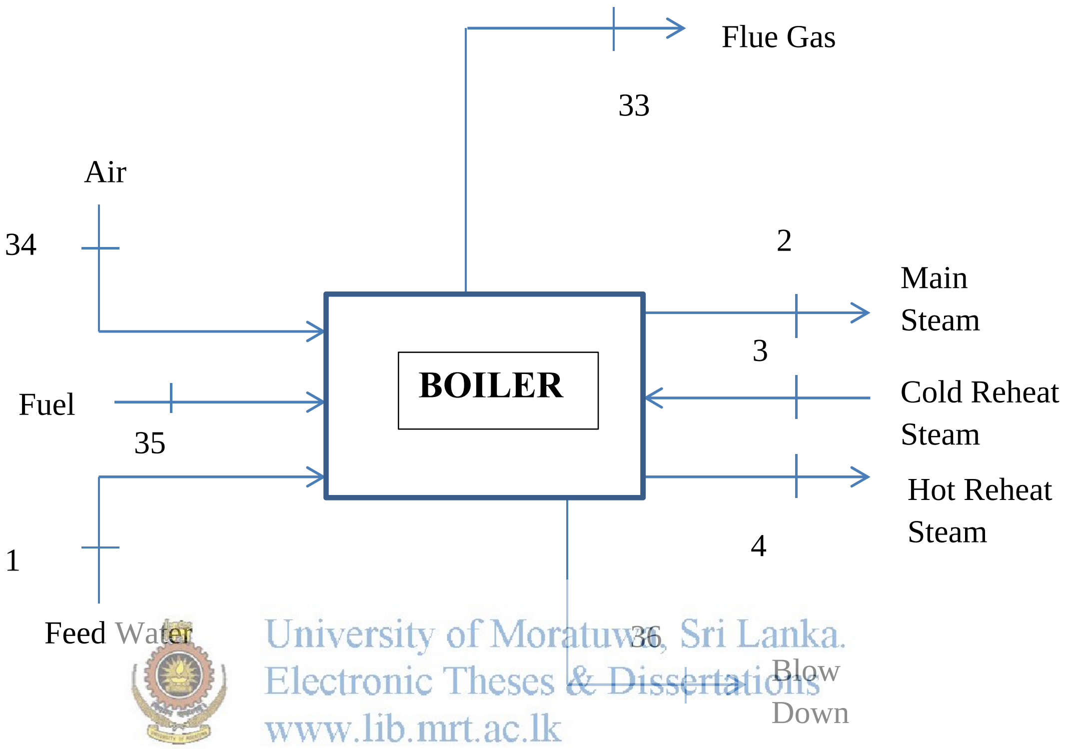

Figure 3.7: Sketch of Exergy input and output in boiler sub system

According to the exergy balance of the boiler sub system, considering equation No: (17)

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{34} + E_{35} + E_1 + E_3$$

$$E_o = E_2 + E_4 + E_{36} + E_{33}$$

Therefore;

$$E_{34} + E_{35} + E_1 + E_3 = E_2 + E_4 + E_{36} + E_{33} + \mathbf{E_D}$$

The exergy value of each component can be calculated separately. Such as

$$E = E^{KN} + E^{PT} + E^{PH} + E^{CH}$$

For some selected systems, the kinetic and potential exergy values can be neglected as those values are considerably smaller than the other components. Therefore the exergy values depend only on the physical and chemical Exergy values.

Therefore;

$$E = E^{PH} + E^{CH}$$

Also the chemical exergy value of some input and output components are lesser than physical exergy values. So in such conditions, only physical exergy values of that components could be considered. Therefore considering equation No: (13)

$$E_1 = (h_1 - h_0) - T_0 (S_1 - S_0)$$

$$\dot{E}_1 = \dot{m}_1[(h_1 - h_0) - T_0 (S_1 - S_0)]$$

$$\dot{E}_3 = \dot{m}_3[(h_3 - h_0) - T_0 (S_3 - S_0)]$$

Considering input air from equation No: (14)

$$\dot{E}_{34} = \dot{m}_{34}[C_p (T_{34} - T_0) - C_p T_0 \ln\left(\frac{T_{34}}{T_0}\right)]$$

Chemical exergy value of supply fuel;

$$\dot{E}_{35} \approx \text{HHV of selected coal}$$

$$\dot{E}_2 = \dot{m}_2[(h_2 - h_0) - T_0 (S_2 - S_0)]$$

$$\dot{E}_4 = \dot{m}_4[(h_4 - h_0) - T_0 (S_4 - S_0)]$$

$$\dot{E}_{36} = \dot{m}_{36}[(h_{36} - h_0) - T_0 (S_{36} - S_0)]$$

Considering flue gas of boiler sub system

$$\dot{E}_{33} = \dot{m}_{33}[C_p (T_{33} - T_0) - C_p T_0 \ln\left(\frac{T_{33}}{T_0}\right)]$$

$$E_{D_{boiler}} = \{\dot{m}_1[(h_1 - h_0) - T_0\,(S_1 - S_0)]\} + \{\dot{m}_3\,[(h_3 - h_0) - T_0\,(S_3 - S_0)]\}$$
$$+ \left\{\dot{m}_{34}\left[C_p\,(T_{34} - T_0) - C_p T_0 \ln\left(\frac{T_{34}}{T_0}\right)\right]\right\} + \text{HHV of selected coal}$$
$$- \{\dot{m}_2[(h_2 - h_0) - T_0\,(S_2 - S_0)]\}$$
$$- \{\dot{m}_4[(h_4 - h_0) - T_0\,(S_4 - S_0)]\}$$
$$- \{\dot{m}_{36}[(h_{36} - h_0) - T_0\,(S_{36} - S_0)]\}$$
$$- \{\dot{m}_{33}[C_p\,(T_{33} - T_0) - C_p T_0 \ln\left(\frac{T_{33}}{T_0}\right)]\}$$

Exergy efficiency of boiler sub system;

$$\text{Exergy Efficency}_{boiler} = 1 - \frac{(E_D + E_L)}{E_{Fuel}}$$

$$\textbf{Exergy Efficency}_{\textbf{boiler}} = 1 - \frac{E_D + E_{33} + E_{36}}{E_{34} + E_{35} + E_1}$$

3.12.2 HP Turbine

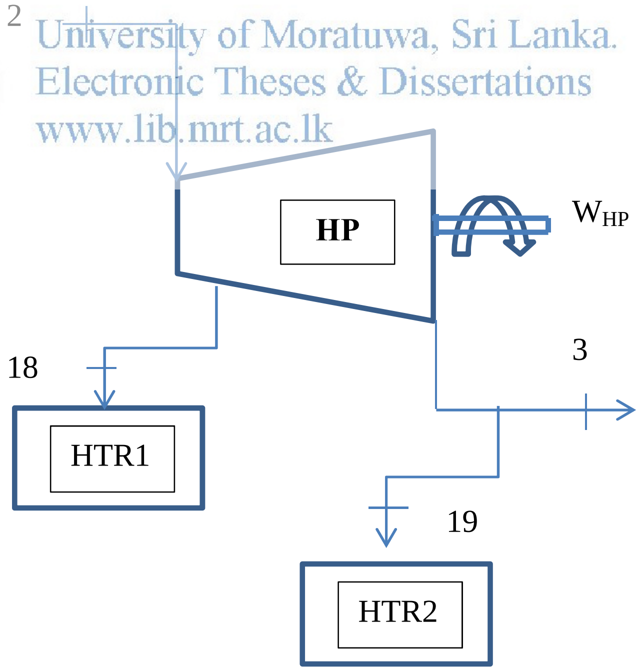

Figure 3.8: Sketch of Exergy input and output in HP turbine sub system

According to HP turbine sub system;

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_2$$

$$E_o = E_{18} + E_{19} + E_3$$

$$E_2 = E_3 + E_{18} + E_{19} + W_{HP\ Turbine} + \mathbf{E_D}$$

Where;

$$\dot{E_2} = \dot{m}_2[(h_2 - h_0) - T_0 (S_2 - S_0)]$$

$$\dot{E_3} = \dot{m}_3[(h_3 - h_0) - T_0 (S_3 - S_0)]$$

$$\dot{E}_{19} = \dot{m}_{19}[(h_{19} - h_0) - T_0 (S_{19} - S_0)]$$

$$\dot{E}_{18} = \dot{m}_{18}[(h_{18} - h_0) - T_0 (S_{18} - S_0)]$$

$$W_{HP\ Turbine} = \dot{m}\ (h_2 - h_3)$$

Therefore;

$$\mathbf{E_{D_{HP\ Turbine}}} = \{\dot{m}_2[(h_2 - h_0) - T_0 (S_2 - S_0)]\} - \{\dot{m}_3[(h_3 - h_0) - T_0 (S_3 - S_0)]\} - \{\dot{m}_{19}[(h_{19} - h_0) - T_0 (S_{19} - S_0)]\} - \{\dot{m}_{18}[(h_{18} - h_0) - T_0 (S_{18} - S_0)]\} - \{\dot{m}\ (h_2 - h_3)\}$$

$$\text{Exergy Efficency}_{HP\ Turbine} = \frac{W_{HP\ turbine}}{E_{in} - E_{out}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HP\ Turbine}} = \frac{W_{HP\ Turbine}}{E_2 - (E_{18} + E_{19} + E_3)}$$

3.12.3 IP Turbine

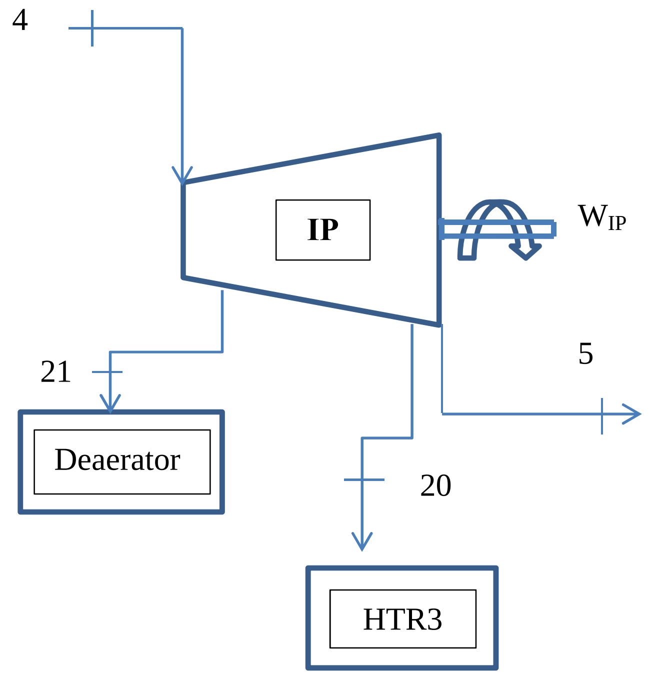

Figure 3.9: Sketch of Exergy input and output in IP turbine sub system

According to IP turbine sub system;

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_4$$

$$E_o = E_{20} + E_{21} + E_5$$

$$E_4 = E_{20} + E_{21} + E_5 + W_{IP\ Turbine} + \mathbf{E_D}$$

Where;

$$\dot{E}_4 = \dot{m}_4[(h_4 - h_0) - T_0 (S_4 - S_0)]$$

$$\dot{E}_5 = \dot{m}_5[(h_5 - h_0) - T_0 (S_5 - S_0)]$$

$$\dot{E}_{19} = \dot{m}_{20}[(h_{20} - h_0) - T_0 (S_{20} - S_0)]$$

$$\dot{E}_{20} = \dot{m}_{21}[(h_{21} - h_0) - T_0 (S_{21} - S_0)]$$

$$W_{IP\ Turbine} = \dot{m} (h_4 - h_5)$$

Therefore;

$$\mathbf{E_{D\,IP\,Turbine}} = \{\dot{m}_4[(h_4 - h_0) - T_0\,(S_4 - S_0)]\} - \{\dot{m}_{20}[(h_{20} - h_0) - T_0\,(S_{20} - S_0)]\} - \{\dot{m}_{21}[(h_{21} - h_0) - T_0\,(S_{21} - S_0)]\} - \{\dot{m}_5[(h_5 - h_0) - T_0\,(S_5 - S_0)]\} - \{\dot{m}\,(h_4 - h_5)\}$$

$$\text{Exergy Efficency}_{HP\,Turbine} = \frac{W_{IP\,Turbine}}{E_{in} - E_{out}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HP\,Turbine}} = \frac{W_{IP\,Turbine}}{E_4 - (E_{20} + E_{21} + E_5)}$$

3.12.4 LP Turbine

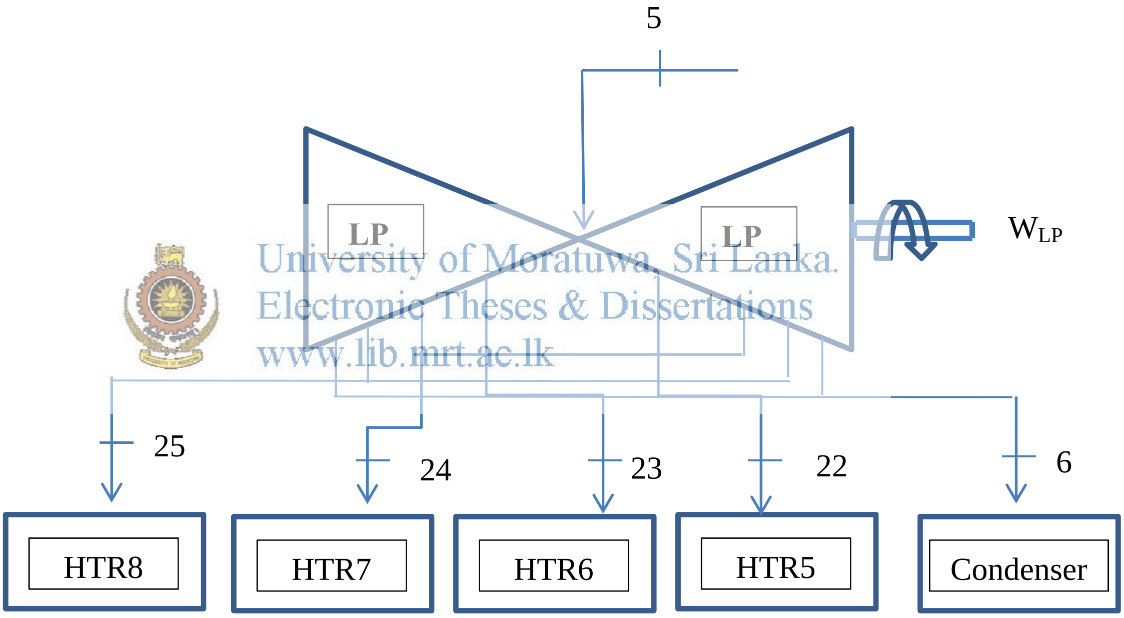

Figure 3.10: Sketch of Exergy input and output in LP turbine sub system

According to LP turbine Sub system

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_5$$

$$E_o = E_{22} + E_{23} + E_{24} + E_{25} + E_6$$

$$E_5 = E_{22} + E_{23} + E_{24} + E_{25} + E_6 + W_{LP\,Turbine} + \mathbf{E_D}$$

Where;

$$\dot{E}_5 = \dot{m}_5[(h_5 - h_0) - T_0 (S_5 - S_0)]$$

$$\dot{E}_6 = \dot{m}_6[(h_6 - h_0) - T_0 (S_6 - S_0)]$$

$$\dot{E}_{22} = \dot{m}_{22}[(h_{22} - h_0) - T_0 (S_{22} - S_0)]$$

$$\dot{E}_{23} = \dot{m}_{23}[(h_{23} - h_0) - T_0 (S_{23} - S_0)]$$

$$\dot{E}_{24} = \dot{m}_{24}[(h_{24} - h_0) - T_0 (S_{24} - S_0)]$$

$$\dot{E}_{25} = \dot{m}_{25}[(h_{25} - h_0) - T_0 (S_{25} - S_0)]$$

$$W_{IP\ Turbine} = \dot{m}\ (h_5 - h_6)$$

Therefore;

$$\mathbf{E_{D_{LP\ Turbine}}} = \{\dot{m}_5[(h_5 - h_0) - T_0 (S_5 - S_0)]\} - \{\dot{m}_6[(h_6 - h_0) - T_0 (S_6 - S_0)]\} - \{\dot{m}_{22}[(h_{22} - h_0) - T_0 (S_{22} - S_0)]\} - \{\dot{m}_{23}[(h_{23} - h_0) - T_0 (S_{23} - S_0)]\} - \{\dot{m}_{24}[(h_{24} - h_0) - T_0 (S_{24} - S_0)]\} - \{\dot{m}_{25}[(h_{25} - h_0) - T_0 (S_{25} - S_0)]\} - \{\dot{m}\ (h_5 - h_6)\}$$

$$\text{Exergy Efficency}_{LP\ Turbine} = \frac{W_{LP\ Turbine}}{E_{in} - E_{out}}$$

$$\textbf{Exergy Efficency}_{\mathbf{LP\ Turbine}} = \frac{W_{LP\ Turbine}}{E_5 - (E_{22} + E_{23} + E_{24} + E_{25} + E_6)}$$

3.12.5 Condenser

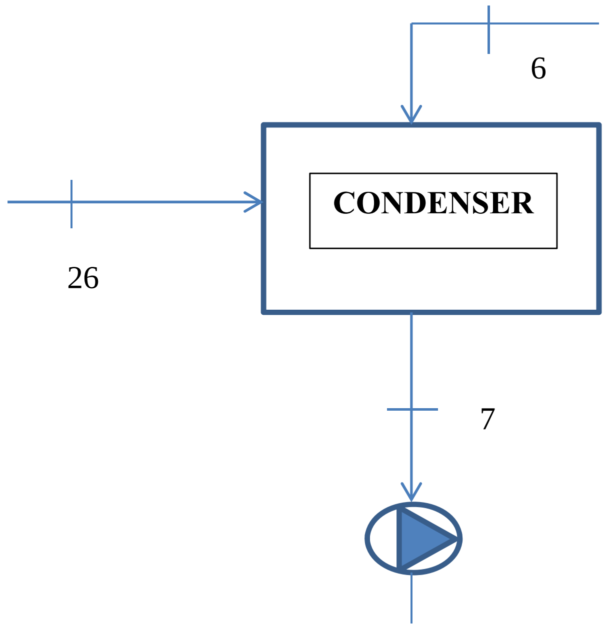

Figure 3.11: Sketch of Exergy input and output in Condenser sub system

According to Condenser Sub system

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_6 + E_{26}$$

$$E_o = E_7$$

$$E_6 + E_{26} = E_7 + \mathbf{E_D}$$

$$\dot{E}_6 = \dot{m}_6[(h_6 - h_0) - T_0\,(S_6 - S_0)]$$

$$\dot{E}_7 = \dot{m}_7[(h_7 - h_0) - T_0\,(S_7 - S_0)]$$

$$\dot{E}_{25} = \dot{m}_{26}[(h_{26} - h_0) - T_0\,(S_{26} - S_0)]$$

$$\mathbf{E_{D_{Condenser}}} = \{\dot{m}_6[(h_6 - h_0) - T_0\,(S_6 - S_0)]\} + \{\dot{m}_{26}[(h_{26} - h_0) - T_0\,(S_{26} - S_0)]\} - \{\dot{m}_7[(h_7 - h_0) - T_0\,(S_7 - S_0)]\}$$

$$\text{Exergy Efficency}_{\text{Condenser}} = \frac{E_D}{E_{in}}$$

$$\textbf{Exergy Efficency}_{\textbf{Condenser}} = \frac{E_D}{E_6 + E_{26}}$$

3.12.6 Condensate pump

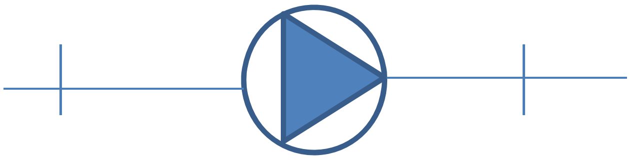

Figure 3.12: Sketch of Exergy input and output in Condensate pump sub system

According to Condenser Sub system condensate pump can be expressed explain as;

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_7$$

$$E_o = E_8$$

$$E_7 + W_{\text{condensate pump}} = E_8 + E_D$$

$$\dot{E}_7 = \dot{m}_7[(h_7 - h_0) - T_0\,(S_7 - S_0)]$$

$$\dot{E}_8 = \dot{m}_8[(h_8 - h_0) - T_0\,(S_8 - S_0)]$$

$$W_{\text{condensate pump}} = \dot{m}\;(h_{in} - h_{out})$$

$$\mathbf{E_{D_{con.pump}}} = \{\dot{m}_7[(h_7 - h_0) - T_0\,(S_7 - S_0)]\} + \{\dot{m}\;(h_{in} - h_{out})\} - \{\dot{m}_8[(h_8 - h_0) - T_0\,(S_8 - S_0)]\}$$

$$\text{Exergy Efficency}_{\text{Con.Pump}} = \frac{E_{out} - E_{in}}{W_{\text{Con.pump}}}$$

$$\textbf{Exergy Efficency}_{\textbf{Con.pump}} = 1 - \frac{E_8 - E_7}{W_{\text{Con.pump}}}$$

3.12.7 Boiler feed pump

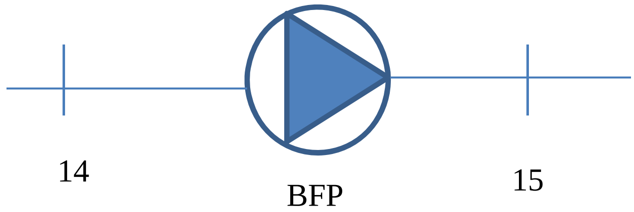

Figure 3.13: Sketch of Exergy input and output in Boiler feed pump sub system

According to the boiler feed pump

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{14}$$

$$E_o = E_{15}$$

$$E_{14} + W_{BFP} = E_{15} + E_D$$

$$\dot{E}_{14} = \dot{m}_{14}[(h_{14} - h_0) - T_0 (S_{14} - S_0)]$$

$$\dot{E}_8 = \dot{m}_{15}[(h_{15} - h_0) - T_0 (S_{15} - S_0)]$$

$$W_{BFP} = \dot{m} (h_{in} - h_{out})$$

$$\mathbf{E_{D_{BFP}}} = \dot{m}_{14}[(h_{14} - h_0) - T_0 (S_{14} - S_0)]\} + \{\dot{m} \ (h_{in} - h_{out})\} - \{\dot{m}_{15}[(h_{15} - h_0) - T_0 (S_{15} - S_0)]\}$$

$$\text{Exergy Efficency}_{BFP} = \frac{E_{out} - E_{in}}{W_{BFP}}$$

$$\textbf{Exergy Efficency}_{\mathbf{BFP}} = 1 - \frac{E_{15} - E_{14}}{W_{BFP}}$$

3.12.8 Feed water heater No: 01

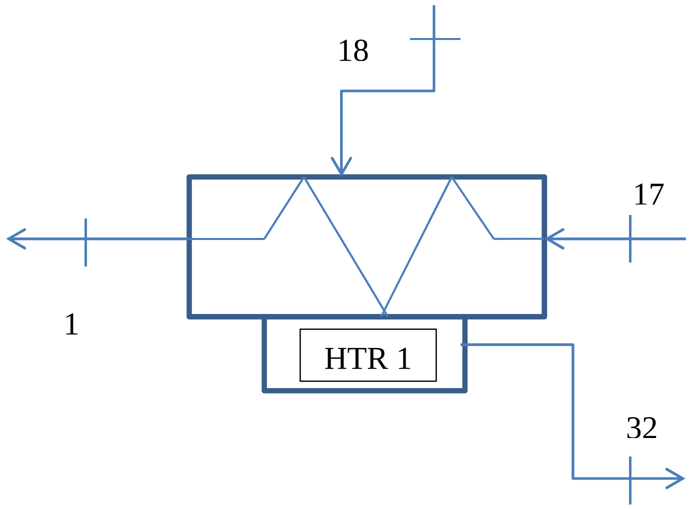

Figure 3.14: Sketch of Exergy input and output in feed water heater No.01

Considering High Pressure Heaters

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{18} + E_{17}$$

$$E_o = E_1 + E_{32}$$

$$E_{18} + E_{17} = E_{32} + E_1 + \mathbf{E_D}$$

$$\dot{E_{18}} = \dot{m_{18}}[(h_{18} - h_0) - T_0\,(S_{18} - S_0)]$$

$$\dot{E_{17}} = \dot{m_{17}}[(h_{17} - h_0) - T_0\,(S_{17} - S_0)]$$

$$\dot{E_1} = \dot{m_1}[(h_1 - h_0) - T_0\,(S_1 - S_0)]$$

$$\dot{E_{32}} = \dot{m_{32}}[(h_{32} - h_0) - T_0\,(S_{32} - S_0)]$$

$$\mathbf{E_{D_{HTR1}}} = \dot{m_{18}}[(h_{18} - h_0) - T_0\,(S_{18} - S_0)]\} + \{\dot{m_{17}}[(h_{17} - h_0) - T_0\,(S_{17} - S_0)]\} - \{\dot{m_{32}}[(h_{32} - h_0) - T_0\,(S_{32} - S_0)]\} - \{\dot{m_1}[(h_1 - h_0) - T_0\,(S_1 - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR1} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HTR1}} = 1 - \frac{E_D}{E_{18} - E_{32}}$$

3.12.9 Feed water heater No: 02

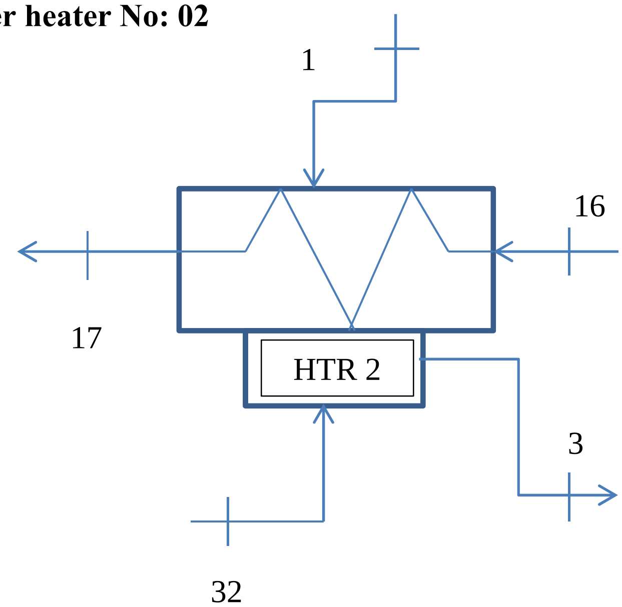

Figure 3.15: Sketch of Exergy input and output in feed water heater No.02

Considering High Pressure Heaters No: 02

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{19} + E_{16} + E_{32}$$

$$E_o = E_{31} + E_{17}$$

$$E_{19} + E_{16} + E_{32} = E_{31} + E_{17} + \mathbf{E_D}$$

$$\dot{E}_{19} = \dot{m}_{19}[(h_{19} - h_0) - T_0\,(S_{19} - S_0)]$$

$$\dot{E}_{16} = \dot{m}_{16}[(h_{16} - h_0) - T_0\,(S_{16} - S_0)]$$

$$\dot{E}_{32} = \dot{m}_{32}[(h_{32} - h_0) - T_0\,(S_{32} - S_0)]$$

$$\dot{E}_{31} = \dot{m}_{31}[(h_{31} - h_0) - T_0\,(S_{31} - S_0)]$$

$$\dot{E}_{17} = \dot{m}_{17}[(h_{17} - h_0) - T_0\,(S_{17} - S_0)]$$

$$\mathbf{E_{D_{HTR2}}} = \{\dot{m}_{19}[(h_{19} - h_0) - T_0\,(S_{19} - S_0)]\} + \{\dot{m}_{16}[(h_{16} - h_0) - T_0\,(S_{16} - S_0)]\} - \{\dot{m}_{32}[(h_{32} - h_0) - T_0\,(S_{32} - S_0)]\} - \{\dot{m}_{31}[(h_{31} - h_0) - T_0\,(S_{31} - S_0)]\} - \{\dot{m}_{17}[(h_{17} - h_0) - T_0\,(S_{17} - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR2} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HTR2}} = 1 - \frac{E_D}{(E_{19} + E_{32}) - E_{31}}$$

3.12.10 Feed water heater No: 03

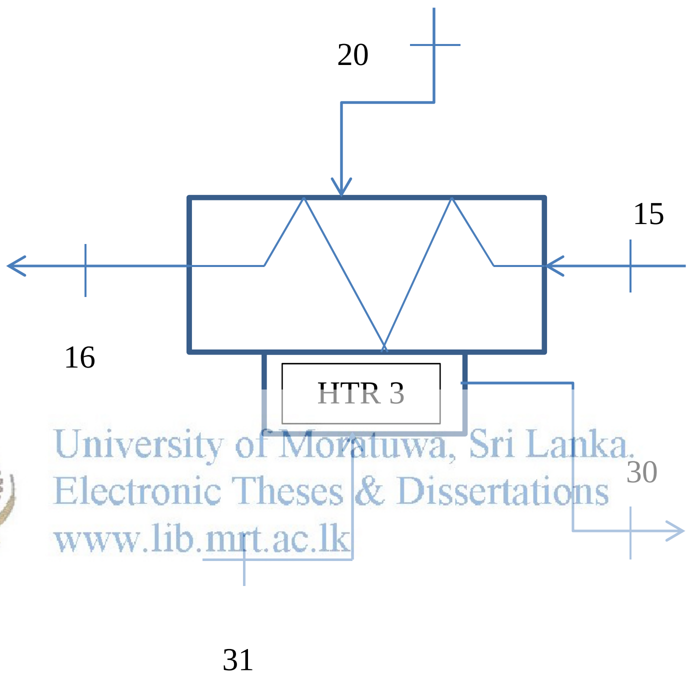

Figure 3.16: Sketch of Exergy input and output in feed water heater No.03

Considering High Pressure Heaters No: 03

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{20} + E_{31} + E_{15}$$

$$E_o = E_{16} + E_{30}$$

$$E_{20} + E_{31} + E_{15} = E_{16} + E_{30} + \mathbf{E_D}$$

$$\dot{E}_{20} = \dot{m}_{20}[(h_{20} - h_0) - T_0\,(S_{20} - S_0)]$$

$$\dot{E}_{31} = \dot{m}_{31}[(h_{31} - h_0) - T_0\,(S_{31} - S_0)]$$

$$\dot{E}_{15} = \dot{m}_{15}[(h_{15} - h_0) - T_0\,(S_{15} - S_0)]$$

$$\dot{E}_{16} = \dot{m}_{16}[(h_{16} - h_0) - T_0\,(S_{16} - S_0)]$$

$$\dot{E}_{30} = \dot{m}_{30}[(h_{30} - h_0) - T_0\,(S_{30} - S_0)]$$

$$\mathbf{E_{D_{HTR3}}} = \{\dot{m}_{20}[(h_{20} - h_0) - T_0\,(S_{20} - S_0)]\} + \{\dot{m}_{31}[(h_{31} - h_0) - T_0\,(S_{31} - S_0)]\} + \{\dot{m}_{15}[(h_{15} - h_0) - T_0\,(S_{15} - S_0)]\} - \{\dot{m}_{16}[(h_{16} - h_0) - T_0\,(S_{16} - S_0)]\} - \{\dot{m}_{30}[(h_{30} - h_0) - T_0\,(S_{30} - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR3} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\textbf{Exergy Efficency}_{HTR3} = 1 - \frac{E_D}{(E_{20} + E_{31}) - E_{30}}$$

3.12.11 Deaerator

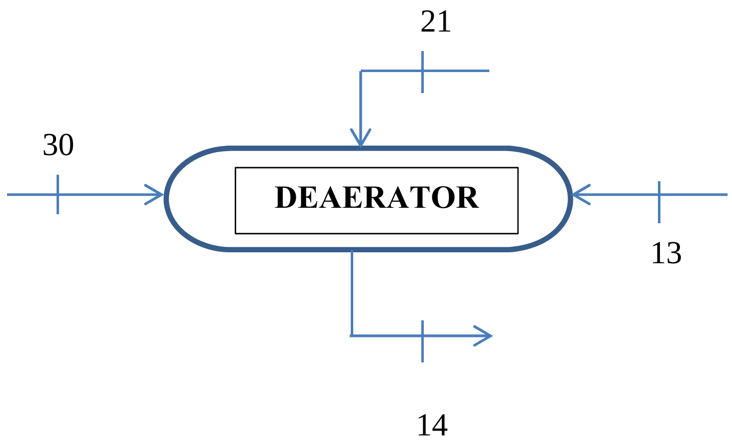

Figure 3.17: Sketch of Exergy input and output in Deaerator sub system

According to the Deaerator exergy flow balance;

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{30} + E_{21} + E_{13}$$

$$E_o = E_{14}$$

$$E_{30} + E_{21} + E_{13} = E_{14} + \mathbf{E_D}$$

$$\dot{E_{30}} = \dot{m_{30}}[(h_{30} - h_0) - T_0\,(S_{30} - S_0)]$$

$$\dot{E_{21}} = \dot{m_{21}}[(h_{21} - h_0) - T_0\,(S_{21} - S_0)]$$

$$\dot{E_{13}} = \dot{m_{13}}[(h_{13} - h_0) - T_0\,(S_{13} - S_0)]$$

$$\dot{E_{14}} = \dot{m_{14}}[(h_{14} - h_0) - T_0\,(S_{14} - S_0)]$$

$$\mathbf{E_{D_{Deaerator}}} = \{\dot{m_{30}}[(h_{30} - h_0) - T_0\,(S_{30} - S_0)]\} + \{\dot{m_{21}}[(h_{21} - h_0) - T_0\,(S_{21} - S_0)]\} + \{\dot{m_{13}}[(h_{13} - h_0) - T_0\,(S_{13} - S_0)]\} - \{\dot{m_{14}}[(h_{14} - h_0) - T_0\,(S_{14} - S_0)]\}$$

$$\text{Exergy Efficency}_{\text{Deaerator}} = 1 - \frac{E_D}{E_{Source}}$$

$$\textbf{Exergy Efficency}_{\textbf{Deaerator}} = 1 - \frac{E_D}{(E_{30} + E_{21} + E_{13})}$$

3.12.12 Feed water heater No: 05

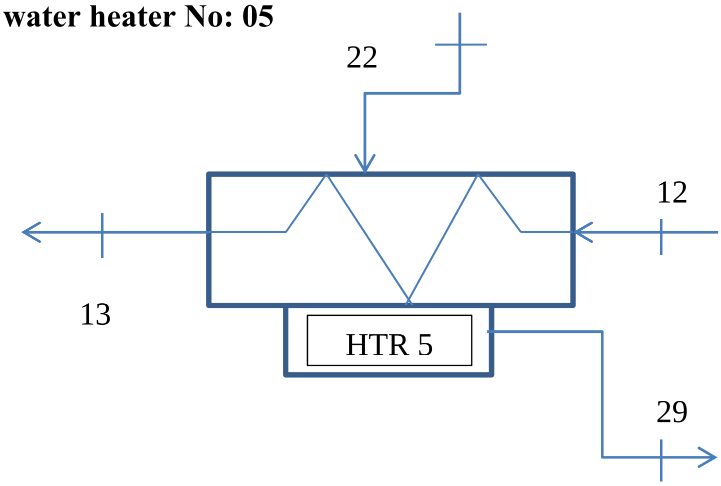

Figure 3.18: Sketch of Exergy input and output in feed water heater No.05

Considering Low Pressure Heaters

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{22} + E_{12}$$

$$E_o = E_{13} + E_{29}$$

$$E_{22} + E_{12} = E_{13} + E_{29} + \mathbf{E_D}$$

$$\dot{E}_{22} = \dot{m}_{22}[(h_{22} - h_0) - T_0 (S_{22} - S_0)]$$

$$\dot{E}_{12} = \dot{m}_{12}[(h_{12} - h_0) - T_0 (S_{12} - S_0)]$$

$$\dot{E}_{13} = \dot{m}_{13}[(h_{13} - h_0) - T_0 (S_{13} - S_0)]$$

$$\dot{E}_{29} = \dot{m}_{29}[(h_{29} - h_0) - T_0 (S_{29} - S_0)]$$

$$\mathbf{E_{D_{HTR5}}} = \{\dot{m}_{22}[(h_{22} - h_0) - T_0 (S_{22} - S_0)]\} + \{\dot{m}_{12}[(h_{12} - h_0) - T_0 (S_{12} - S_0)]\} - \{\dot{m}_{13}[(h_{13} - h_0) - T_0 (S_{13} - S_0)]\} - \{\dot{m}_{29}[(h_{29} - h_0) - T_0 (S_{29} - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR5} = 1 - \frac{E_D}{\Delta E_{source}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HTR5}} = 1 - \frac{E_D}{E_{22} - E_{29}}$$

3.12.13 Feed water heater No: 06

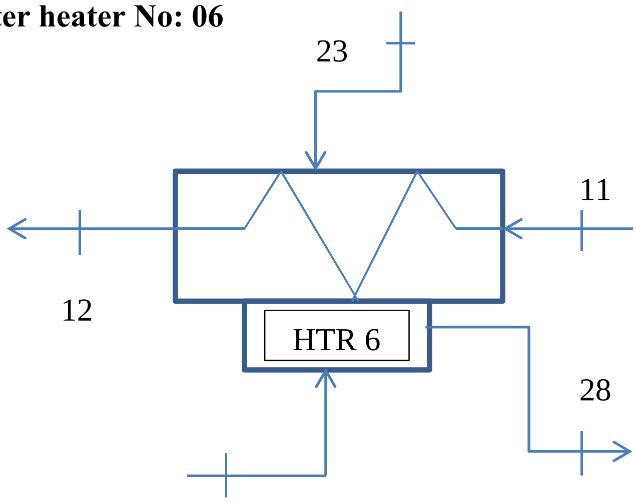

Figure 3.7: Sketch of Exergy input and output in feed water heater No: 06

Considering Low Pressure Heaters No: 06

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{11} + E_{23} + E_{29}$$

$$E_o = E_{12} + E_{28}$$

$$E_{11} + E_{23} + E_{29} = E_{12} + E_{28} + \mathbf{E_D}$$

$$\dot{E}_{11} = \dot{m}_{11}[(h_{11} - h_0) - T_0 (S_{11} - S_0)]$$

$$\dot{E}_{23} = \dot{m}_{23}[(h_{23} - h_0) - T_0 (S_{23} - S_0)]$$

$$\dot{E}_{29} = \dot{m}_{29}[(h_{29} - h_0) - T_0 (S_{29} - S_0)]$$

$$\dot{E}_{12} = \dot{m}_{12}[(h_{12} - h_0) - T_0 (S_{12} - S_0)]$$

$$\dot{E}_{28} = \dot{m}_{28}[(h_{28} - h_0) - T_0 (S_{28} - S_0)]$$

$$\mathbf{E_{D_{HTR6}}} = \{\dot{m}_{11}[(h_{11} - h_0) - T_0 (S_{11} - S_0)]\} + \{\dot{m}_{23}[(h_{23} - h_0) - T_0 (S_{23} - S_0)]\} + \{\dot{m}_{29}[(h_{29} - h_0) - T_0 (S_{29} - S_0)]\} - \{\dot{m}_{12}[(h_{12} - h_0) - T_0 (S_{12} - S_0)]\} - \{\dot{m}_{28}[(h_{28} - h_0) - T_0 (S_{28} - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR6} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HTR6}} = 1 - \frac{E_D}{(E_{23} + E_{29}) - E_{28}}$$

3.12.14 Feed water heater No: 07

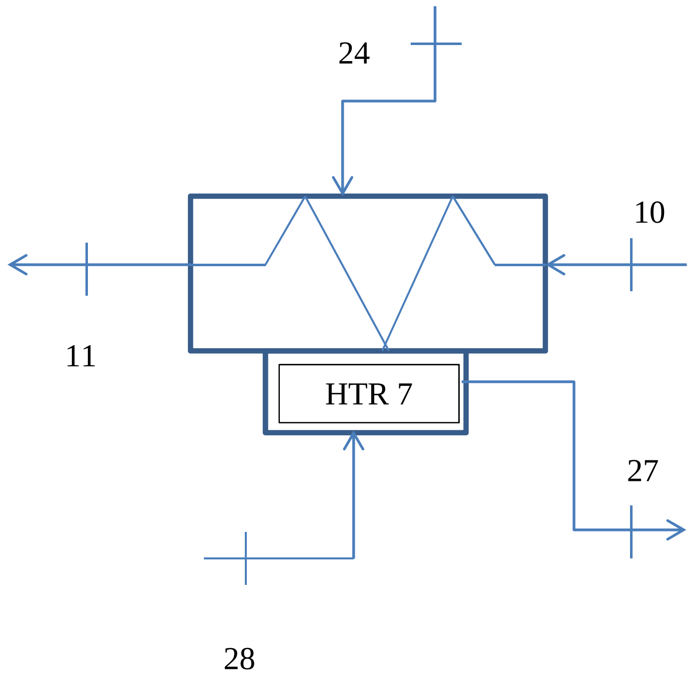

Figure 3.7: Sketch of Exergy input and output in feed water heater No.07

Considering Low Pressure Heaters No: 07

$$\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D$$

$$E_i = E_{10} + E_{28} + E_{24}$$

$$E_o = E_{11} + E_{27}$$

$$E_{10} + E_{28} + E_{24} = E_{11} + E_{27} + \mathbf{E_D}$$

$$\dot{E}_{10} = \dot{m}_{10}[(h_{10} - h_0) - T_0 (S_{10} - S_0)]$$

$$\dot{E}_{28} = \dot{m}_{28}[(h_{28} - h_0) - T_0 (S_{28} - S_0)]$$

$$\dot{E}_{24} = \dot{m}_{24}[(h_{24} - h_0) - T_0 (S_{24} - S_0)]$$

$$\dot{E}_{11} = \dot{m}_{11}[(h_{11} - h_0) - T_0 (S_{11} - S_0)]$$

$$\dot{E}_{27} = \dot{m}_{27}[(h_{27} - h_0) - T_0 (S_{27} - S_0)]$$

$$
\begin{aligned}
E_{D_{HTR7}} = {} & \{\dot{m}_{10}[(h_{10} - h_0) - T_0\,(S_{10} - S_0)]\} + \{\dot{m}_{28}[(h_{28} - h_0) - T_0\,(S_{28} - S_0)]\} \\
& + \{\dot{m}_{24}[(h_{24} - h_0) - T_0\,(S_{24} - S_0)]\} \\
& - \{\dot{m}_{11}[(h_{11} - h_0) - T_0\,(S_{11} - S_0)]\} - \{\dot{m}_{27}[(h_{27} - h_0) \\
& - T_0\,(S_{27} - S_0)]\}
\end{aligned}
$$

$$
\text{Exergy Efficency}_{HTR7} = 1 - \frac{E_D}{\Delta E_{Source}}
$$

$$
\textbf{Exergy Efficency}_{\mathbf{HTR7}} = 1 - \frac{E_D}{(E_{24} + E_{28}) - E_{27}}
$$

3.12.15 Feed water heater No: 08

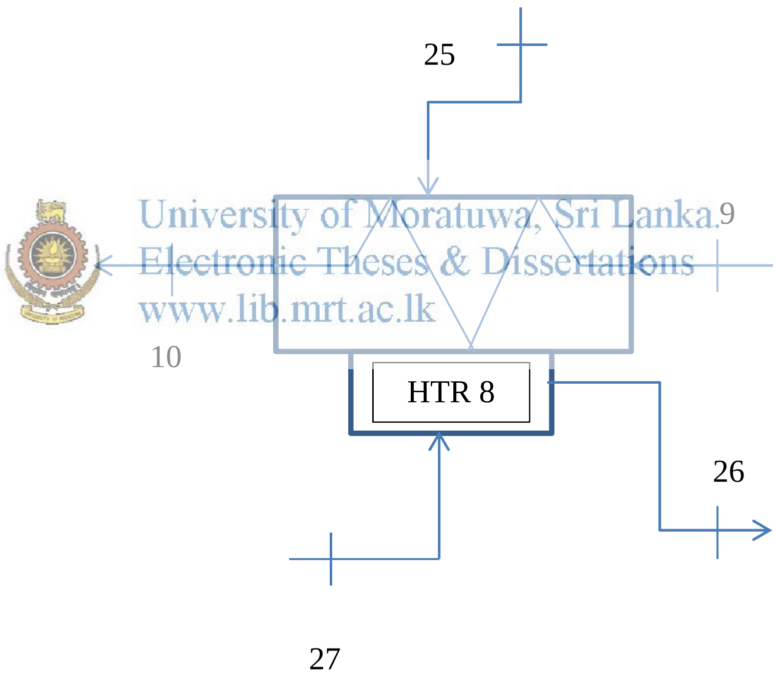

Figure 3.7: Sketch of Exergy input and output in feed water heater No.08

Considering Low Pressure Heaters No: 08

$$
\sum_{i=1}^{i} E_i = \sum_{o=1}^{o} E_o + E_D
$$

$$
E_i = E_9 + E_{25} + E_{27}
$$

$$
E_o = E_{10} + E_{26}
$$

$$E_9 + E_{25} + E_{27} = E_{10} + E_{26} + \mathbf{E_D}$$

$$\dot{E}_9 = \dot{m}_9[(h_9 - h_0) - T_0 (S_9 - S_0)]$$

$$\dot{E}_{25} = \dot{m}_{25}[(h_{25} - h_0) - T_0 (S_{25} - S_0)]$$

$$\dot{E}_{27} = \dot{m}_{27}[(h_{27} - h_0) - T_0 (S_{27} - S_0)]$$

$$\dot{E}_{10} = \dot{m}_{10}[(h_{10} - h_0) - T_0 (S_{10} - S_0)]$$

$$\dot{E}_{26} = \dot{m}_{26}[(h_{26} - h_0) - T_0 (S_{26} - S_0)]$$

$$\mathbf{E_{D_{HTR8}}} = \{\dot{m}_9[(h_9 - h_0) - T_0 (S_9 - S_0)]\} + \{\dot{m}_{25}[(h_{25} - h_0) - T_0 (S_{25} - S_0)]\} - \{\dot{m}_{27}[(h_{27} - h_0) - T_0 (S_{27} - S_0)]\} - \{\dot{m}_{10}[(h_{10} - h_0) - T_0 (S_{10} - S_0)]\} - \{\dot{m}_{26}[(h_{26} - h_0) - T_0 (S_{26} - S_0)]\}$$

$$\text{Exergy Efficency}_{HTR8} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\textbf{Exergy Efficency}_{\mathbf{HTR8}} = 1 - \frac{E_D}{(E_{25} + E_{27}) - E_{26}}$$

Table 3.2: Summary of set of equation of Exergy destruction & Exergy efficiency of major equipment in coal power plants

Equipment	Exergy Destruction (E_D)	Exergy Efficiency ($\acute{\eta}$)
Boiler	$E_D = (E_{34} + E_{35} + E_1 + E_3) - (E_2 + E_4 + E_{36} + E_{33})$	$\acute{\eta} = 1 - \frac{E_D + E_{33} + E_{36}}{E_{34} + E_{35} + E_1}$
HP Turbine	$E_D = E_2 - (E_3 + E_{18} + E_{19} + W_{HP\ Turbine})$	$\acute{\eta} = \frac{W_{HP\ Turbine}}{E_2 - (E_{18} + E_{19} + E_3)}$
IP Turbine	$E_D = E_4 - (E_{20} + E_{21} + E_5 + W_{IP\ Turbine})$	$\acute{\eta} = \frac{W_{IP\ Turbine}}{E_4 - (E_{20} + E_{21} + E_5)}$
LP Turbine	$E_D = E_5 - (E_{22} + E_{23} + E_{24} + E_{25} + E_6 + W_{LP\ Turbine})$	$\acute{\eta} = \frac{W_{LP\ Turbine}}{E_5 - (E_{22} + E_{23} + E_{24} + E_{25} + E_6)}$
Condenser	$E_D = E_6 + E_{26} - E_7$	$\acute{\eta} = \frac{E_D}{E_6 + E_{26}}$
Condensate Pump	$E_D = E_7 + W_{condensate\ pump} - E_8$	$\acute{\eta} = 1 - \frac{E_8 - E_7}{W_{Con.pump}}$
Boiler Feed Pump	$E_D = E_{14} + W_{BFP} - E_{15}$	$\acute{\eta} = 1 - \frac{E_{15} - E_{14}}{W_{BFP}}$
HTR1	$E_D = (E_{18} + E_{17}) - (E_{32} + E_1)$	$\acute{\eta} = 1 - \frac{E_D}{E_{18} - E_{32}}$
HTR2	$E_D = (E_{19} + E_{16} + E_{32}) - (E_{31} + E_{17})$	$\acute{\eta} = 1 - \frac{E_D}{(E_{19} + E_{32}) - E_{31}}$
HTR3	$E_D = (E_{20} + E_{31} + E_{15}) - (E_{16} + E_{30})$	$\acute{\eta} = 1 - \frac{E_D}{(E_{20} + E_{31}) - E_{30}}$
Deaerator	$E_D = E_{30} + E_{21} + E_{13} - E_{14}$	$\acute{\eta} = 1 - \frac{E_D}{(E_{30} + E_{21} + E_{13})}$
LPH5	$E_D = (E_{22} + E_{12}) - (E_{13} + E_{29})$	$\acute{\eta} = 1 - \frac{E_D}{E_{22} - E_{29}}$
LPH6	$E_D = (E_{11} + E_{23} + E_{29}) - (E_{12} + E_{28})$	$\acute{\eta} = 1 - \frac{E_D}{(E_{23} + E_{29}) - E_{28}}$
LPH7	$E_D = (E_{10} + E_{28} + E_{24}) - (E_{11} + E_{27})$	$\acute{\eta} = 1 - \frac{E_D}{(E_{24} + E_{28}) - E_{27}}$
LPH8	$E_D = (E_9 + E_{25} + E_{27}) - (E_{10} + E_{26})$	$\acute{\eta} = 1 - \frac{E_D}{(E_{25} + E_{27}) - E_{26}}$

CHAPTER 04

4.0 Introduction of Lak Vijaya Coal Power Station

Figure 4.1: Picture of Lak Vijaya coal power station

Lak Vijaya Coal power station is the biggest power station in Sri Lanka and it is the one and only coal power plant in the country. It is located near the village of Narakkalli on the Kalpitiya Peninsula, approximately 12 km west of the city of Puttalam. The total capacity of power plant is 900MW. Lak Vijaya coal power plant is already generating 600MW and remaining 300MW will be added to power system in the near future. A pre-feasibility report for the plant was done in 1993 and detailed feasibility study was begun in 1996 and completed in 2000 including EIA study.

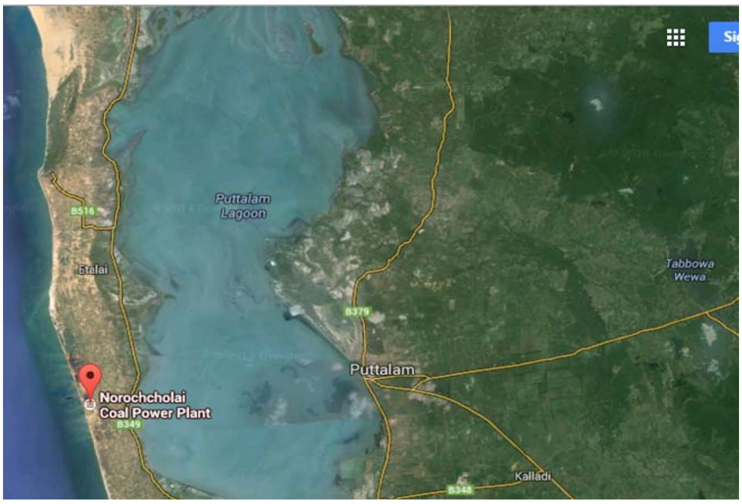

Figure 4.2: Location of Lak Vijaya coal power plant

The full capacity of the plant has been planned to be completed in 2 phases. The first phase comprises the installation of a unit with a gross capacity of 300 MW with 85% plant factor [15], providing 2122 GWh per annum. Construction of first phase had begun in year 2004 and completed in 2010 and commissioned in midyear 2011. The phase 2 will be completed in the end of 2014. The total project cost is estimated for phase 1 as 455 million USD and phase 2 as 950 million USD [15].

The Power Plant is fueled by imported coal of high quality and low Sulphur content. The mode of coal supply and especially its delivery methods to site are more important criteria for the economic performance of the power plant .Coal required to fuel the power plant is imported from Indonesia and transported by sea. Light oil is used to support the coal combustion at low load, during the unit startup and shutdown.

4.1 Design coal characteristics of LVPS

Table 4.1: Coal characteristic which is used in LVPS [16]

Particle Size	< 50 mm
Moisture Content	< 12 %
Gross Calorific Value	5920-6900 kcal/kg
Ash Content	< 15 %
Bulk Density	0.8-0.85 t/m^3
Sulphur content	0.2 –1.2%
Volatile matter	> 22%
Fixed carbon	> 43%.

4.2 Introduction of boiler in LVPS unit 01

The boiler HG-1025/17.3-YM25 is of subcritical pressure, once reheat, natural circulation, single drum, semi-out door, tangential firing, balanced draft, steel suspension structure type, designed to burn the range of imported good quality thermal bituminous coals specified. The boiler plant is equipped with low NOx burners, equipment silencers, ESP and 150 meter high stack for environmental controls. In addition, a flue gas desulphurization system is included [16].

4.2.1 Specific data of boiler sub system

Table 4.2: Specific Data of Boiler in LVPS unit 01[16]

Fuel	Coal
Igniting oil	Light oil (Diesel)
Draft system	Balanced draft
Firing system	Tangential corner firing & Tilting burners
Maximum continuous rating (BMCR)	1025 t/h
Steam pressure at superheater outlet	17.3 MPa
Steam temperature at superheater outlet	541 °C
Reheat steam inlet pressure	3.99 MPa
Reheat steam outlet pressure	3.79 MPa
Reheat steam temperature inlet	337.8 °C
Reheat steam temperature outlet	541 °C
Boiler feed water temp	282.1 °C
Boiler efficiency (higher heat value)	Around 88.58%
Minimum Stable load (MSL)	Around 35%
Steam temperature control method of super heater	Two-stage water spray
Steam temperature control method of Re heater:	Tilting burners and emergency water spray

4.2.2 Boiler furnace

The furnace is enclosed by welded membrane water wall tubes. The water wall consists of four parts. There are upper, intermediate, lower and burner panel. Except for the burner panels, each part is classed into front, rear and side elements. The lower front and rear water wall tubes have an angle of 55° with the horizontal, forming the cold ash hopper. To ensure liable boiler water circulation, water walls are classed into 28 circuits according to geometric and heating properties. All load of the water wall is hanged to the boiler top girder through the hangers. During the operation the water wall expands downward as a whole. The adjustment of hangers will ensure that the upper header axial is horizontal without any deflection.

4.2.3 Super heater system of boiler

The super heaters in this boiler consist of 5 major elements. Which are SH division panel, SH platen, SH finish, low temperature vertical SH, low temperature horizontal SH.

4.2.4 Re-heater system of boiler

Re heater system of boiler mainly includes wall radiant RH, RH platen and RH finishing panels.

4.2.5 Economizer

The economizer is a major waste heat recovery item in boiler sub system. This is used to absorb wasted flue energy to boiler feed water. The LVPS unit 01 economizer is made from 20G material and those tubes are smooth tube type. The heating surface is around 5741m^2 and pipe outer diameter and thickness of pipes are respectively 51mm & 6mm [16].

4.2.6 Air preheater

There are trisected two air pre heaters fixed with the boiler. It is used to heat exchange between flue gas and air is in counter flow. The air preheater was equipped with double axial and radial seals device to keep the amount of leakage air to a minimum.

4.3 Introduction of turbine systems in LVPS unit 01

The steam turbine N300/541/541/17.3 is subcritical, reheat, two casings and double exhaust, condensing steam type. 300MW capacity turbine is divided in to three major parts based on their working pressure called as High pressure, intermediate and Low pressure turbine [17].

4.3.1 HP Turbine

HP turbine made as HP-IP portion together 130Cr1MolV heat-resistant alloy steel non-central hole structure, high voltage part for the drum structure, medium part is a drum-shaped structure, a total of 6983.6rnm long, with the maximum leaf outer diameter 1532 mm. HP flow path is counterclockwise arranged, All moving blade uses integral shroud which is connected to form a circle. Reverse T type moving blades are used for HP turbine. The steam entering the HP turbine is discharged into reheater at both sides of outer casing after expanding through one impulse control stage and 12 reaction HP stages.

4.3.2 IP Turbine

IP turbine has 9 reaction stages and it is also connected to HP turbine as one set .IP flow path is clockwise arranged. All moving blades use integral shroud which is connected to form a circle and P type moving blades are used for IP turbine.

4.3.3 LP Turbine

LP turbine made as 30Cr2Ni4MoV alloy steel integral structure with total length of 8181.6mm and the maximum external diameter of 3528mm with blades. LP rotor is of double flow symmetric structure with Stage 1 to 5 of half drum structure and stage 6-7 having big integral wheel. 900mm L-0 blade is used for LP turbine for good strength and good transonic performance. Rigid coupling is used between LP rotor and generator rotor.

4.3.4 Specific data of turbine system

Table 4.3: Specific Data of Turbine in LVPS unit 01[17].

Steam pressure at HP turbine stop valve	16.7 MPa
Steam temperature at HP turbine stop valve	538 °C
Steam temperature at IP turbine stop valve	538 °C
Final feed water temperature	274.2 °C
HP turbine bypass capacity	% 60 TMCR flow
LP turbine bypass capacity	% 60 TMCR flow
Turbine speed nominal	3000 rpm

4.4 Introduction of generator in LVPS unit 01

The generator is a two-pole, cylindrical rotor type, synchronous machine. It has a closed-circuit hydrogen cooling system to cool the stator core and the rotor, including direct hydrogen cooling of field winding. The stator winding, leads and terminals are cooled by deionized water.

4.5 Introduction of cooling system in LVPS unit 01

The Power Plant is located by the sea shore. In this plant, the once-through cooling system is adopted. Cooling water is taken from the Indian Ocean. The water flows through the intake installation to the inlet fore bay of the cooling water pump house. Then after being filtered through mechanical bar screen and traveling screen, it is pumped to the condenser and other plant heat exchangers via pressurized FRP pipes by the cooling water pump after heat-exchanging, the cooling water is discharged back to the sea. To maintain the water head of the cooling water pumps, on the drainage pipes, a seal pit is arranged. After the seal pit, the drainage water is used as the water source of the seawater FGD system, then the water is discharged to the sea through a drainage culvert by gravity.

Also the main function of the Cooling Water System (CWS) is to provide cooling water to the condenser of the steam turbine and the various auxiliary coolers inside the turbine house.

4.5.1 Specific data of power plant cooling system

Table 4.4: Specific Data of cooling system in LVPS unit 01[18]

Condenser cooling capacity (VWO)	1537 kJ/h
FGD capacity	180.83 kJ/h
Condenser cooling water flow rate	15.33 m^3/s
Auxiliary coolers cooling water flow rate	0.92 m^3/s
Total CW flow rate	16.25 m^3/s
Design of Seawater temperature	28 °C
Total CW temperature rise (VWO)	7 °C

4.6 Introduction of condenser cooling system in LVPS unit 01

The condenser is equipped with 16000 special tubes to condense low pressure exhaust steam. The main cooling water is taken from sea in this power plant. Therefore condenser tubes are manufactured using special Titanium material to protect from corrosion.

Table 4.5: Specific Data of condenser in LVPS unit 01[18]

Condenser pressure (Absolute)	7.0 kPa
Cooling water inlet temperature	28.0 °C
Cooling water temperature rise	≤ 7.0 °C
Cleanliness factor for surface calculation	0.85
Min. hot well capacity	≥ 55 m^3

4.7 Introduction of feed water system in LVPS unit 01

The function of the boiler feed-water system is to deliver feed-water from the outlet of deaerator feed-water tank to the inlet of boiler economizer inlet header. In the process of handling the feed-water is heated by the extraction steam from the steam turbine to improve the cycle efficiency. The system also supplies the feed-water to the boiler super heater attemperator to moderate the superheated steam temperature. Besides, feed-water tapped from the feed-water pump intermediate stage is sent to the two sides of attemperator before the steam reheaters to protect them from overheat. The feed-water system also supplies feed-water to turbine HP by-pass system, acting as attemperating water to reduce the main steam temperature. The feed-water system is provided with three numbers of motor operated pumps which has 50% of total capacity of feed-water demand. Variable speed hydraulic coupling is provided for each pump to meet the pressure capacity requirements of the system with the varying loads. Further booster pump is provided to maintain the required suction pressure at the main feed water pump.

4.8 Feed water heaters in LVPS unit 01

Three numbers of full capacity, horizontal type, double flow HP heaters are provided. Those heaters are designated No.3, 2 and 1 respectively in the order along the direction of water flow. The feed-water is heated by turbine extraction steam while passing through the tube bundles. Three heaters are provided with a motor operated by-pass in order that it may be isolated during a fault. Also the condensate system is equipped with another four numbers of LP heaters to increase the feed water temperature of boiler system. Those heaters are also double flow horizontal type heaters which are heated by low pressure steam from LP turbine extraction steam. Those LP heaters can be by-passed individually in any fault condition of heater occurred while keeping the power plant in operation.

4.9 Emission control system in LVPS unit 01

In this plant, low Sulphur content coal (less than 0.5%) is used as the fuel to minimize the generation of SO_2. Seawater desulphurization system is provided to remove 90% SO_2 from flue gas [19]. Low NO_X burners are provided to reduce the NO_X emission rate. High efficiency ESP (Dust removal efficiency no less than 99.5%) is equipped to lower the concentration of dust at the outlet of ESP [19]. By taking the above measures, it is calculated that the emit concentration of SO_2 is 56 mg/MJ, concentration of NO_X is 260 mg/MJ, concentration of dust is 15 mg/MJ, meet the environmental requirements. At the BMCR condition, the amount of NOx emitted to the air is 0.687 t/h, SO_2 emitted to the air is 0.148 t/h, and dust emitted to the air is 0.038 t/h. Without seawater FGD, concentration of SO_2 is 373 mg/MJ [19]. Power plant monitoring tower, Kalmunai point monitoring tower, jetty monitoring tower and Puttalam monitoring towers are located to control and inspect emission levels of LVPS plant.

4.10 Ash removing system in LVPS unit 01

Ash handling and slag removing system adopts method of handling ash and slag separately, handling dry ash in dry pneumatically. For the slag, it can be taken directly from slag silo for utilization. For the dry ash, it can be loaded to truck directly from ash silo and transported to users for integrated utilization. For the ash not for integrated utilization, it can be mixed to be wet under ash silo and transported to ash yard by dump truck. ESP adopts four (4) electric fields of electro static precipitator with ash handling efficiency of 99.5%. Ash in ash hopper of ESP is transported to ash silo for storage in positive-pressure pneumatic transportation manner. Slag removing system adopts mechanical slag removing; its discharged sewage water is reused after reclaiming and processing. The boiler is solid state slag removing type, slag at bottom of the boiler is taken out by scrapper and transported to slag silo directly for storage.

CHAPTER 05

5.0 Approaches to Case Study (Calculations)

Table 5.1: Steam water properties of LVPS unit 01 in design condition [20]

State	Temperature (°C) T	Pressure (MPa) P	Flow Rate (t/h) m	Enthalpy (kJ/kg) h	Entropy (kJ/kgK) S
1	274.60	19.80	911.70	1204.60	2.978
2	538.00	16.70	911.69	3396.90	6.415
3	326.90	3.74	762.84	3043.00	6.528
4	538.00	3.37	762.84	3537.60	7.287
5	355.73	0.91	697.50	3172.60	7.366
6	39.00	0.01	585.36	2376.60	0.559
7	39.00	0.01	699.51	163.40	0.559
8	39.40	3.50	699.51	165.10	0.564
9	40.00	3.50	699.51	167.50	0.572
10	60.50	3.00	699.51	254.40	0.837
11	84.40	2.50	699.51	354.90	1.127
12	105.20	2.00	699.51	442.20	1.365
13	138.00	0.89	699.51	581.20	1.719
14	174.20	0.89	911.70	740.00	2.083
15	178.00	20.0	911.70	765.50	2.120
16	203.40	20.0	911.70	875.20	2.363
17	243.40	20.0	911.70	1055.90	2.733
18	389.70	6.06	65.41	3152.40	6.497
19	326.90	3.74	70.94	3043.00	6.528
20	442.50	1.76	28.80	3344.80	7.326
21	356.00	0.93	38.52	3172.60	7.357
22	252.90	0.39	38.81	2970.80	7.406
23	155.30	0.14	23.95	2783.90	7.476
24	88.50	0.07	26.90	2653.30	7.499
25	64.40	0.02	22.85	2515.70	7.840
26	45.60	-	112.52	190.70	0.646
27	66.00	-	89.67	276.30	0.906
28	90.00	-	62.77	376.90	1.193
29	110.70	-	38.81	464.50	1.426
30	183.60	-	167.97	779.00	2.174
31	208.90	-	136.35	892.80	2.414
32	249.00	-	65.41	1080.70	2.784
33	346.00	-	1050.00	-	-
34	30.00	-	1000.00	-	-

5.1 Exergy values calculation for design parameters

Considering the equation (01) in Chapter 03;

$$E = E^{KN} + E^{PT} + E^{PH} + E^{CH}$$

The kinetic and potential exergy are negligible compared to other two components. Therefore we can consider only physical and chemical exergy of relevant state. Also when considering that some states are totally depended on physical exergy and some are on chemical exergy values.

$$E = E^{PH} + E^{CH}$$

Physical exergy of liquid components;

$$E^{PH} = (h - h_0) - T_0 (S - S_0)$$

Physical exergy of gas component

$$E^{PH} = C_p (T - T_0) - C_p T_0 \ln(T/T_0)$$

Therefore considering above system flow diagram, State 01 exergy value can be calculated as follows. Reference environmental condition was taken as T_o=27 ^oC, P_o=101 kPa.

$$E_1 = (h - h_0) - T_0 (S - S_0)$$

$$T = 274.60°C$$

$$P = 19.80 \text{ MPa}$$

$$h = 1204.60 \text{ kJ/kg}$$

$$h_0 = 113.20 \text{ kJ/kg}$$

$$S = 2.978 \text{kJ/kgK}$$

$$S_0 = 0.39 \text{ kJ/kgK}$$

$$\dot{m} = 911.70 \text{ t/h}$$

$$E_1 = (1204.60 \text{ kJ/kg} - 113.20 \text{ kJ/kg}) - 300 \text{ K}(2.978 \text{ kJ/kgK} - 0.39 \text{ kJ/kgK})$$

$$E_1 = 315.0 \text{ kJ/kg}$$

$$\dot{E_1} = 315.0 \text{ kJ/kg} \times 253.25 \text{ kg/s}$$

$\dot{E_1} = 79773.75 \text{ kJ/s}$

$\dot{E_1} = 79773.75 \text{ kW}$

Considering state 02;

$E_2 = (h - h_0) - T_0 (S - S_0)$

$T = 538.00°C$

$P = 16.70 \text{ Mpa}$

$h = 3396.90 \text{ kJ/kg}$

$h_0 = 113.20 \text{ kJ/kg}$

$S = 6.415 \text{ kJ/kgK}$

$S_0 = 0.39 \text{ kJ/kgK}$

$\dot{m} = 911.69 \text{ t/h}$

$E_2 = (3396.90 \text{ kJ/kg} - 113.20 \text{ kJ/kg}) - 300 \text{ K}(6.415\text{kJ/kgK} - 0.39 \text{ kJ/kgK})$

$E_2 = 1476.2 \text{ kJ/kg}$

$\dot{E_2} = 1476.2 \text{ kJ/kg} \times 253.25 \text{ kg/s}$

$\dot{E_2} = 373847.65 \text{ kJ/s}$

$\dot{E_2} = 373847.65 \text{ kW}$

The exergy value of other all states which are in liquid state can easily find out using above calculations.

Considering the states which are in gaseous states;

$E^{PH} = C_p (T - T_0) - C_p T_0 \ln(T/T_0)$

${C_p}_{Air}$ at 27°C and 110 kPa = 1kJ/kgK

Therefore exergy value of input air;

$T = 30 °C$

$T_0 = 27 °C$

$$E_{34} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$$

$$E_{34} = 1kJ/kgK \times (303K - 300K) - 1kJ/kgK \times 300K \times \ln(303K/300K)$$

$$E_{34} = 0.0149kJ/kg$$

$$\dot{E}_{34} = 0.0149kJ/kg \times 277.77kg/s$$

$$\dot{E}_{34} = 4.139\ kJ/s$$

$$\dot{E}_{34} = 4.139\ kW$$

Exergy value of flue gas (before Air pre heater);

$$E^{PH} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$$

$C_{p_{Air}}$ at 27 °C and 110 kPa = 1kJ/kgK

Therefore exergy value of input air;

$T = 345$ °C

$T_0 = 27$ °C

$$E_{33} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$$

$$E_{33} = 1kJ/kgK \times (618K - 300K) - 1kJ/kgK \times 300K \times \ln(618K/300K)$$

$$E_{33} = 101.18\ kJ/kg$$

$$\dot{E}_{33} = 101.18kJ/kg \times 277.77kg/s$$

$$\dot{E}_{33} = 28107.05\ kJ/s$$

$$\dot{E}_{33} = 28107.05\ kW$$

Chemical Exergy Calculation of flue gas;

Considering the fuel using in LVPS coal power plant;

Table 5.2: Specific data of coal on air dried basis

Inherent Moisture	4.40%
Ash	15.15%
Volatile Matter	40.51%
Fixed Carbon	39.94%
Sulphur	0.60%

Table 5.3: specific data of coal on dry Basis

Ash	15.85%
Volatile Matter	42.37%
Fixed Carbon	41.78%
Sulphur	0.63%

Table 5.4: Ultimate analysis of coal

C	63.75%
H	4.5%
N	1.25%
S	2.51%
Cl	0.29%
Ash	9.7%
M	11.12%
O	6.88%

Considering equation No (15) of Chapter 03, Chemical exergy of flue gas

$$\bar{e}_{ch} = \sum x_n (\bar{e}_{ch})_n + \bar{R} T_0 \sum x_n \ln x_n$$

x_n = Mole fraction of nth component

$\bar{R}$ = Universal Gas Constant

Table 5.5: Mole fraction of chemical component

	%	mole	Mole/mole$_C$
C	63.75	5.313	1
H	4.5	4.5	0.85
N	1.25	0.3125	0.06
S	2.51	0.0784	0.015
O	6.88	0.43	0.081

Therefore;

$CH_{0.85}N_{0.06}S_{0.015}O_{0.081}$

Combustion equation for coal

$CH_{0.85}N_{0.06}S_{0.015}O_{0.081} + \propto \times (O_2 + 3.78N_2) = CO_2 + 0.425H_2O + 0.015SO_2 + (3.78 \propto + 0.03)N_2$

$\propto = 1 + 0.425 + 0.015 - 0.0405$

$\propto = 1.19$

N_T = Total No of moles in combustion gas

= 1+0.425+0.015+4.52

= 5.968

Mole fraction of combustion products

Y_{CO2} = 1/5.97 = 0.167

Y_{H2O} = 0.425/5.97 = 0.071

Y_{SO2} = 0.015/5.97 = 0.00251

Y_{N2} = 4.52/5.97 = 0.757

Standard chemical molar exergy values are taken from Fundamental of Engineering thermodynamic text book [21].

$\sum x_n \times e^{ch}$ = (0.167×14175+0.07×8635 +0.0025×301940 +0.757×720) kJ/kmol

= 3712.2 kJ/kmol

$RT_0 \sum x_n \ln x_n$ = 8.314 J/molK×298K×(0.167ln(0.167)+0.071ln(0.071)+ 0.025ln(0.025) + 0.757ln(0.757))

= -1765.10 kJ/kmol

$e^{CH} = 3712.2 - 1765.10$ kJ/kmol

= 1947.2 kJ/kmol

= (1947.2kJ/kmol) / 18.82kg/kmol

= 103.46 kJ/kg

If consider flue gas flow rate as 1050 t/h at maximum load running condition;

= (103.46kJ/kg × 10^3 × 1050) / 3600 kJ/s

= 30175 kJ/s

Total Exergy value of flue gas = $E^{CH} + E^{PH}$

$$= 30{,}175 \text{ kJ/s} + 28{,}107.05 \text{ kJ/s}$$

$$= 58{,}282.88 \text{ kJ/s}$$

$$= 58{,}282.88 \text{ kW}$$

Chemical exergy of fuel (coal)

According to the reference, the exergy value of coal base fuel can calculate using HHV of fuel. It is shown that exergy value of fuel equal to [19]

$e^{ch} \approx \text{HHV of that fuel}$

The HHV of coal which is use in LVPS power plant should be in between,

$\text{HHV} = 5{,}800 - 6{,}900 \text{ kcal/kg}$

According to the design values

If we consider 6300 kcal/kg as average HHV of coal which can be used in LVPS power plant

$\text{HHV} = 6{,}300 \text{ kcal/kg}$

$\text{HHV} = 26{,}370 \text{kJ/kg}$

$e^{ch} \approx 26{,}370 \text{kJ/kg}$

$E_{35} = 26{,}370 \text{ kJ/kg}$

5.1.1 Exergy destruction and exergy efficiency calculation of major equipment

The exergy destruction & efficiency in major component in LVPS unit 01 can be calculated using exergy values of each and every major state which is obtain from above calculations. The exergy values of other all states in flow diagram also calculated using Excel data sheet and only obtained results are used to calculate destruction and efficiency of equipment in following steps.

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- **Boiler sub system**

$\mathbf{E_D} = (E_{34} + E_{35} + E_1 + E_3) - (E_2 + E_4 + E_{36} + E_{33})$

$E_{34} = 4.14 \text{ kW}$

$E_{35} = 805{,}750.67 \text{ kW}$

$E_1 = 77{,}702.51 \text{ kW}$

$E_3 = 230{,}142.30 \text{ kW}$

$E_2 = 374{,}380.61 \text{ kW}$

$E_4 = 287{,}486.83 \text{ kW}$

$E_{36} = 661.34 \text{ kW}$

$E_{33} = 58{,}282.82 \text{ kW}$

$E_D = 392{,}787.33 \text{ kW}$

$\mathbf{E_D = 392.78MW}$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{E_D + E_L}{E_{Fuel}}$$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{E_D + E_{33} + E_{36}}{E_{34} + E_{35} + E_1}$$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{(392{,}787.33 + 58{,}282.82 + 661.34)\text{kW}}{(4.14 + 805{,}750.67 + 77{,}702.51)\text{ kW}}$$

$\mathbf{Exergy\ Efficency_{boiler} = 48.86\%}$

- **Turbine sub system**

HP Turbine

$\mathbf{E_D} = E_2 - (E_3 + E_{18} + E_{19} + W_{\text{HP Turbine}})$

$E_2 = 374{,}380.61 \text{ kW}$

$E_3 = 230{,}142.30 \text{ kW}$

$E_{18} = 20{,}018.89 \text{ kW}$

$E_{19} = 21{,}063.73\ kW$

$W_{HP\ Turbine} = 90{,}951.64\ kW$

$E_D = 12{,}204.05\ kW$

$\mathbf{E_D = 12.204\ MW}$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{W_{\text{HP turbine}}}{E_{in} - E_{out}}$$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{W_{\text{HP Turbine}}}{E_2 - (E_{18} + E_{19} + E_3)}$$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{90{,}951.64\ kW}{374{,}380.61kW - (20{,}018.89 + 21{,}063.73 + 230{,}142.30)kW}$$

$\mathbf{Exergy\ Efficency_{HP\ Turbine} = 88.17\%}$

- **Feed water heat exchanger**

HP Heater No: 01

$\mathbf{E_D} = (E_{18} + E_{17}) - (E_{32} + E_1)$

$E_{18} = 20{,}018.89\ kW$

$E_{17} = 60{,}333.26\ kW$

$E_{32} = 4{,}530.41\ kW$

$E_1 = 77{,}702.51\ kW$

$\mathbf{E_D} = (21{,}710.80 + 61{,}123.46)\ kW - (4{,}530.41 + 77{,}702.51)kW$

$\mathbf{E_D} = 601.34\ kW$

$\mathbf{E_D} = 6.01\ MW$

$$\text{Exergy Efficency}_{\text{HTR1}} = 1 - \frac{E_D}{\Delta E_{\text{Source}}}$$

$$\text{Exergy Efficency}_{\text{HTR1}} = 1 - \frac{601.34\ kW}{20{,}018.89\ kW - 4{,}530.41\ kW}$$

$\mathbf{Exergy\ Efficiency_{HTR1}} = 96.12\%$

- **Feed water and condensate pump**

Condensate Pump

$$\mathbf{E_D} = E_7 + W_{condensate\ pump} - E_8$$

$E_7 = 123.09$ kW

$E_8 = 263.73$ kW

$W_{CP} = 917.814$ kW

$E_D = (123.09 + 917.814)$ kW $- 263.73$ kW

$E_D = 777.174$ kW

$E_D = 0.777$ MW

$$\text{Exergy Efficiency}_{Con.Pump} = 1 - \frac{E_{out} - E_{in}}{W_{Con.pump}}$$

$$\text{Exergy Efficiency}_{Con.pump} = 1 - \frac{E_8 - E_7}{W_{Con.pump}}$$

$$\text{Exergy Efficiency}_{Con.pump} = 1 - \frac{(263.73 - 123.09)\text{kW}}{917.814\text{ kW}}$$

Exergy Efficency$_{Con.pump}$ = 84.67%

5.1.2 Overall Power plant exergy efficiency calculation for design parameters

$$\text{Exergy efficency}_{Overall} = \frac{\text{Use Full Exergy}}{\text{Supplied Exergy}}$$

$$\text{Exergy efficency}_{Overall} = 1 - \frac{\text{Exery Destruction \& Losses}}{\text{Supplied Exergy}}$$

$$= 1 - \frac{(493\text{ MW})}{(805\text{ MW})}$$

Overall Exergy efficiency for Design Condition = 38.75%

5.2 Exergy values calculation for operational parameters

Table 5.6: Steam water properties of LVPS unit 01 in operating conditions

State	Temperature (°C) T	Pressure (MPa) P	Flow Rate(t/h) m	Enthalpy (kJ/kg) h	Entropy (kJ/kgK) S
1	272.95	17.190	869.36	1196.88	2.97
2	540.50	15.250	882.71	3421.84	6.48
3	275.76	3.290	737.52	2919.33	6.37
4	540.50	3.000	737.52	3548.17	7.35
5	355.73	0.914	697.50	3172.00	7.37
6	41.00	0.009	585.36	171.72	0.59
7	40.00	0.009	650.00	167.54	0.57
8	41.00	3.100	650.00	171.72	0.59
9	43.00	3.005	650.00	180.08	0.61
10	60.50	3.005	650.00	253.25	0.84
11	87.00	1.200	650.00	364.35	1.16
12	107.00	1.200	650.00	448.67	1.39
13	137.00	0.945	650.00	576.33	1.71
14	162.00	0.725	910.00	684.28	1.96
15	175.00	17.500	910.00	741.15	2.09
16	203.00	17.500	910.00	865.94	2.36
17	239.00	17.500	910.00	1032.76	2.69
18	395.00	5.490	65.41	3175.07	6.58
19	302.00	3.330	70.94	2989.13	6.49
20	450.00	1.520	28.80	3364.39	7.42
21	315.00	0.733	38.52	3090.12	7.33
22	285.00	0.245	38.81	3040.55	7.75
23	205.00	0.056	23.95	2887.30	8.13
24	88.50	0.040	26.90	2661.12	7.74
25	64.40	0.020	22.85	2617.45	7.93
26	46.00	-	112.52	192.62	0.65
27	72.00	-	89.67	301.40	0.98
28	93.00	-	62.77	389.59	1.23
29	94.06	-	38.81	394.06	1.24
30	181.95	-	167.97	771.81	2.16
31	208.52	-	136.35	890.98	2.41
32	244.97	-	65.41	1061.35	2.75
33	345.00	-	1100.00	-	-
34	30.00	-	940.00	-	-

Also the Exergy calculation equations which are derived from Chapter 3 can be used to identify exergy values, exergy destruction and exergy efficiency of relevant state and objectives in actual operating conditions. Therefore considering above system flow diagram, state 01 exergy value can be calculated as follows. Reference environmental condition was taken as T_0=270°C, P_0=101kPa

$E_1 = (h - h_0) - T_0 (S - S_0)$

$T = 272.95\ °C$

$P = 17.190\ MPa$

$h = 1196.88\ kJ/kg$

$h_0 = 113.20\ kJ/kg$

$S = 2.97\ kJ/kgK$

$S_0 = 0.39\ kJ/kgK$

$\dot{m} = 869.36\ t/h$

$E_1 = (1196.88\ kJ/kg - 113.20\ kJ/kg) - 300\ K(2.97\ kJ/kgK - 0.39\ kJ/kgK)$

$E_1 = 309.68\ kJ/kg$

$\dot{E}_1 = 309.68 kJ/kg \times 241.49 kg/s$

$\dot{E}_1 = 74{,}784.62\ kJ/s$

$\dot{E}_1 = 74{,}784.62\ kW$

Considering state 02;

$E_2 = (h - h_0) - T_0 (S - S_0)$

$T = 540.50\ °C$

$P = 15.250\ MPa$

$h = 3421.84\ kJ/kg$

$h_0 = 113.20\ kJ/kg$

$S = 6.48\ kJ/kgK$

$S_0 = 0.39\ \mathrm{kJ/kgK}$

$\dot{m} = 882.71\ \mathrm{t/h}$

$E_2 = (3421.84\ \mathrm{kJ/kg} - 113.20\ \mathrm{kJ/kg}) - 300\ \mathrm{K}(6.48\ \mathrm{kJ/KgK} - 0.39\ \mathrm{kJ/kgK})$

$E_2 = 1481.64\ \mathrm{kJ/kg}$

$\dot{E_2} = 1481.64\ \mathrm{kJ/kg} \times 245.19\ \mathrm{kg/s}$

$\dot{E_2} = 363{,}294.01\ \mathrm{kJ/s}$

$\dot{E_2} = 363{,}294.01\ \mathrm{kW}$

The exergy value of other all states which is in liquid state can easily find out using above calculations.

Considering the states which are in gaseous form;

$E^{PH} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$

$C_{p_{Air}}$ at 27°C and 110 Kpa = 1kJ/kgK

Therefore exergy value of input air;

$T = 30°C$

$T_0 = 27°C$

$E_{34} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$

$E_{34} = 1\mathrm{kJ/kgK} \times (303\mathrm{K} - 300\mathrm{K}) - 1\mathrm{kJ/kgK} \times 300\mathrm{K} \times \ln(303\mathrm{K}/300\mathrm{K})$

$E_{34} = 0.0149\mathrm{kJ/kg}$

$\dot{E_{34}} = 0.0149\mathrm{kJ/kg} \times 261.11\mathrm{kg/s}$

$\dot{E_{34}} = 3.890\ \mathrm{kJ/s}$

$\dot{E_{34}} = 3.890\mathrm{kW}$

Exergy value of flue gas (before air pre heater);

$E^{PH} = C_p\,(T - T_0) - C_p T_0 \ln(T/T_0)$

$C_{p_{Air}}$ at 27°C and 110 Kpa = 1kJ/kgK

Therefore exergy value of input air;

$T = 345°C$

$T_0 = 27°C$

$E_{33} = C_p (T - T_0) - C_p T_0 \ln(T/T_0)$

$E_{33} = 1kJ/kgK \times (618K - 300K) - 1kJ/kgK \times 300K \times \ln(618K/300K)$

$E_{33} = 101.18 \; kJ/kg$

$\dot{E}_{33} = 101.18kJ/kg \times 305.55kg/s$

$\dot{E}_{33} = 62{,}530.61 \; kJ/s$

$\dot{E}_{33} = 62.530 \; MW$

Chemical exergy of flue gas

$$\bar{e}_{ch} = \sum x_n (\bar{e}_{ch})_n + \bar{R} T_0 \sum x_n \ln x_n$$

x_n = Mole fraction of nth component

$\bar{R}$ = Universal Gas Constant

Table 5.7: Mole fraction of chemical component

	%	mole	Mole/mole$_C$
C	63.75	5.313	1
H	4.50	4.500	0.85
N	1.25	0.313	0.06
S	2.51	0.078	0.015
O	6.88	0.430	0.081

Therefore;

$CH_{0.85}N_{0.06}S_{0.015}O_{0.081}$

Combustion equation for coal

$CH_{0.85}N_{0.06}S_{0.015}O_{0.081} + \propto \times (O_2 + 3.78N_2) = CO_2 + 0.425H_2O + 0.015SO_2 + (3.78 \propto + 0.03)N_2$

$\propto = 1 + 0.425 + 0.015 - 0.0405$

$\propto = 1.19$

N_T = Total no of moles in combustion gas

= 1+0.425+0.015+4.52

= 5.968

Mole fraction of combustion products

Y_{CO2} = 1/5.97 = 0.167

Y_{H2O} = 0.425/5.97 = 0.071

Y_{SO2} = 0.015/5.97 = 0.00251

Y_{N2} = 4.52/5.97 = 0.757

Standard chemical molar exergy values are taken from Fundamental of Engineering thermodynamic text book [21].

$\sum x_n \times e^{ch}$ = (0.167×14175 +0.07×8635 +0.0025×301940 +0.757×720) kJ/km

= 3712.2 kJ/kmol

$RT_0 \sum x_n \ln x_n$ = 8.314J/molK × 298K × (0.167ln(0.167) + 0.071ln(0.071)+ 0.025ln(0.025) + 0.757ln(0.757))

= -1765.10 kJ/kmol

$e^{CH} = 3712.2 - 1765.10$ kJ/kmol

= 1947.2 kJ/kmol

= (1947.2kJ/kmol) / 18.82kg/kmol

= 103.46 kJ/kg

If consider operational flue gas flow rate as 1100 t/h at maximum load running condition;

= (103.46kJ/kg × 10^3×1100) / 3600 kJ/s

= 31,612 kJ/s

Total Exergy value of flue gas = $E^{CH} + E^{PH}$

= 31,612 kJ/s +28,107.05 kJ/s

= 59,719.05 kJ/s

= 59,719 kW

According to the reference, the exergy value of coal based fuel can be calculated using HHV of fuel. It is shown that exergy value of fuel equal to [19]

$e^{ch} \approx$ HHV of that fuel

Therefore coal which is use in LVPS power plant

$\mathrm{HHV} = 6{,}605\ \mathrm{kcal/kg}$

$\mathrm{HHV} = 27{,}647\mathrm{kJ/kg}$

$e^{ch} \approx 27{,}647\ \mathrm{kJ/kg}$

$E_{35} = 27{,}647\ \mathrm{kJ/kg}$

5.2.1 Exergy destruction and Exergy efficiency calculation of major equipment

Calculate the exergy destruction in major component in LVPS coal power plant using exergy values of each and every major state which is obtain from above calculations.

- **Boiler sub system**

$\mathbf{E_D} = (E_{34} + E_{35} + E_1 + E_3) - (E_2 + E_4 + E_{36} + E_{33})$

$E_{34} = 3.84\ \mathrm{kW}$

$E_{35} = 883{,}168.06\ \mathrm{kW}$

$E_1 = 73{,}629.83\ \mathrm{kW}$

$E_3 = 207{,}032.36\ \mathrm{kW}$

$E_2 = 363{,}070.66\ \mathrm{kW}$

$E_4 = 275{,}899.34\ \mathrm{kW}$

$E_{36} = 661.34\ \mathrm{kW}$

$E_{33} = 62{,}530.61\ \mathrm{kW}$

$E_D = 461{,}672.13\ \mathrm{kW}$

$\mathbf{E_D = 461.67\ MW}$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{E_D + E_L}{E_{Fuel}}$$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{E_D + E_{33} + E_{36}}{E_{34} + E_{35} + E_1}$$

$$\text{Exergy Efficency}_{\text{boiler}} = 1 - \frac{(461{,}672.13 + 62{,}530.61 + 661.34)\ \text{kW}}{(3.84 + 883{,}168.06 + 73{,}629.83)\ \text{kW}}$$

$$\mathbf{Exergy\ Efficency_{boiler} = 45.14\%}$$

- **Turbine sub system**

HP Turbine

$$\mathbf{E_D} = E_2 - (E_3 + E_{18} + E_{19} + W_{\text{HP Turbine}})$$

$$E_2 = 363{,}070.66\ \text{kW}$$

$$E_3 = 216{,}415.56\ \text{kW}$$

$$E_{18} = 21{,}804.04\ \text{kW}$$

$$E_{19} = 20{,}670.84\ \text{kW}$$

$$W_{HP\ Turbine} = 100{,}312.52\ \text{kW}$$

$$E_D = 5061.632901\ \text{kW}$$

$$\mathbf{E_D = 5.06\ MW}$$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{W_{\text{HP turbine}}}{E_{in} - E_{out}}$$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{W_{\text{HP Turbine}}}{E_2 - (E_{18} + E_{19} + E_3)}$$

$$\text{Exergy Efficency}_{\text{HP Turbine}} = \frac{100{,}312.52\ \text{kW}}{363{,}070.66\ \text{kW} - (21{,}804.04 + 20{,}670.84 + 216{,}415.56)\text{kW}}$$

$$\mathbf{Exergy\ Efficency_{HP\ Turbine} = 88.33\%}$$

- **Feed water heat exchanger**

HP Heater No: 01

$\mathbf{E_D} = (E_{18} + E_{17}) - (E_{32} + E_1)$

$E_{18} = 21{,}804.04\ kW$

$E_{17} = 60{,}333.26\ kW$

$E_{32} = 4{,}341.95\ kW$

$E_1 = 77{,}702.50\ kW$

$\mathbf{E_D} = (21{,}804.04 + 60{,}333.26)\ kW - (4{,}341.95 + 77{,}702.50) kW$

$\mathbf{E_D} = 92.85\ kW$

$\mathbf{E_D} = 0.093\ MW$

$$\text{Exergy Efficency}_{HTR1} = 1 - \frac{E_D}{\Delta E_{Source}}$$

$$\text{Exergy Efficency}_{HTR1} = 1 - \frac{92.85\ kW}{21{,}804.04\ kW - 4{,}341.95\ kW}$$

$\mathbf{Exergy\ Efficency_{HTR1} = 99.46\%}$

- **Condensate and feed water pump**

Condensate Pump

$\mathbf{E_D} = E_7 + W_{condensate\ pump} - E_8$

$E_7 = 123.09\ kW$

$E_8 = 244.89\ kW$

$W_{CP} = 852.25\ kW$

$E_D = (123.09 + 852.25) kW - 244.89\ kW$

$E_D = 730.45\ kW$

$E_D = 0.73$ MW

$$\text{Exergy Efficency}_{\text{Con.Pump}} = 1 - \frac{E_{out} - E_{in}}{W_{\text{Con.pump}}}$$

$$\text{Exergy Efficency}_{\text{Con.pump}} = 1 - \frac{E_8 - E_7}{W_{\text{Con.pump}}}$$

$$\text{Exergy Efficency}_{\text{Con.pump}} = 1 - \frac{(244.89 - 123.09)\text{kW}}{852.25\text{ kW}}$$

$$\textbf{Exergy Efficency}_{\textbf{Con.pump}} = \mathbf{85.70\%}$$

5.2.2 Overall power plant exergy efficiency calculation for operational parameters

$$\text{Exergy efficency}_{\text{Overall}} = \frac{\text{Use Full Exergy}}{\text{Supplied Exergy}}$$

$$\text{Exergy efficency}_{\text{Overall}} = 1 - \frac{\text{Exery Destruction \& Losses}}{\text{Supplied Exergy}}$$

$$= 1 - \frac{(570\text{ MW})}{(883\text{ MW})}$$

Overall Exergy efficiency for
Operation conditions = 35.44%

5.3 Energy efficiency of boiler

5.3.1 For design values of LVPS unit 01

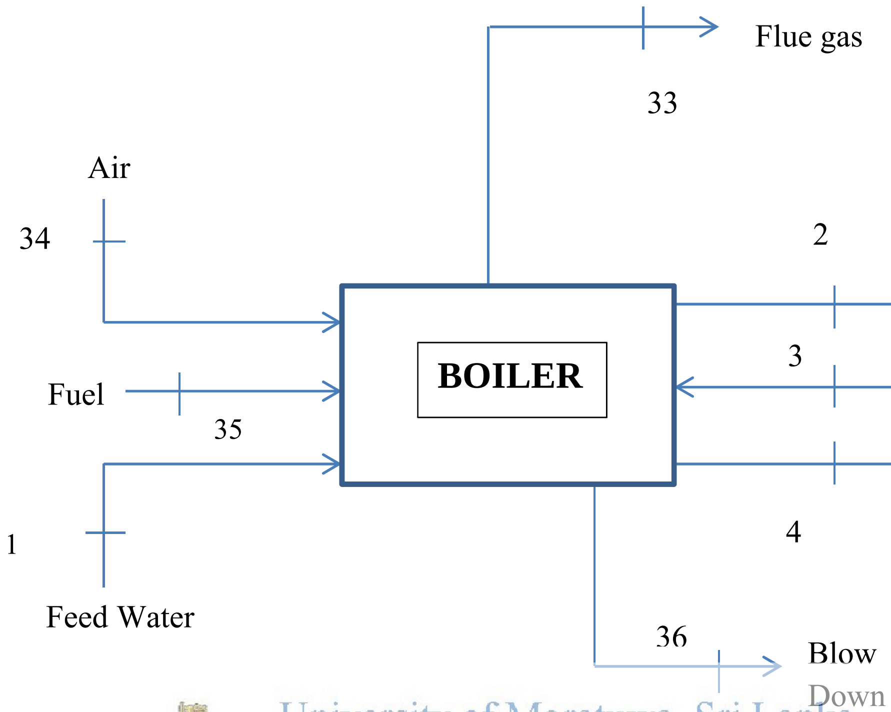

Figure 5.1: Sketch of Energy input and output in boiler sub system

Energy balance of boiler

$$E_1 + E_{34} + E_{35} + E_3 = E_2 + E_4 + E_{33} + E_{36} + E_{loss}$$

Also E_{33} & E_{36} can take as energy losses.

Therefore

$$E_1 + E_{34} + E_{35} + E_3 = E_2 + E_4 + E_{loss}$$

E1 = 911 t/h× 1,204 kJ/kg

= 304,612 kW

E_2 = 911t/h × 3,396.9 kJ/kg

= 859,415.7 kW

$E_3 = 762.84 \text{ t/h} \times 3043 \text{ kJ/kg}$

$= 644{,}101.6 \text{ kW}$

$E_4 = 762.84 \text{ t/h} \times 3{,}537.6 \text{ kJ/kg}$

$= 748{,}792 \text{ kW}$

$E_{35} = 110 \text{ t/h} \times 26370 \text{ kJ/kg}$

$= 805{,}750 \text{ kW}$

$E_{loss} = E_{flue} + E_{Blow\ down} + E_{other}$

$= E_1 + E_{34} + E_{35} + E_3 - (E_2 + E_4)$

$= 146256.6 \text{ kW}$

$$\text{Energy Efficiency} = \frac{\text{Energy Output}}{\text{Energy Input}}$$

$$= 1 - \frac{\text{Energy Loss}}{\text{Energy Input}}$$

$$= 1 - \frac{146{,}256.6 \text{ kW}}{1{,}754{,}463.6 \text{ kW}}$$

$$= 0.9166$$

$$\approx \mathbf{92\%}$$

5.3.2 For actual operating values of LVPS unit 01

Energy balance of boiler

$E_1 + E_{34} + E_{35} + E_3 = E_2 + E_4 + E_{33} + E_{36} + E_{loss}$

Also E_{33} & E_{36} can take as energy losses.

Therefore

$E_1 + E_{34} + E_{35} + E_3 = E_2 + E_4 + E_{loss}$

$E1 = 869 \text{ t/h} \times 1{,}196.88 \text{ kJ/kg}$

$= 288{,}913.53 \text{ kW}$

$E_2 = 882.71 \text{t/h} \times 3{,}421.84 \text{ kJ/kg}$

$= 839{,}025.66 \text{ kW}$

E_3 = 737.52t/h × 2,919.33kJ/kg

= 598,073.40 kW

E_4 = 737.52t/h×3,548.17kJ/kg

= 726,901.76 kW

E_{35} = 115t/h ×27,647 kJ/kg

= 883,168.056 kW

E_{loss} = $E_{flue} + E_{Blow\ down} + E_{other}$

$= E_1 + E_{34} + E_{35} + E_3 - (E_2 + E_4)$

= 163,435.53 kW

$$\text{Energy Efficiency} = \frac{\text{Energy Output}}{\text{Energy Input}}$$

$$= 1 - \frac{\text{Energy Loss}}{\text{Energy Input}}$$

$$= 1 - \frac{223{,}673.75\ \text{kW}}{1{,}831{,}881\ \text{kW}}$$

= 0.87

≈ **87%**

5.4 Calculation of exergy cost

From equation (22);

$$\sum_e (C_e \dot{E}_e)_k + C_{w,k}\dot{W}_k = C_{q,k}\dot{E}_{q,k} + \sum_i (C_i \dot{E}_i)_k + \dot{Z}_k$$

5.4.1 Calculation of levelised capital investment cost

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{OM}$$

Considering LVPS power plant unit 01

Total Capital investment for unit 01 = USD 450 million

Interest rate of loan = 2%

Salvage value ratio of plant = 15%

Life time of plant =30yrs

According to the equ.no (24)

$PW = C_{plant} - S_{plant} \times PWF(i, n)$

From equation No (26)

$PWF \quad = 1/(1 + i)^{n}$

$\quad = 1/(1 + 0.02)^{30}$

= 0.5520

From equation No (25)

$S_{plant} \; = C_{plant} \times j$

= USD450 million×15/100

= USD 67.5 million

PW = USD 450 million- USD67.5 million×0.5520

=USD 412.74

From equation (28)

$$CRF \; = \frac{i \times (i + 1)^{n}}{(i + 1)^{n} - 1}$$

$$= \frac{0.02 \times (0.02 + 1)^{30}}{(0.02 + 1)^{30} - 1}$$

= 0.0446

From equation No (27)

$CA_{plant} = \; PW_{plant} \times CRF(i, n)$

$= \; USD\ 412.74\ million \times 0.0446$

= USD 18.42 million

Consider last year (2013) total running hours of LVPS power plant unit 01 to calculate followings,

$$\dot{Z}^{CI} = CA_{plant} / \tau$$

$$= \frac{\text{USD18.42 million}}{\text{6153 hr}}$$

= USD **2,993.66/hr**

The above result shows levelised total capital investment cost of power plant, if we consider only boiler sub system in LVPS unit 01;

$$\dot{Z}^{CI}_{boiler} = \dot{Z}^{CI}_{Plant} \times \ PEC_k / \sum_{plant} PEC$$

$$\dot{Z}^{CI}_{boiler} = \text{USD2,993.66/hrs} \times \ \text{USD63million/USD450million}$$

= USD **419.11/hr**

5.4.2 Calculation of operation and maintenance cost of the power plant

$$\dot{Z}^{OM}_{plant} = \dot{Z}^{OM}_{Plant} \times (\frac{PEC_k}{\sum_{plant} PEC})$$

Consider Total O&M cost of LVPS power plant unit 01 in year 2013 (USD7.5 million)

$$\dot{Z}^{OM}_{boiler} = \frac{\text{USD7.0million}}{\text{6153 hr}} \times (\frac{\text{USD63million}}{\text{450MUSD}})$$

= USD **170/hr**

5.4.3 Calculation of fuel cost

Normal average coal price of power plant	= LKR16.57/Kg
Total coal consumption in year 2013	= 585,589.0t
Total Energy generation in year 2013	= 1,422,152.875 MWh
Total coal price (Million Rs)	= LKR9704.51million
Unit price for kWh	= $\frac{\text{LKR9,704.51 million}}{\text{1,422,152.875 MWh}}$
	= LKR 6.82/kWh

5.4.4 Calculation of demineralize water production cost

Normal demineralize water cost = LKR 156.83/m^3

Normal makes up water requirement per day = 500m^3

Total boiler capacity = 600m^3

Total cost for water per day = LKR156.83 /m^3× 1100m^3

= LKR 172,513.00

Average energy generation per day = 6.0 GWh

Average Demineralize cost = $\frac{\text{LKR 172,513.00}}{\text{6.0 GWh}}$

= LKR **0.03/kWh**

5.5 Exergy cost balance in boiler sub system

The exergy cost balance of boiler sub system can express as follows.

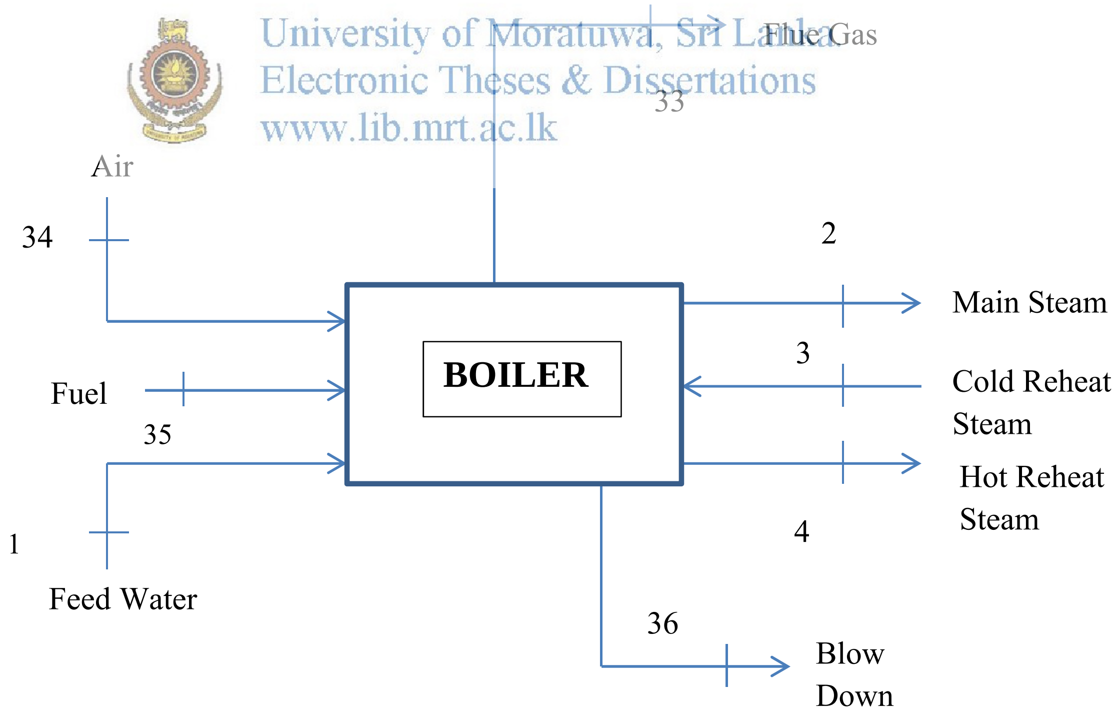

Figure 5.2: Sketch of Exergy cost flow input and output in boiler sub system

$\dot{C}_{34} + \dot{C}_{35} + \dot{C}_1 + \dot{C}_3 + \dot{Z}^{CI} + \dot{Z}^{OM} = \dot{C}_2 + \dot{C}_4 + \dot{C}_{36} + \dot{C}_{33}$

Cost of boiler blow down water, cost of supply air and cost of flue gas can be neglected compared to other cost component in above equations. For simplicity, we assume the combustion air enters the boiler with negligible exergy and cost, and the combustion products are discharged directly to the surroundings with negligible cost. Also assume the economical value of entering cold reheat and leaving hot reheat of boiler is almost same. Therefore above cost balancing equation can be simplified as follows,

$\dot{C}_{35} + \dot{C}_1 + \dot{Z}^{CI} + \dot{Z}^{OM} = \dot{C}_2$

From equation 23;

$\dot{C}_1 = c_1 \times \dot{E}_1$

$\dot{C}_{35} = c_{35} \times \dot{E}_{35}$

$\dot{C}_2 = c_2 \times \dot{E}_2$

5.5.1 Calculation of the boiler main steam unit cost

Therefore;

$c_2 \times \dot{E}_2 = c_{35} \times \dot{E}_{35} + c_1 \times \dot{E}_1 + \dot{Z}^{CI} + \dot{Z}^{OM}$

$c_2 = c_{35} \times (\dot{E}_{35}/\dot{E}_2) + c_1 \times (\dot{E}_1/\dot{E}_2) + \dot{Z}^{CI}/\dot{E}_2 + \dot{Z}^{OM}/\dot{E}_2$

$$C_2 = \frac{\text{LKR6.82}}{\text{kWh}} \times \left(\frac{883{,}168.056\text{kW}}{363070.655\text{kW}}\right) + \frac{\text{LKR0.03}}{\text{kWh}} \times \left(\frac{73{,}629.825\text{kW}}{363{,}070.655\text{kW}}\right) + \frac{\left(\frac{\text{LKR41911}}{\text{hrs}}\right)}{363{,}070.655\text{kW}} + \frac{(\text{LKR17000/hrs})}{363{,}070.655\text{kW}}$$

C_2 = LKR 16.75/kWh

5.5.2 Calculation of boiler main steam cost

$$\textbf{Boiler main steam unit cost} \quad = \textbf{LKR 16.75/kWh}$$

Boiler main steam cost at plant running with rated capacity (300MW);

Boiler main steam exergy value$(\dot{E}_2) = 363{,}070.655\ \text{kW}$

Boiler main steam unit cost$(c_2) \quad = \text{LKR}16.75/\text{kWh}$

Boiler main steam cost rate ($\dot{C}_2$) $\quad = 363{,}070.655\text{kW} \times \text{LKR}16.75/\text{kWh}$

= LKR **6.081 million/h**

CHAPTER 06

6.0 Results and Improvements of Exergy Efficiency

Considering design parameters of power plant, Exergy value of each state in system flow diagram as follows.

Table 6.1: Exergy of each state in system flow diagram for design parameters

State	Exergy kJ/s	**Exergy MW**	**State**	Exergy kJ/s	**Exergy MW**
1	77,702.51	**77.70**	19	21,364.64	**21.36**
2	374,380.61	**374.38**	20	9,161.41	**9.16**
3	230,142.30	**230.14**	21	10,443.17	**10.44**
4	287,486.83	**287.49**	22	8,092.02	**8.09**
5	187,347.08	**187.35**	23	3,599.45	**3.60**
6	14,158.58	**14.16**	24	3,047.70	**3.05**
7	123.09	**0.12**	25	1,674.67	**1.68**
8	263.73	**0.26**	26	117.43	**0.12**
9	263.73	**0.26**	27	246.43	**0.25**
10	1,390.55	**1.39**	28	429.33	**0.43**
11	4,080.91	**4.08**	29	445.51	**0.45**
12	7,121.49	**7.12**	30	6,125.21	**6.12**
13	13,693.73	**13.69**	31	6,569.96	**6.57**
14	29,803.12	**29.80**	32	4,530.41	**4.53**
15	31,298.93	**31.30**	33	58,282.83	**58.28**
16	41,392.73	**41.39**	34	4.14	**0.01**
17	60,333.26	**60.33**	35	805,750.00	**805.75**
18	21,710.80	**21.71**	36	661.34	**0.66**

The Design Exergy destruction & efficiency values of major equipment in the power plant are shown in Table 6.2.

Table 6.2: Exergy destruction and Exergy efficiency of major equipment in the power plant for design parameters

Equipment	Exergy Destruction MW	Exergy Efficiency of Equipment (%)
Boiler	392.78	48.86
HP Turbine	12.20	89.91
IP Turbine	2.99	96.45
LP Turbine	2.70	98.30
Condenser	14.15	99.14
Condensate pump	0.78	84.68
Feed pump	2.96	66.43
LP Heater 8	0.68	62.47
LP Heater 7	0.53	83.49
LP Heater 6	0.57	84.10
LP Heater 5	1.07	85.95
HP Heater 3	2.20	77.05
HP Heater 2	0.38	98.01
HP Heater 1	0.60	96.50
Deaerator	0.46	98.48
Total Exergy destruction of power plant	**435.09**	

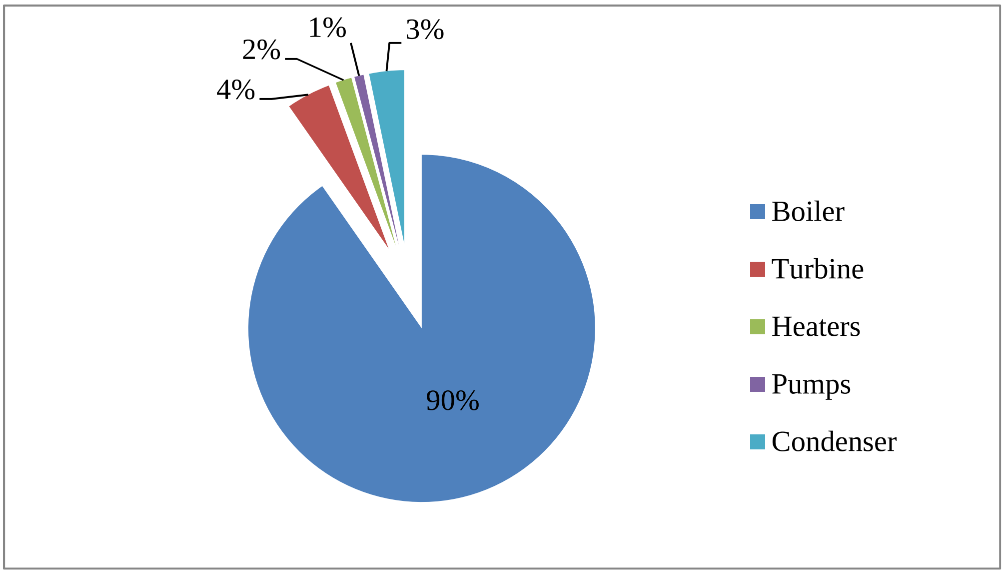

Figure 6.1: Exergy Destruction percentage of major equipment in LVPS unit 01 for Design Conditions

The figure 6.1 shows the design exergy destruction in major equipment in LVPS coal power plant. The boiler exergy destruction of this power plant is 435.086 MW. This is about 90% of total exergy destruction in the power plant. The exergy destruction values of other all-major equipment, which include turbine, pumps, condenser & heaters, are below 10%. Considering the above exergy values it can be easily identified that, the boiler is the major exergy destruction component in power plant.

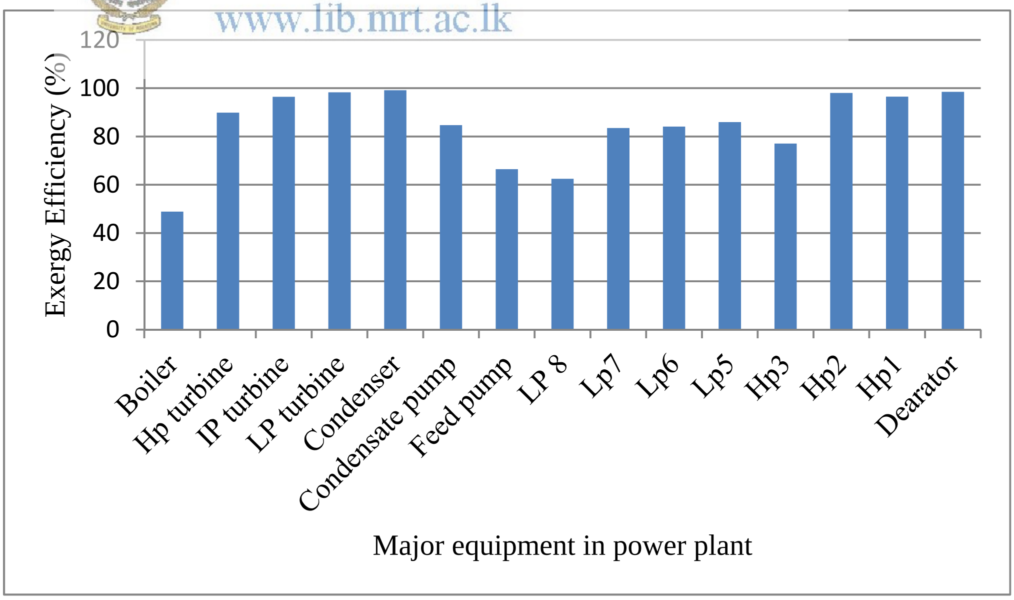

Figure 6.2: Exergy efficiency of major equipment in LVPS unit 01 for design conditions

The Figure 6.2 shows the exergy efficiency valves in major equipment in the power plant. Except the boiler, all the other major equipment in the power plant shows more than 60% exergy efficiency. The boiler exergy efficiency of LVPS power plant for design parameters is around 49%.

When considering full load (300 MW) operating conditions of LVPS unit 01, the exergy values of each state in flow diagram as follows.

Table 6.3: Exergy of each state in system flow diagram for operational parameters

State	Exergy kJ/s	**Exergy MW**	**State**	Exergy kJ/s	**Exergy MW**
1	73,629.83	**73.63**	19	20,670.84	**20.67**
2	363,070.66	**363.07**	20	8,896.89	**8.90**
3	207,032.36	**207.03**	21	9,967.43	**9.97**
4	275,899.34	**275.90**	22	7,855.02	**7.85**
5	178,493.52	**178.49**	23	3,599.45	**3.60**
6	14,158.58	**14.16**	24	2,584.66	**2.58**
7	123.09	**0.12**	25	1,552.17	**1.55**
8	244.89	**0.24**	26	92.84	**0.09**
9	244.89	**0.24**	27	323.99	**0.32**
10	1,291.23	**1.29**	28	469.82	**0.47**
11	4,040.10	**4.04**	29	298.43	**0.30**
12	6,932.81	**6.93**	30	5,982.76	**5.98**
13	12,505.68	**12.51**	31	6,569.96	**6.57**
14	25,512.01	**25.51**	32	4,341.95	**4.34**
15	30,174.01	**30.17**	33	62,530.61	**62.53**
16	41,392.73	**41.39**	34	3.84	**0.01**
17	58,274.37	**58.27**	35	883,168.06	**883.17**
18	21,804.04	**21.80**	36	661.34	**0.66**

Table 6.4: Exergy destruction and Exergy efficiency of major equipment in the power plant for operational parameters

Equipment	Exergy Destruction in MW	Exergy efficiency of equipment (%)
Boiler	461.67	45.14
HP Turbine	5.06	88.33
IP Turbine	2.54	98.14
LP Turbine	3.44	96.81
Condenser	14.15	99.31
Condensate pump	0.72	87.82
Feed pump	9.73	67.61
LP Heater 8	0.74	58.67
LP Heater 7	0.05	98.04
LP Heater 6	0.54	84.35
LP Heater 5	1.98	73.75
HP Heater 3	1.94	79.55
HP Heater 2	1.56	91.54
HP Heater 1	0.88	94.94
Deaerator	3.15	88.92
Total Exergy destruction of power plant	**508.17**	

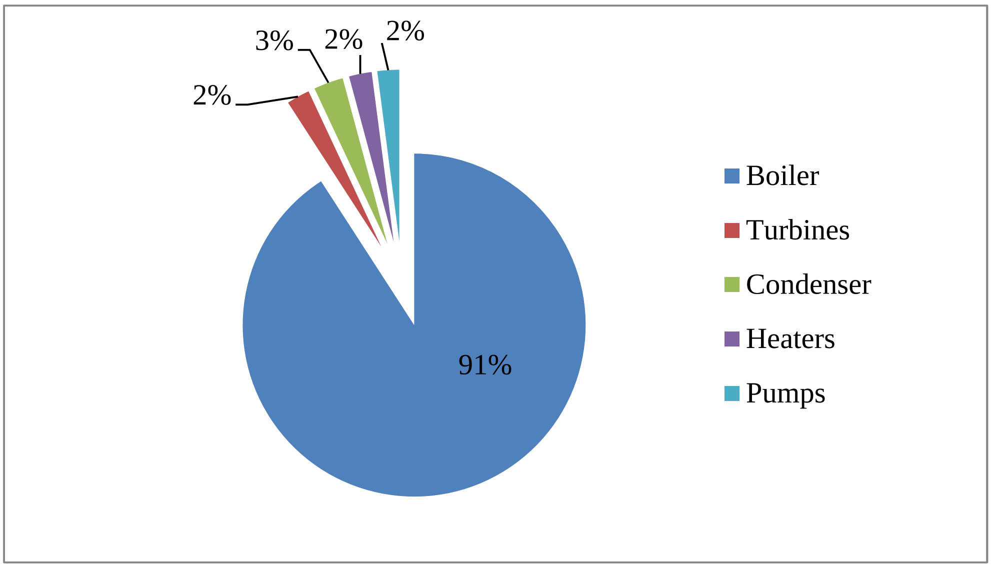

Figure 6.3: Exergy Destruction percentage of major equipments in LVPS unit 01 for operational condition

This Figure 6.3 shows the exergy destruction of major equipment in LVPS for operational parameters. It also displays, the major exergy destruction is occurred in boiler sub system in the power plant same as design conditions. The operational exergy destruction in the boiler is around 508.174 MW. This exergy destruction values are greater than the design condition and it is around 91% of total destruction of the power plant. The turbine, condenser, pumps and heaters destruction values are less than 10%; it is same as design conditions.

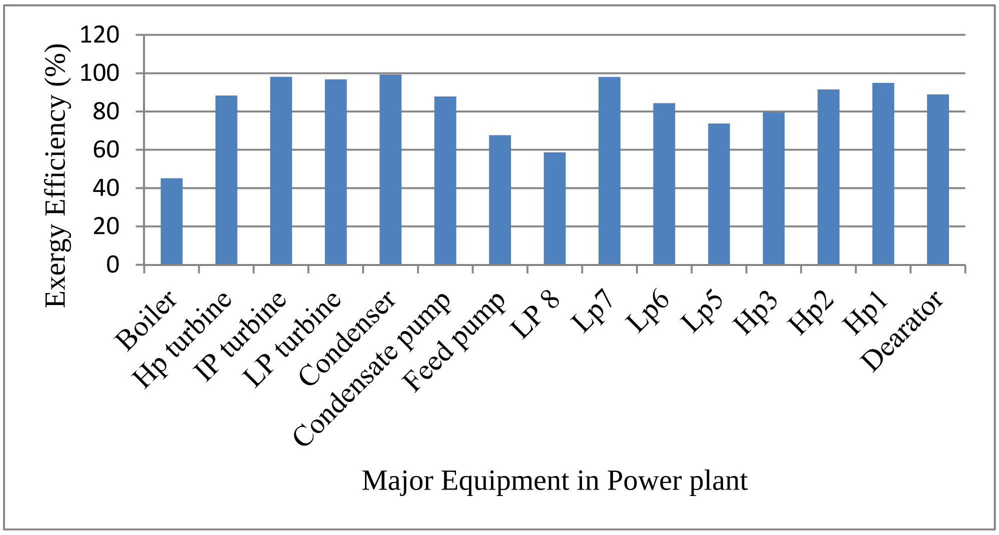

Figure 6.4: Exergy efficiency of major equipment in LVPS unit 01 for operational condition

The Figure 6.4 shows the exergy efficiency of major equipment of LVPS power plant in actual operation conditions. The boiler exergy efficiency is around 45.14%. This efficiency is less than the design values. Considering all the other major equipment of the power plant it is obvious that, exergy efficiency of those items are more than 60% same as deign conditions.

Obtained exergy efficiency results from above calculations for both design and operational conditions are summarized as follows.

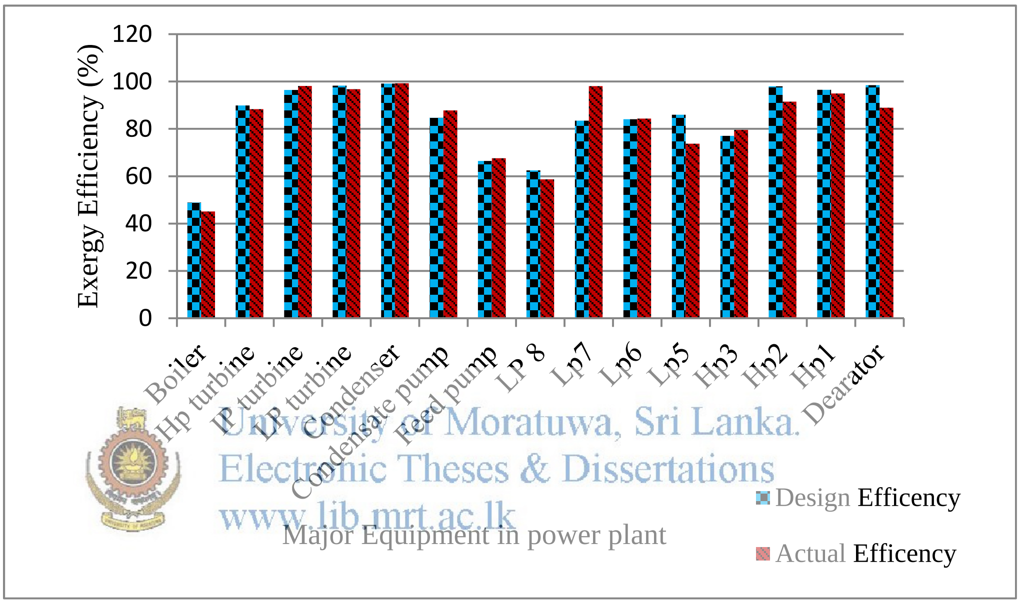

Figure 6.5: Exergy efficiency of major equipment in LVPS unit 01 for both design & operational conditions.

Most of the major equipment in power plant deliver lesser exergy efficiency under operation condition than design conditions. Some equipment show high exergy efficiency values than design conditions. Considering both exergy destruction and efficiency values of equipment, It was easily identified boiler as the major contributor of power plant exergy efficiency reduction process. Exergy destruction of boiler under design and operational conditions are 392 MW and 461 MW respectively. Also exergy efficiency of the boiler under design condition is 49% while 45% under operation condition. Exergy destruction of all other equipment are very much lesser than that of the boiler. Therefore boiler was identified as the major component which affects the power plant exergy performance. Hence there is high possibility of improving power plant efficiency by reducing the exergy destruction of the boiler system.

When considering above obtained results, it is obvious that the boiler system is the major exergy destruction equipment of the power plant. Therefore, cost calculation of the power plant was done based on the boiler sub system. The fuel cost of boiler, feed water cost, capital investment and operation and maintance cost of boiler were used for the exergy cost calculation of the boiler. The unit cost of boiler main steam was obtained as LKR16.75/kWh and total exergy cost rate of boiler main steam was around LKR6.081millon/hr. Therefore reduction of boiler exergy destruction is a crictic l parameter for efficiency improvement process in the whole power plant.

6.1 Identification of exergy efficiency improvement opportunities

As explained in the previous section, it was identified the boiler as the major exergy destruction as well as less exergy efficient equipment in the power generation process of LVPS unit 01. Therefore there is higher possibility to improve the overall exergy efficiency of the power plant by improving of the boiler exergy efficiency and reducing of exergy destruction in boiler subsystem process. Further the maximum exergy destruction in boiler system was occurred due to irreversibility in the combustion process compared to other losses. The major heat losses are occurred in the boiler as flue gas losses, blow down and internal exergy destruction. Flue gas losses occurred in several ways. There are conduction, convection and radiation. Blow down water also carrying some considerable amount of heat from feed water. Boiler blow down is an essential measure to maintain the water quality parameters in acceptable limit which prevents the boiler tube scale formation. Blow down process is done continuously and periodically based on to the boiler water quality. Heat recovery processes can be introduced to the system to recover the heat from blow down water which will improve the boiler efficiency. But the amount which can be recovered from waste heat is negligible comparing the internal exergy destruction of the boiler. The Figure 6.6 shows the comparison of flue gas loss, blow down loss and exergy destruction loss of boiler.

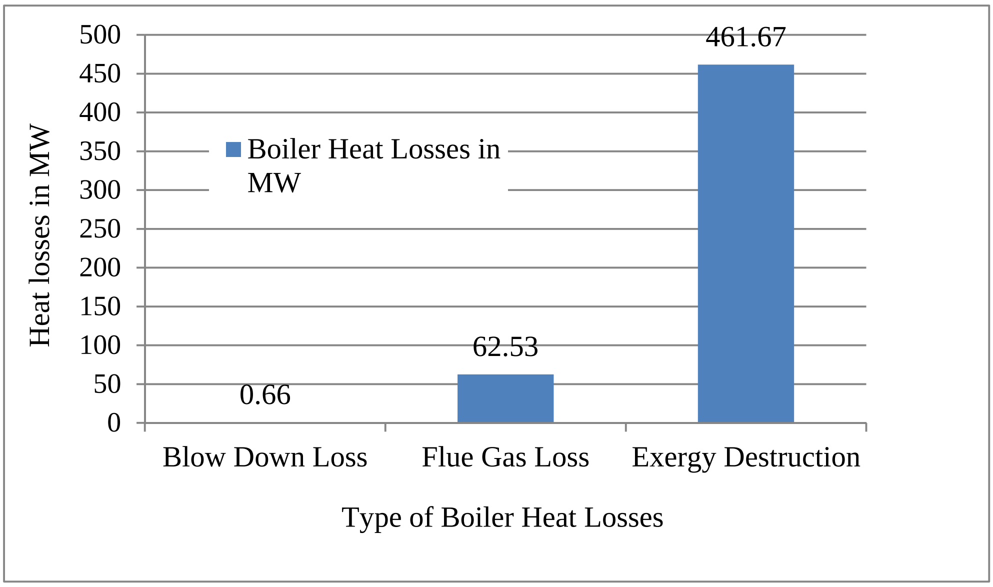

Figure 6.6: Types of boiler heat losses in MW

Therefore reduction of internal exergy destruction due to irreversibility of boiler should be the major target of improving the exergy efficiency of the boiler.

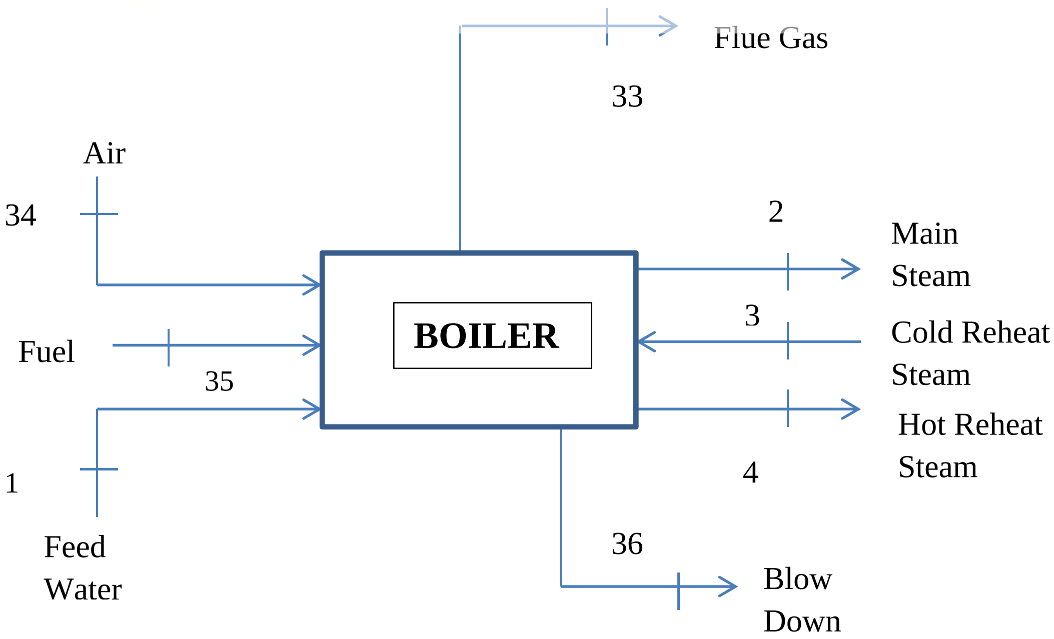

Table 6.5: Exergy input and output values in boiler sub system

Component	State	Exergy Value MW
Air	E_{34}	0.01
Fuel	E_{35}	883.17
Feed Water	E_1	73.63
Flue gas	E_{33}	62.53
Main Steam	E_2	363.07
Cold Reheat Steam	E_3	207.03
Hot Reheat Steam	E_4	275.90
Blow down water	E_{36}	0.66

$$\mathbf{E_D} = (E_{34} + E_{35} + E_1 + E_3) - (E_2 + E_4 + E_{36} + E_{33})$$

$$\mathbf{E_D} = \mathbf{461.67\ MW}$$

Unlike energy, exergy is not conserved but destroyed by irreversibility within a system. This irreversibility may be classified as internal and external irreversibility. Main reasons of internal irreversibility are friction, unrestrained expansion, mixing and chemical reaction. External irreversibility arises due to heat transfer due to a finite temperature difference.

Therefore the reduction of internal irreversibility can be done in two ways. Redesign the boiler and improve exergy efficiency or optimize the operation condition to reduce exergy destruction of it. When considering the existing power plant it is difficult to redesign and the best way to improve exergy efficiency through better operating practices. When designing new power plant, it is required to consider above results and optimize the design in order to minimize the exergy destruction.

It is required to consider some critical parameters to reduce the boiler exergy destruction. So behavior of exergy destruction and exergy efficiency of the boiler can be obtained with the changing of critical parameters. Those critical parameters can be identified as Load, Main steam pressure, Main steam temperature, Feed water temperature and Gross calorific value of fuel.

6.1.1 The variation of power plant load

Generated power from any power plant depends on the power grid demand-supply requirement. So the unit 01 of LVPS also operated under different load conditions to meet the power system requirements. The Figure 6.7 shows the total power demand of the country and power supplied by LVPS unit 01 to achieve the said demand. (Consider 2014.06.01 24 hours data as example)

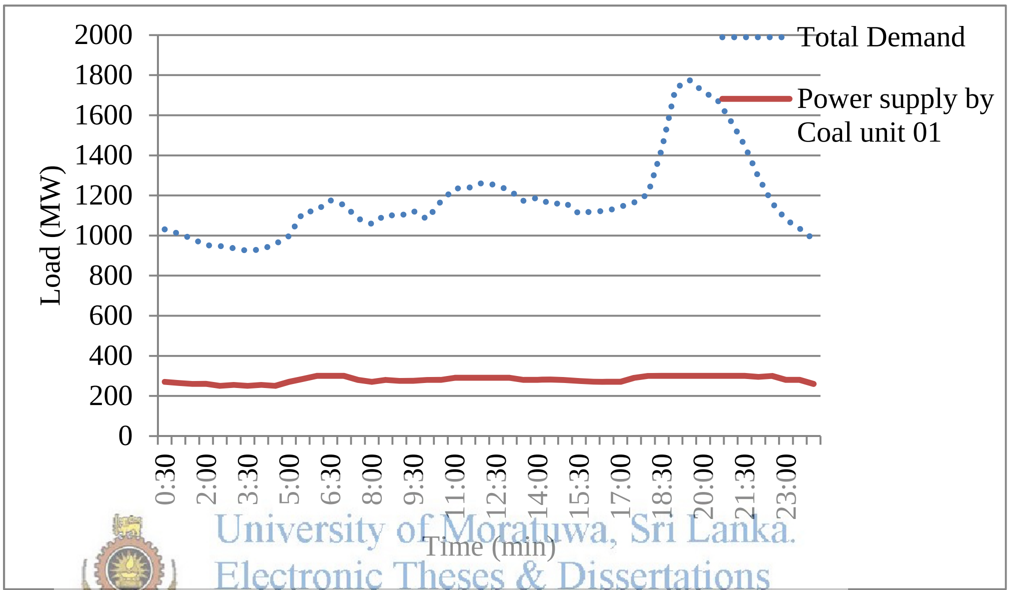

Figure 6.7: Daily total load demand pattern in Sri Lanka and its contribution from LVPS unit 01

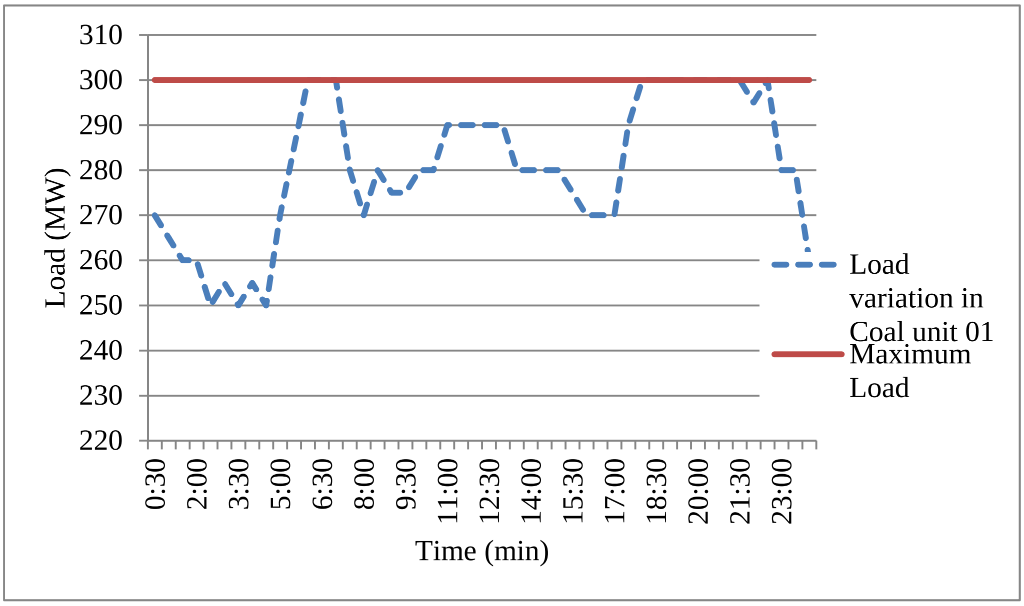

Figure 6.8: Daily load Pattern in LVPS unit 01

Power plant operating condition within 24hrs is shown in above Figure 6.8. According to the figure, it is obvious that, power plant is not operated at its rated capacity throughout the day. Therefore exergy destruction and exergy efficiency of the power plant was calculated with varying load. Obtained results are presented in Table 6.6. (Exergy Values are in MW)

Table 6.6: The variation of Exergy destruction and Exergy efficiency with load

Load	E34	E1	E35	E3	E33	E36	E2	E4	Ed	Eff.
300	0.004	73.55	888.78	207.74	56.85	0.71	363.59	276.30	472.62	44.91
275	0.004	67.74	837.84	183.66	55.01	0.69	323.00	244.65	465.90	42.40
250	0.004	59.04	782.89	162.74	54.73	0.85	293.22	222.07	433.80	41.87
200	0.003	45.78	666.20	129.05	50.65	0.82	240.33	181.26	367.99	41.09
180	0.003	39.13	613.86	99.27	50.38	0.78	188.48	142.09	370.53	35.42

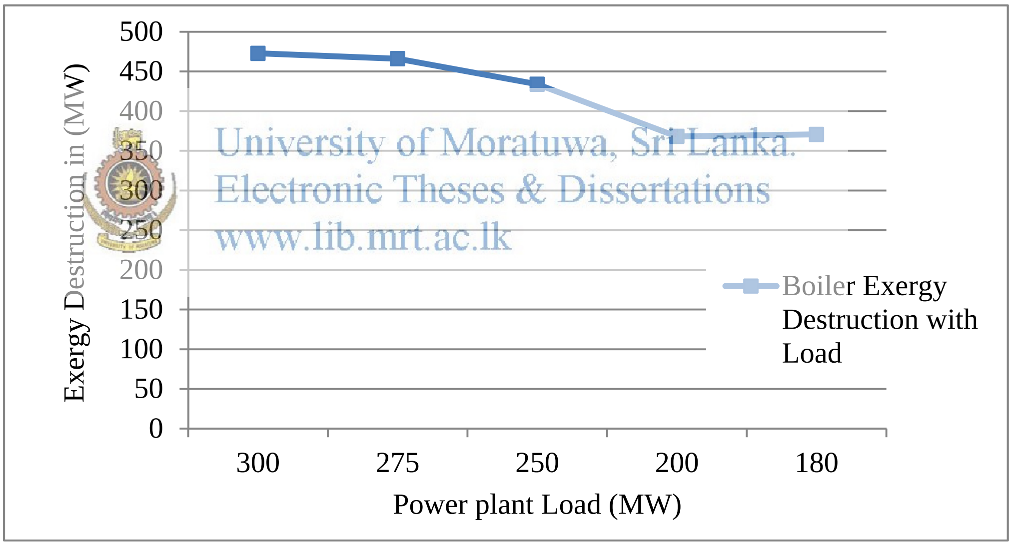

Figure 6.9: The variation of Boiler exergy destruction with load under operation conditions.

Behavior of the boiler exergy destruction with load is shown in the Figure 6.9. According to the figure, destruction of exergy decreases with the boiler load reduction and at the loads less than 200MW exergy destruction becomes almost constant value.

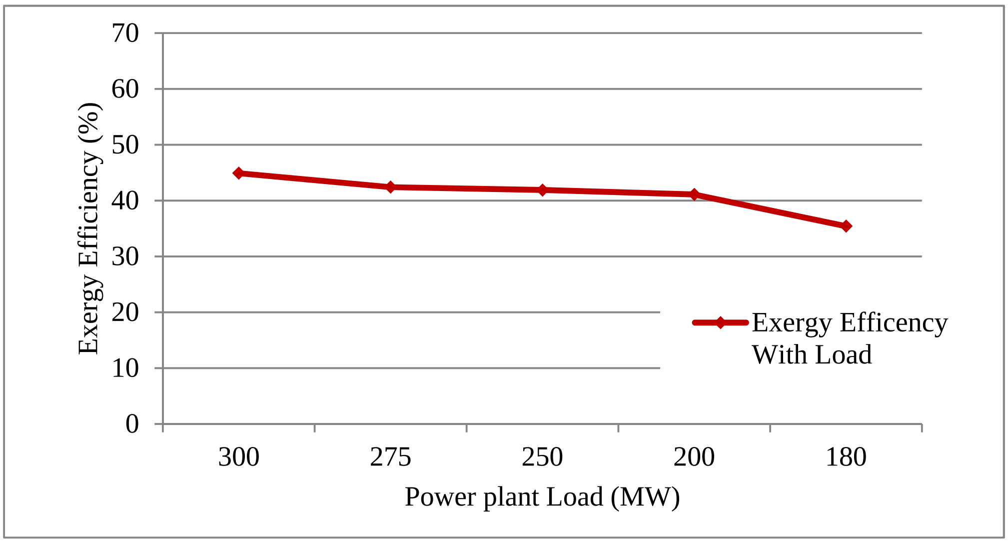

Figure 6.10: The variation of Boiler Exergy efficiency with load under operation conditions.

The variation of boiler exergy efficiency with load is shown in the Figure 6.10. The exergy efficiency of boiler is around 45% at 300MW and it decreases with the load. Therefore, higher exergy efficiency can be obtained when the power plant operating under rated load condition. And also the exergy efficiency of the boiler varies with its load variation due to system requirements or any other reasons. Hence power plant should be operated at its rated load in order to achieve the maximum exergy efficiency of the boiler.

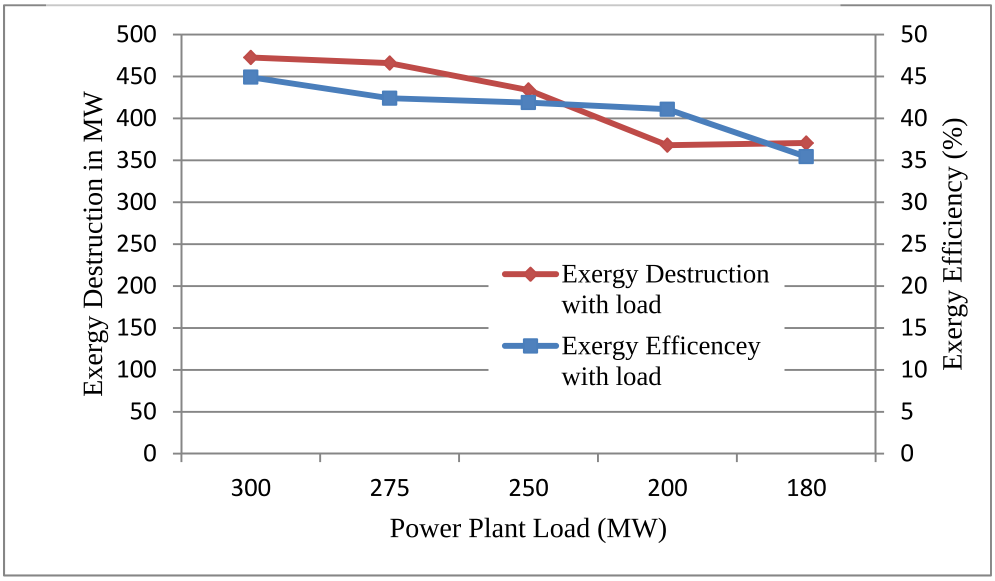

Figure 6.11: The variation of the boiler exergy destruction and exergy efficiency with load under operation conditions.

6.1.2 The variation of main steam pressure

The variation of the main steam pressure is shown in the Figure 6.12 under actual running condition of LVPS unit 01. The boiler exergy destruction and exergy efficiency at various main steam pressure and rated load are tabulated in Table 6.7. The main steam pressure varies between 15.0MPa to 17.2MPa. The maximum permissible pressure of unit 01 of LVPS is 17.2MPa.

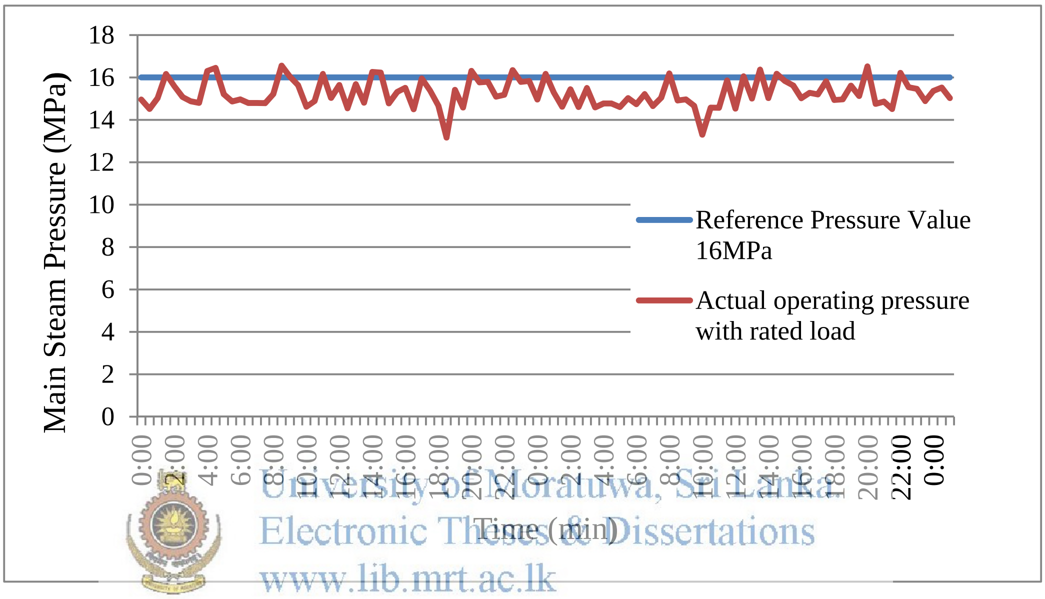

Figure 6.12: The variation of the Main steam pressure under rated load running condition of LVPS unit 01

The variation of the main steam pressure at rated load is shown in the above graph for unit 01 of LVPS. The variation of the boiler performance with varying main steam pressure is tabulated as follows.

Table 6.7: The variation of Exergy destruction and Exergy efficiency with main steam pressure.

P (MPa)	E34	E1	E35	E3	E33	E36	E2	E4	ED	Effi.
15.0	0.004	73.55	883.17	207.74	56.85	0.71	363.51	276.30	467.09	45.16
15.2	0.004	73.55	871.39	207.74	56.85	0.71	363.58	276.30	455.25	45.73
15.4	0.004	73.55	859.62	207.74	56.85	0.71	363.63	276.30	443.42	46.31
15.6	0.004	73.55	847.84	207.74	56.85	0.71	363.68	276.30	431.59	46.91
15.8	0.004	73.55	836.07	207.74	56.85	0.71	363.73	276.30	419.78	47.52
16.0	0.004	73.55	824.29	207.74	56.85	0.71	363.77	276.30	407.96	48.15
16.2	0.004	73.55	812.51	207.74	56.85	0.71	363.80	276.30	396.16	48.79
16.4	0.004	73.55	800.74	207.74	56.85	0.71	363.82	276.30	384.35	49.45
16.6	0.004	73.55	788.96	207.74	56.85	0.71	363.84	276.30	372.56	50.13
16.8	0.004	73.55	777.19	207.74	56.85	0.71	363.86	276.30	360.77	50.83
17.0	0.004	73.55	765.41	207.74	56.85	0.71	363.86	276.30	348.99	51.54
17.2	0.004	73.55	753.64	207.74	56.85	0.71	363.87	276.30	337.21	52.28

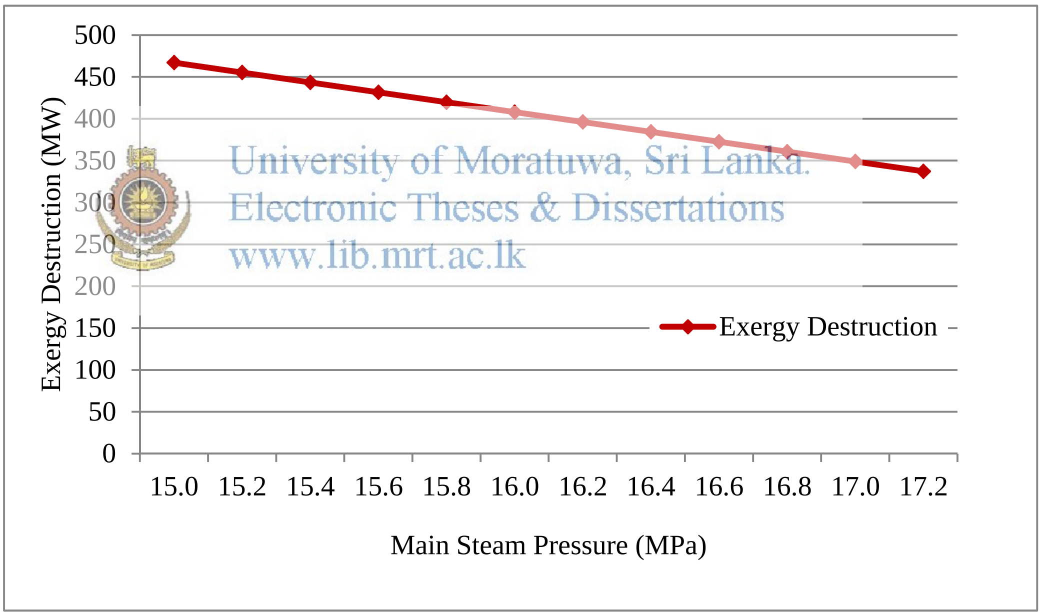

Figure 6.13: The variation of exergy destruction with main steam pressure under rated load operation condition.

According to the Figure 6.13 exergy destruction of boiler is decreased with the main steam pressure increment. Exergy destruction of the boiler is around 521MW and 391MW at the main steam pressure of 15.0MPa and 17.2MPa respectively. Hence the exergy destruction of the boiler can be reduced by maintaining higher main steam pressure as much as possible.

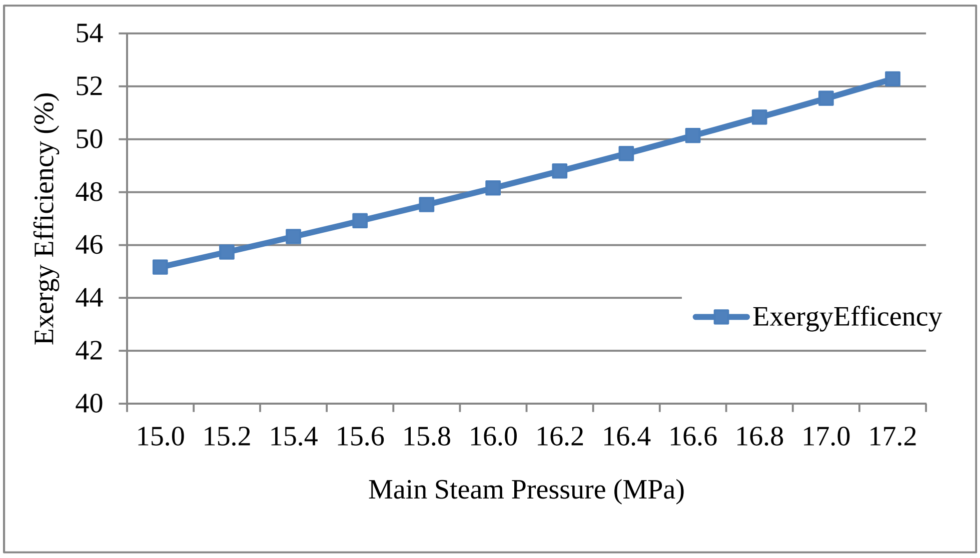

Figure 6.14: The variation of boiler exergy efficiency with main steam pressure under rated load condition.

The variation of the boiler exergy efficiency with its main steam pressure is shown in the Figure 6.14. Exergy efficiency of the boiler is around 45% when its main steam pressure is around 15MPa and exergy efficiency of the boiler is increased linearly with main steam pressure. Therefore the maximum exergy efficiency of the boiler can be achieved when the boiler is operating its possible maximum pressure.

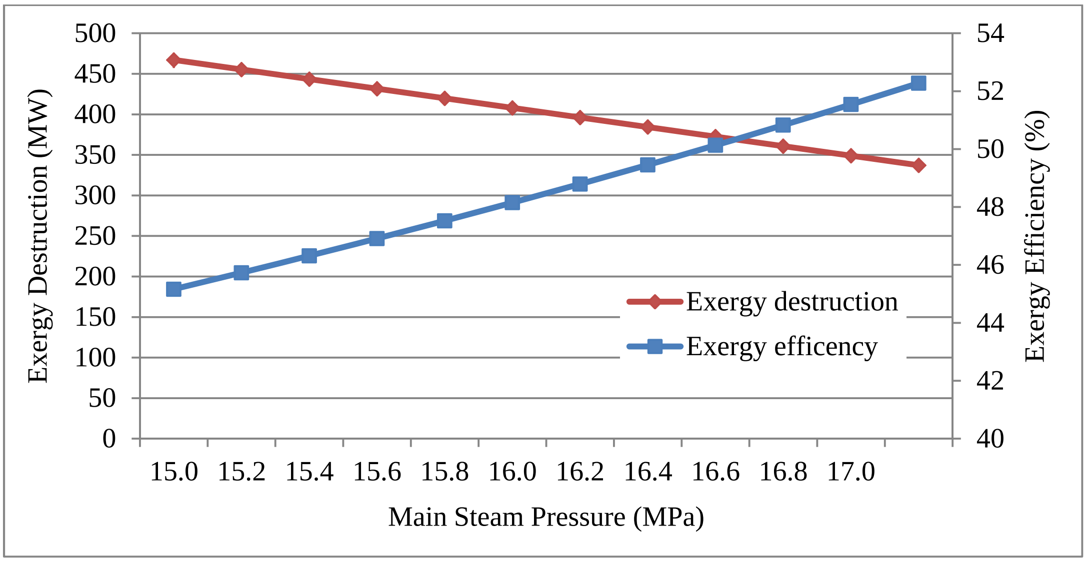

Figure 6.15: The variation of Boiler exergy efficiency and exergy destruction with main steam pressure under rated load condition.

6.1.3 The variation of main steam temperature

The variation of the main steam temperature is shown in the Figure 6.16 under the rated load of the power plant. Main steam temperature varies between 538°C and 541°C due to instabilities in boiler operations in actual working condition. The maximum permissible temperature of the boiler is 541°C.

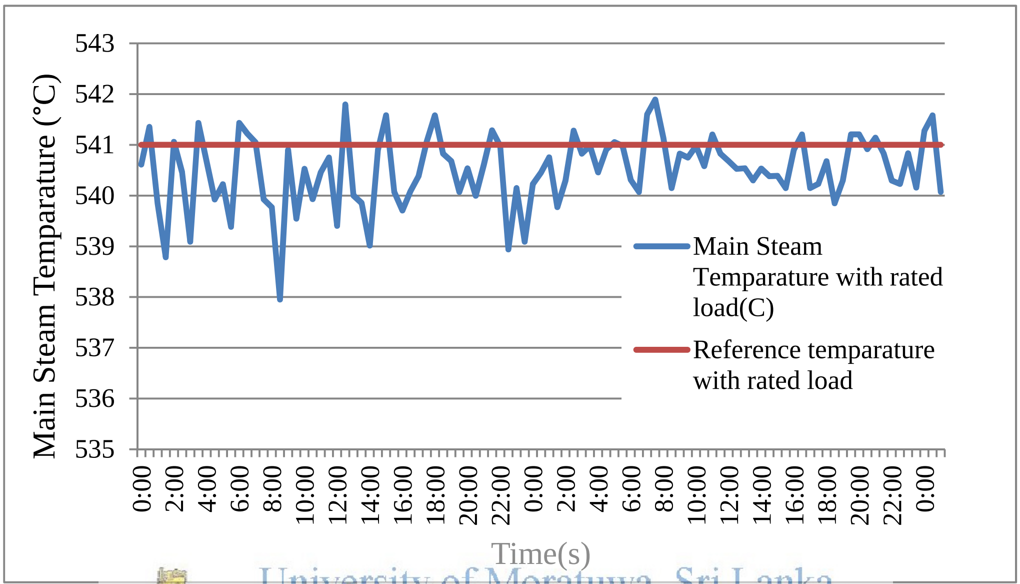

Figure 6.16: The variation of Boiler main steam temperature under rated load condition.

The boiler exergy destruction and its exergy efficiency with various main steam temperatures are shown in the following table under the rated load condition.

Table 6.8: The variation of exergy destruction and exergy efficiency with main steam temperature.

T(°C)	E34	E1	E35	E3	E33	E36	E2	E4	ED	Effi.
535	0.004	73.55	888.78	207.74	56.85	0.71	361.25	276.30	474.97	44.66
536	0.004	73.55	888.78	207.74	56.85	0.71	361.67	276.30	474.54	44.71
537	0.004	73.55	888.78	207.74	56.85	0.71	362.10	276.30	474.11	44.75
538	0.004	73.55	888.78	207.74	56.85	0.71	362.53	276.30	473.69	44.80
539	0.004	73.55	888.78	207.74	56.85	0.71	362.95	276.30	473.26	44.84
540	0.004	73.55	888.78	207.74	56.85	0.71	363.38	276.30	472.83	44.88
541	0.004	73.55	888.78	207.74	56.85	0.71	363.80	276.30	472.41	44.93

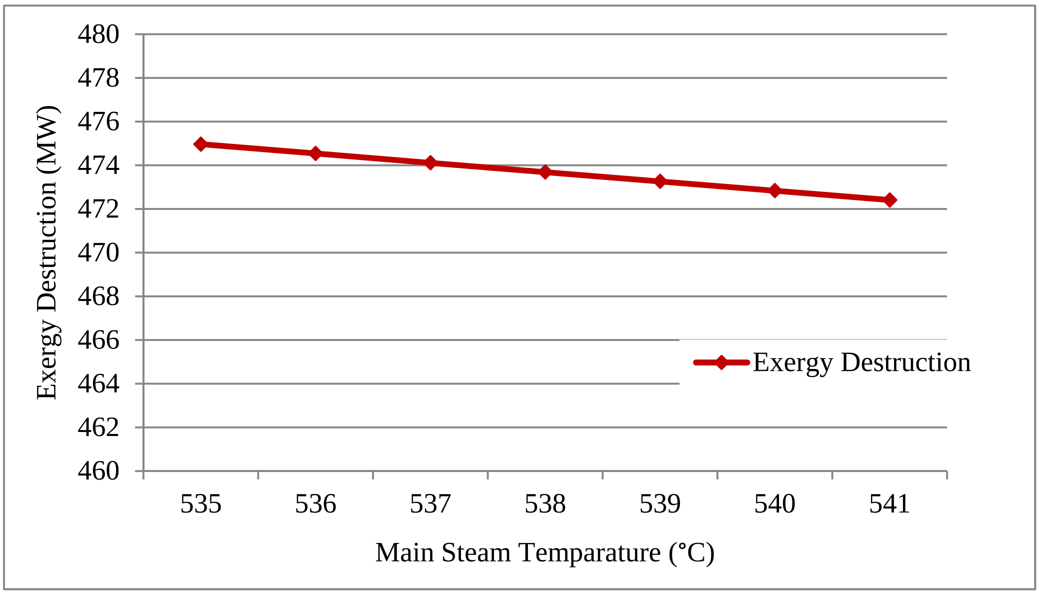

Figure 6.17: The variation of the boiler exergy destruction with main steam temperature under rated load condition.

When considering the exergy destruction with varying main steam temperature, it is noted that, exergy destruction at higher temperate is lesser than that of lower temperature. The lowest exergy destruction was occurred at the maximum temperature of 541°C.

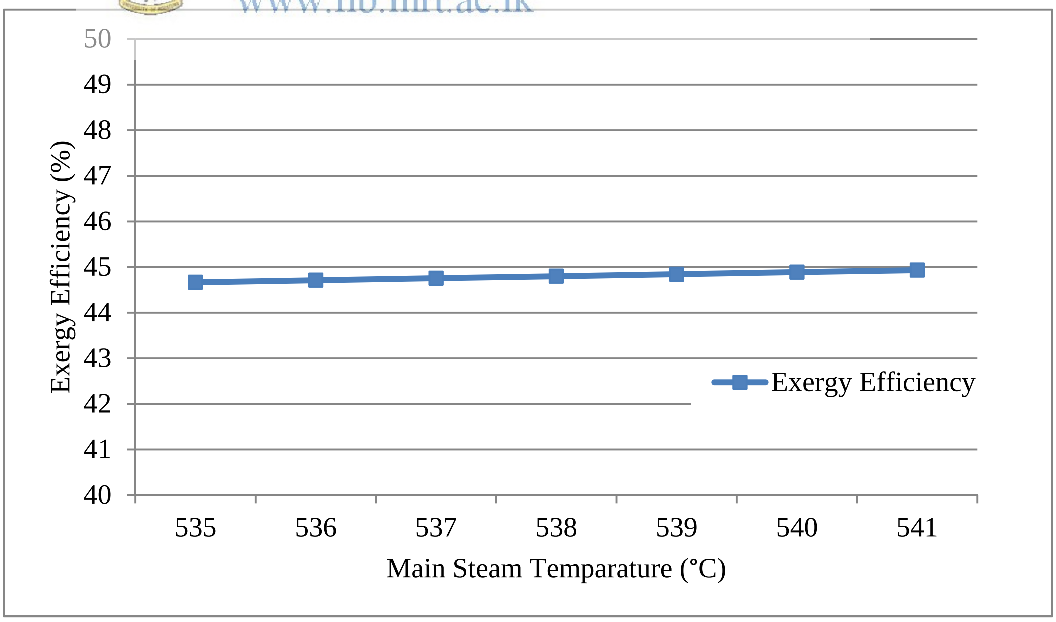

Figure 6.18: The variation of boiler exergy efficiency with main steam temperature under rated load condition.

The behavior of the exergy efficiency with the variation of main steam temperature is shown in the Figure 6.18. The exergy efficiency vary around 44% to 45% with the variation of MST considered. Variation of the exergy efficiency upon main steam temperature variation is too small when comparing to its variation due to change of the other critical parameters discussed here. Although when considering the cost of steam generation in this kind of the power plant, even small variation in exergy efficiency is also important.

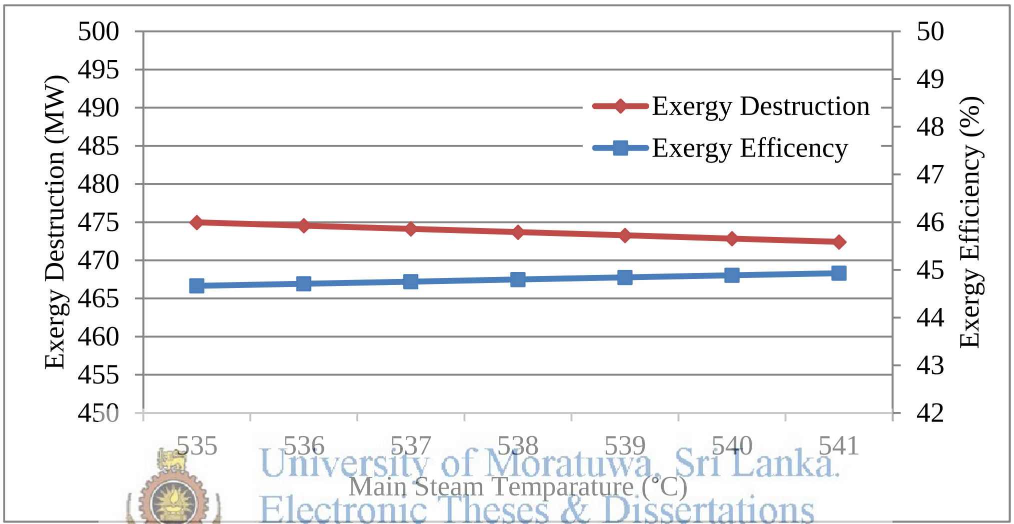

Figure 6.19: The variation of boiler exergy destruction and exergy efficiency with main steam temperature.

6.1.4 The variation of feed water temperature

The behavior of the boiler exergy destruction and its exergy efficiency is shown in the Table 6.9 at rated load of the power plant. The feed water temperature varies between 272°C and 280°C.

Table 6.9: The variation of exergy destruction and exergy efficiency with feed water temperature.

FW(°C)	E34	E1	E35	E3	E33	E36	E2	E4	ED	Effi.
272	0.004	73.00	888.78	207.74	56.85	0.71	363.59	276.30	472.08	44.93
273	0.004	73.58	888.78	207.74	56.85	0.71	363.59	276.30	472.65	44.91
274	0.004	74.15	888.78	207.74	56.85	0.71	363.59	276.30	473.22	44.88
275	0.004	74.73	888.78	207.74	56.85	0.71	363.59	276.30	473.80	44.85
276	0.004	75.31	888.78	207.74	56.85	0.71	363.59	276.30	474.38	44.82
277	0.004	75.89	888.78	207.74	56.85	0.71	363.59	276.30	474.97	44.80
278	0.004	76.48	888.78	207.74	56.85	0.71	363.59	276.30	475.55	44.77
279	0.004	77.07	888.78	207.74	56.85	0.71	363.59	276.30	476.14	44.74
280	0.004	77.67	888.78	207.74	56.85	0.71	363.59	276.30	476.74	44.72

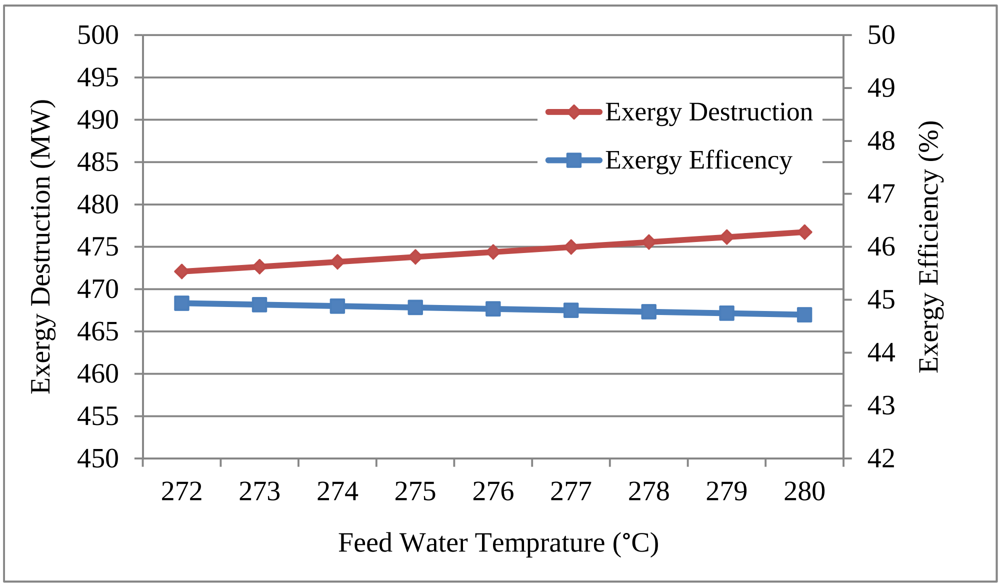

Figure 6.20: The variation of boiler exergy destruction and exergy efficiency with feed water temperature.

The exergy efficiency of the boiler is decreased with the increment of feed water temperature. When the feed water temperature is increased to 280°C, boiler exergy destruction is increased to 476MW.

6.1.5 Altered gross calorific value

The behavior of the boiler exergy destruction and exergy efficiency with various coal is shown in the Table 6.10 at the rated load of the plant. The gross calorific value of coal is changed between 5,600kcal/kg to7,000kcal/kg. The recommended GCV of coal of this power plant is 5,920kcal/kg to 6,900kcal/kg.

Table 6.10: The variation of exergy efficiency and exergy destruction with GCV of used coal

GCV (kcal/kg)	E34	E1	E35	E3	E33	E36	E2	E4	ED	Effi.
5,600	0.004	73.548	862.229	207.738	56.847	0.710	363.593	276.295	446.073	46.18
5,700	0.004	73.548	866.094	207.738	56.847	0.710	363.593	276.295	449.938	45.99
5,800	0.004	73.548	869.517	207.738	56.847	0.710	363.593	276.295	453.361	45.82
5,900	0.004	73.548	872.571	207.738	56.847	0.710	363.593	276.295	456.416	45.67
6,000	0.004	73.548	875.185	207.738	56.847	0.710	363.593	276.295	459.029	45.55
6,100	0.004	73.548	877.428	207.738	56.847	0.710	363.593	276.295	461.273	45.44
6,200	0.004	73.548	879.232	207.738	56.847	0.710	363.593	276.295	463.076	45.35
6,300	0.004	73.548	880.665	207.738	56.847	0.710	363.593	276.295	464.509	45.28
6,400	0.004	73.548	881.692	207.738	56.847	0.710	363.593	276.295	465.536	45.24
6,500	0.004	73.548	882.281	207.738	56.847	0.710	363.593	276.295	466.125	45.21
6,600	0.004	73.548	882.497	207.738	56.847	0.710	363.593	276.295	466.342	45.20
6,700	0.004	73.548	882.277	207.738	56.847	0.710	363.593	276.295	466.121	45.21
6,800	0.004	73.548	881.682	207.738	56.847	0.710	363.593	276.295	465.526	45.24
6,900	0.004	73.548	880.682	207.738	56.847	0.710	363.593	276.295	464.527	45.28
7,000	0.004	73.548	879.247	207.738	56.847	0.710	363.593	276.295	463.091	45.35

The variation of exergy destruction and exergy efficiency with the GCV of used coal is shown in the above chart. GCV range between 5,600kcal/kg to 7000kcal/kg was adopted to analyze the behavior of exergy with respect to GCV of coal. It was observed that, exergy efficiency of the boiler is higher when using a low GCV coal due to lesser exergy destruction in the process.

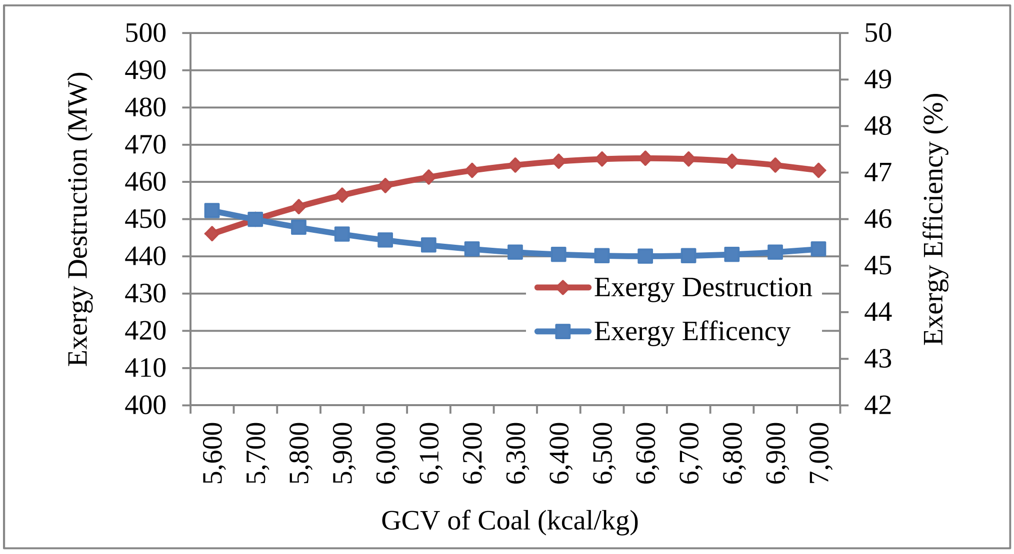

Figure 6.21: The variation of Boiler exergy destruction and exergy efficiency with GCV of used coal.

However it is not possible to identify the coal with less GCV as the best coal to improve the exergy efficiency of the boiler. The behavior of coal flow rate with the GCV of coal is shown in the Figure 6.22. Therefore, it is required to select the best coal with suitable GCV by considering the exergy destruction, exergy efficiency as well as the coal flow rate to improve the efficiency of the power plant.

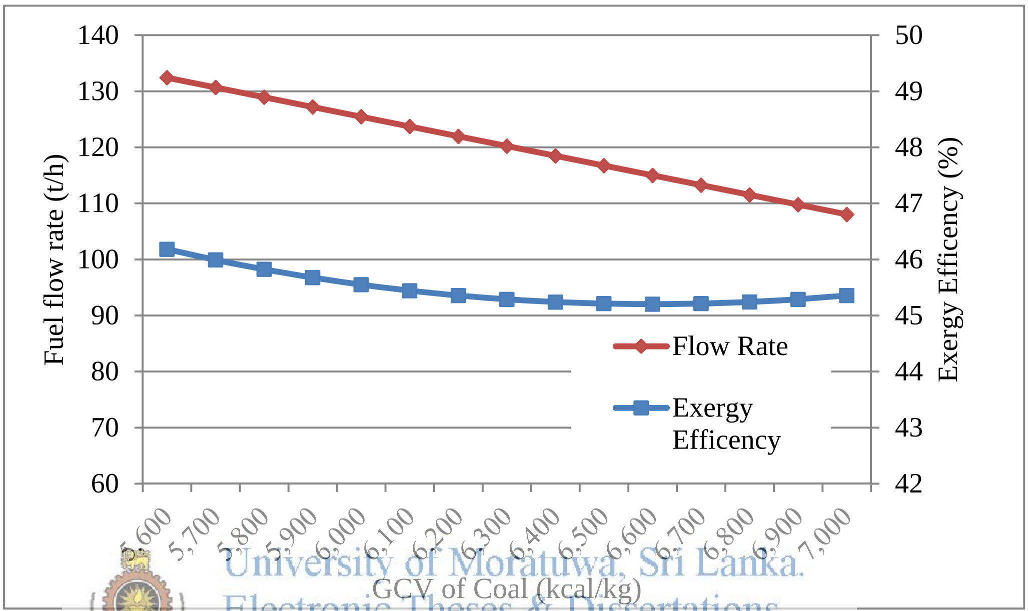

Figure 6.22: The variation of boiler exergy efficiency and its coal flow rate with GCV of used coal.

The variation of exergy destruction, exergy efficiency and coal flow rate with GCV of used coal is presented in the Figure 6.21 & 6.22. It was observed that, higher exergy efficiency and less exergy destruction can be achieved with coal having lesser GCV. But the coal flow rate is higher than that of other types of coal. If high calorific value of coal is selected (which has GCV of 7,000kcal/kg) exergy efficiency of boiler can be improved. The boiler of the LVPS unit 01 has been designed to utilize the coal which is having maximum GCV of 6,900 kcal/kg. Therefore it is required to re- design and modify the boiler if higher calorific value coal is used. Therefore for the existing boiler design, it is required to select the best coal with calorific value between 6,200kcal/kg to 6,900kcal/kg which will deliver the best exergy efficiency.

6.2 Benefits of exergy efficiency improvements opportunities

6.2.1 Saving of boiler steam generating cost.

It is required to identify the benefits which can be obtained from the improvements of exergy efficiency as discussed in previous sections; the exergy cost calculation shows steam generating cost of boiler is equal to 6.081million rupees per hour for full load running conditions. Following cost calculation shows how much of cost could be saved from exergy efficiency improvement opportunities.

Design exergy efficiency of Boiler	=	49%
Actual operational Exergy efficiency of boiler	=	45%
Fuel consumption for design full load conditions	=	110 t/h
Fuel consumption for actual full load conditions	=	115 t/h
Fuel consumption different between design and actual	=	115t/h – 110t/h
Condition	=	5 t/h
Fuel consumption increment due to 1% exergy loss	=	1.25 t/h

Therefore we can calculate boiler steam generating cost saving due to increase exergy efficiency of boiler using any of efficiency improvement opportunities;

$$\dot{C}_{35} + \dot{C}_1 + \dot{Z}^{CI} + \dot{Z}^{OM} = \dot{C}_2$$

If we consider boiler exergy efficiency increase with 1% the fuel consumption will reduce 1.25 t/h for full load operating conditions.

Therefore exergy value of fuel E_{fuel} = 27,647kJ/kg×31.597 kg/s

= 873,568.40 kW

$$c_2 \times \dot{E}_2 = c_{35} \times \dot{E}_{35} + c_1 \times \dot{E}_1 + \dot{Z}^{CI} + \dot{Z}^{OM}$$

$$c_2 = c_{35} \times (\dot{E}_{35}/\dot{E}_2) + c_1 \times (\dot{E}_1/\dot{E}_2) + \dot{Z}^{CI}/\dot{E}_2 + \dot{Z}^{OM}/\dot{E}_2$$

$$C_2 = \frac{6.82\text{LKR}}{\text{kWh}} \times \left(\frac{873{,}568.40\text{kW}}{363{,}070.655\text{kW}}\right) + \frac{0.03\text{LKR}}{\text{kWh}} \times \left(\frac{73{,}629.825\text{kW}}{363{,}070.655\text{kW}}\right) + \frac{\left(\frac{41{,}911\text{LKR}}{\text{hrs}}\right)}{363{,}070.655\text{kW}} + \frac{(\text{LKR}17{,}000/\text{hrs})}{363{,}070.655\text{kW}}$$

$$C_2 = 16.57\ \text{LKR/kWh}$$

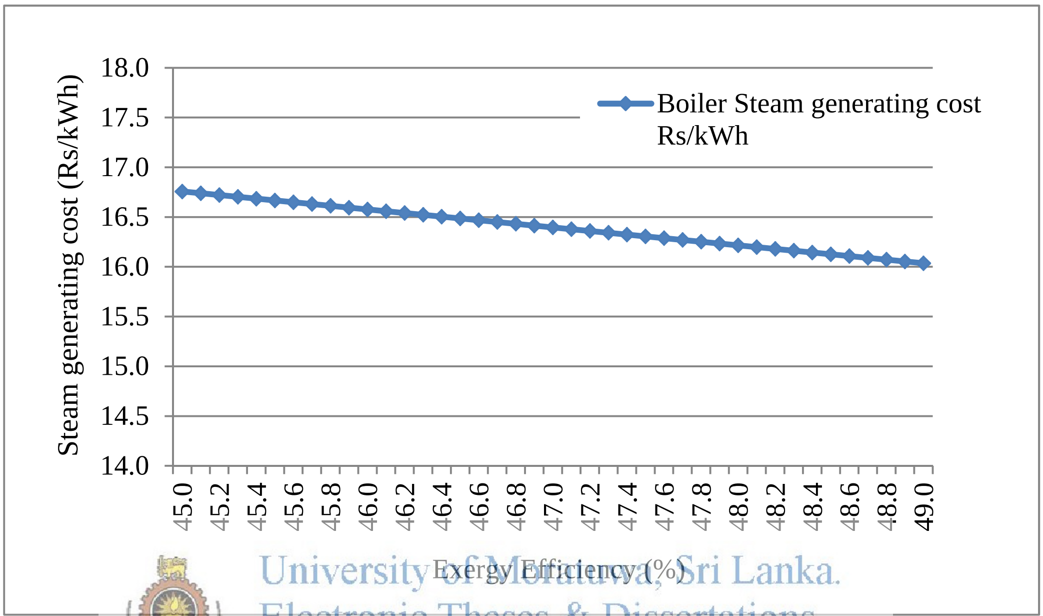

Figure 6.23: The variation of boiler steam generating cost with boiler exergy efficiency.

Total steam cost for full load conditions $= c_2 \times \dot{E}_2$

=LKR16.57/kWh× 363070kW

= LKR6.017million/h

Cost saving due to 1% exergy efficiency improvement of boiler

= LKR (6.081– 6.017) million/h

= LKR0.0633million/h

= LKR63,303.51/h

6.2.2 Reduction of CO_2 emission.

As a result of exergy efficiency improvement of the boiler, fuel consumption can be reduced. This reduction of fuel consumption directly affected on the reduction of flue gas emissions.

Ultimate analysis of fuel used in LVPS unit 1

C	63.75%
H	4.5%
N	1.25%
S	2.51%
Cl	0.29%
Ash	9.7%
M	11.12%
O	6.88%

If we consider the complete combustion of coal in boiler;

$C + O_2 = CO_2$

If we burn 1kg of C, it will emit CO_2	=	44kg/12kg
	=	3.66 kg
Amount of C contain in1kg coal which is used in LVPS	=	0.64kg
Amount of CO_2 emission from 1kg of Coal	=	3.66kg×0.64kg
	=	2.34 kg
Required coal amount to produce 300MWh in LVPS	=	115 t/h
CO_2 emission rate of power plant during full load condition	=	269.1 t/h
CO_2 emission rate per MWh	=	269.1/300
	=	0.89 t/MWh

If we improve boiler exergy efficiency, it will reduce the coal consumption of the boiler; Therefore

CO_2 emission due to 1% efficiency improved condition	=	2.34×113.75
	=	266.175 t/h

CO_2 emission saving per hour	=	(269.1-266.17)t/h
	=	2.92 t/h
	=	2.92×24×365
CO_2 emission saving per year	=	25.579 kton/year

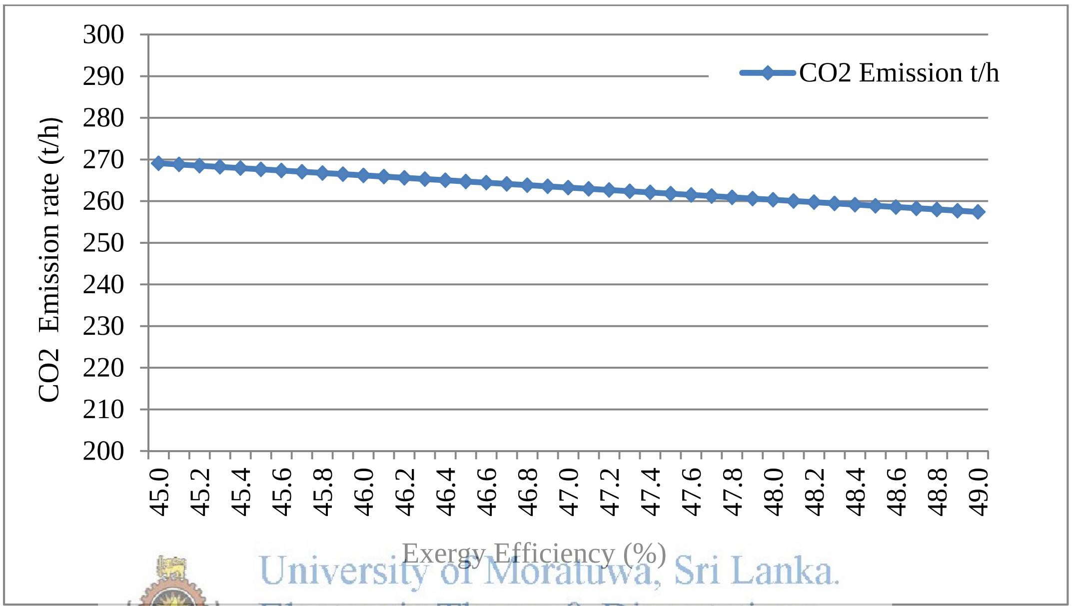

Figure 6.24: The variation of CO_2 emission with boiler exergy efficiency.

CHAPTER 07

7.0 Conclusion and Recommendation

This thesis was based on exergy analysis of coal power plant to identify the improvement opportunities of the exergy efficiency of that. Also a methodology was developed to identify the exergy values and the exergy efficiency of major equipment in coal power plants by using general equation of thermodynamics. Then the developed methodology was applied to LVPS unit 01 as the case study.

The exergy destruction of the boiler of LVPS unit 01 is around 392.78MW and it is nearly 90% of the total exergy destruction under the design condition of the power plant. However this value under the actual operational condition is around 461.67MW and it is almost 91% of the total exergy destruction. The exergy destruction of all other major equipment are lesser than 10% under both design and operation conditions. Hence, the exergy efficiency of most of other equipment are greater than 80%. HP, IP and LP turbines show 88%, 98% and 96% exergy efficiency respectively in actual operational conditions. These exergy efficiencies are almost same as the exergy efficiency of design conditions in the power plant. The exergy efficiency of the feed pump was around 66% in both design and actual operation conditions. The exergy efficiency of the all feed water heaters including deaerator was more than 75% under both design and operation conditions.

Also the overall exergy efficiency of the power plant was calculated by using above calculated exergy values. It was around 39% and 35% in design and operation condition respectively.

The energy balance of a power plant can be find out using the energy conservation law which was based on 1st law of thermodynamics. Same theory could be applied to the major equipment of the power plant to get an idea of its energy efficiency. In order to identify the difference between the exergy and energy efficiency of equipment, the energy efficiency of boiler sub system was calculated in this study. However, it is not possible to compare the energy and exergy efficiency. The calculated energy efficiency of boiler sub system in LVPS unit 01 is around 92% in design condition and it is around 87% in actual operational conditions. When considering LVPS unit 01 case study, Boiler shows the less exergy efficiency and high exergy destruction in both design and operational conditions. The boiler design exergy efficiency is around 49% and operational exergy efficiency is around 45%. The turbines, pumps, heat exchangers and deaerator show high efficiency than boiler sub system.

According to the above results, lowest exergy efficiency as well as the highest exergy destruction was recorded in the boiler sub system compared to the other equipment of the power plant. Therefore reduction of exergy destruction in boiler will directly affect to increase the overall exergy efficiency of the power plant. In this thesis, opportunities of reduction of exergy destruction were considered in order to improve the exergy efficiency of the power plant. Hence the reduction of exergy destruction and improvement of exergy efficiency of boiler sub system can be realized in two ways which were identified as the design modification of the boiler sub system and optimize the operation of the boiler sub system. In this thesis, the existing coal power plant in Sri Lanka (Unit 01 of LVPS) was studied. Therefore it was considered only optimizing the operation parameters in order to improve the exergy efficiency of the boiler of the said power plant.

Following five parameters were considered to optimize the boiler operation conditions and improve the exergy efficiency. Those parameters are Main steam pressure of the boiler, Main Steam Temperature, Gross Calorific Value of Coal, Feed Water Temperature and Load variation of power plant. The exergy efficiency of the boiler is mainly affected by the variation of the load and variation of main steam pressure. Based on the actual operation data of unit 01 of LVPS, calculations were done to identify the behavior of exergy efficiency with the variation of said two parameters. The exergy efficiency of the boiler was slightly affected by the remaining three parameters mentioned earlier. When considering the operational behavior of the power plant, it was observed that variation of load and variation of main steam pressure were taken place. The power plant was not operated under rated power condition due to requirements of the power system. And also variation of main steam pressure can be observed even at constant load due to various practical reasons. So increasing of the exergy destruction and reduction of exergy efficiency were observed as direct results of said variation of the parameters. Therefore actual operational exergy efficiency of the boiler totally deviates from its design exergy efficiency. Eventually the overall efficiency of the power plant also affected directly due to these variations. The design exergy efficiency of the power plant can be easily achieved by operating at its rated capacity with maximum permissible main steam pressure.

GCV of coal also was considered as a parameter which affects the exergy efficiency of the boiler. The boiler of the LVPS was designed to utilize the coal which is having the GCV between 5,600 kcal/kg - 6,900 kcal/kg. But the GCV of used coal in LVPS was around 6,300kcal/kg. Therefore it was difficult to find out the effect of variation of GCV of coal on the parameters of boiler as well as exergy of the boiler. Hence theoretical calculation was carried out to find out the behavior of the exergy efficiency of the boiler with the variation of GCV of the coal. That calculation indicates slight exergy efficiency variation with GCV. Also considering flow rate of fuel consumption and other parameters that results show 6200 kcal/kg to 6900 kcal/kg range is better to use in LVPS boiler.

The cost of steam generated as well as CO_2 emission can be reduced by the improvement of exergy efficiency of the boiler as discussed. If boiler exergy efficiency improves by 1%, power plant can reduce steam generating cost by LKR63303.51 per hour and hazardous CO_2 emission can be reduced by 25.579 kton per year.

That means potential of exergy efficiency improvement in coal power plant is directly related to reduction of exergy destruction in overall power plant. The boiler sub system is the major contributor of overall exergy destruction in the coal power plant. Therefore worthy exergy efficiency improvements of overall power plant can be achieved by reducing of destruction of exergy of the boiler. Hence proper consideration shall be given to above discussed boiler parameters to improve its exergy efficiency. As a result overall efficiency of the coal power plant can be improved.

7.1 Recommendation

Coal power plant shall be operated under its rated load condition as base load plant as much as possible. Also the main steam pressure of the boiler shall be maintained at maximum working pressure in order to improve the overall exergy efficiency of the power plant. According to the results obtained, it is required to operate Unit 01 of LVPS at its rated capacity of 300MW and boiler main steam pressure around 16MPa to improve the overall efficiency of the power plant.

7.2 Future work

To develop exergy analysis methodology, excel spread sheet calculation was used. But it can be modified developing a program which can be easier to find out exergy values and exergy efficiency of major equipments.

In this thesis only boiler sub system was considered as major exergy destruction equipment and it used to discuss overall plant efficiency improvement opportunities. Therefore we can consider other equipment also to discuss potential of exergy efficiency improvements.

In this thesis only consider boiler steam cost calculation to find out steam generating cost, but we can use all product and fuel cost of all major equipment in power plant to find out complete exergoeconomics analysis of the power plant.

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APPENDIX A: Contract Price Table of Puttlam Coal Power Project

Contract Price Table
Phase I Puttalam Coal Power Project

Item No.	Description	Plant & Material	Service	Total Amount
Section 1: Unit 1 the 300MW unit plus related common works				
1	**Unit 1, the 300MW unit plus related common works**			
1.1	**Main Power Block (MPB)**			
1.1.1	Boiler and Auxiliaries	53'308'000	9'717'000	63'025'000
1.1.2	Steam Turbine & Generator and Auxiliaries	49'550'000	5'000'000	54'550'000
1.1.3	Steam & Water Piping System	6'400'000	2'956'000	9'356'000
1.1.4	Insulation, Lagging and Painting	2'500'000	1'757'000	4'257'000
1.1.5	Electrical System	39'000'000	4'617'000	43'617'000
1.1.6	Communication System	960'000	103'000	1'063'000
1.1.7	Instrument and Control System	9'550'000	2'510'000	12'060'000
1.1.8	Chemical System	2'500'000	752'000	3'252'000
1.1.9	Civil Work for Main Power Block	5'814'000	45'050'000	50'864'000
1.1.10	Spare Parts (Supplied with equipment)			
	Total (MPB)	**169'582'000**	**72'462'000**	**242'044'000**
1.2	**Balance of Plant (BOP)**			
1.2.1	Coal Handling System	4'976'000	576'000	5'552'000
1.2.2	Fuel-Oil System	100'000	10'000	110'000
1.2.3	FGD	16'985'000	4'000'000	20'985'000
1.2.4	Ash Handling System	2'956'000	320'000	3'276'000
1.2.5	Water Treatment System	3'700'600	970'000	4'670'600
1.2.6	Water Supply System	15'075'000	9'502'000	24'577'000
1.2.7	Waste Water Treatment System	100'000	50'000	150'000
1.2.8	Au[illegible] System	1'400'000	10'000	1'410'000
1.2.9	[illegible]	[illegible]	1'300'000	6'440'000
1.2.10	Civil Work for Balance of Plant	3'964'000	56'100'000	60'064'000
1.2.11	Spare Parts (Supplied with Equipment)			0
	Total BOP	54'396'600	72'838'000	**127'234'600**
1.3	Site Development	150'000	300'000	450'000
1.4	Logistics		18'500'000	18'500'000
1.5	Engineering Survey, Design and Drawing		7'000'000	7'000'000
1.6	Equipment Supervision & Inspection (Contractor & Employer)		2'000'000	2'000'000
1.7	Commissioning, Trial Operation till TOC		6'000'000	6'000'000
1.8	Training Cost Borned by Contractor		3'500'000	3'500'000
		150'000	**37'300'000**	**37'450'000**
	Total (Section 1)	**224'128'600**	**182'600'000**	**406'728'600**

APPENDIX B: Standard Molar Chemical Exergy of Selected Substances

Standard Molar Chemical Exergy, $\bar{e}^{ch}$ (kJ/kmol), of Selected Substances at 298 K and p_0

Substance	Formula	Model I[a]	Model II[b]
Nitrogen	$N_2(g)$	640	720
Oxygen	$O_2(g)$	3,950	3,970
Carbon dioxide	$CO_2(g)$	14,175	19,870
Water	$H_2O(g)$	8,635	9,500
Water	$H_2O(l)$	45	900
Carbon (graphite)	$C(s)$	404,590	410,260
Hydrogen	$H_2(g)$	235,250	236,100
Sulfur	$S(s)$	598,160	609,600
Carbon monoxide	$CO(g)$	269,410	275,100
Sulfur dioxide	$SO_2(g)$	301,940	313,400
Nitrogen monoxide	$NO(g)$	88,850	88,900
Nitrogen dioxide	$NO_2(g)$	55,565	55,600
Hydrogen sulfide	$H_2S(g)$	799,890	812,000
Ammonia	$NH_3(g)$	336,685	337,900
Methane	$CH_4(g)$	824,350	831,650
Ethane	$C_2H_6(g)$	1,482,035	1,495,840
Methyl alcohol	$CH_3OH(g)$	715,070	722,300
Methyl alcohol	$CH_3OH(l)$	710,745	718,000
Ethyl alcohol	$C_2H_5OH(g)$	1,348,330	1,363,900
Ethyl alcohol	$C_2H_5OH(l)$	1,342,085	1,357,700

APPENDIX C: Property Report of Unloaded Coal

[illegible]
Sri Lanka
Tel: [illegible]
Fax: [illegible]

Page: 01 of 02

04th November 2011
Job Order No. 20110310

INSPECTION REPORT

In pursuance of an order received from and on behalf of M/s. LANKA COAL COMPANY, we attended to the inspection of captioned goods and report as under

VESSEL	: M.V. PREM VIDYA
CARGO DESCRIBED AS	: Steam Coal in Bulk
QUANTITY	: 82403.700 MT
PLACE & DATE OF ATTENDANCE	: At Puttalam Coal Power Plant From 08/10/2011 to 23/10/2011
WEATHER CONDITION	: Partly – Sunny Cloudy/Rainy

SAMPLING : Barge wise samples [illegible] mechanical sample installed on Coal discharge conveyor system by Ceylon Electricity Board as per ASTM st[illegible] prepared property [illegible] plastic seal.

AN[illegible] : Barge wise samples were analyzed separately at our in house laboratory as per ASTM standards and the weighted average results are as follows.

ANALYSIS (ON AIR DRIED BASIS)

Inherent Moisture %	4.40 (Four decimal four-zero)
Ash %	15.15 (Fifteen decimal one-five)
Volatile Matter %	40.51 (Forty decimal five-one)
Fixed Carbon %	39.94 (Thirty-nine decimal nine-four)
Sulphur %	0.60 (Zero decimal six-zero)

GCV (Gross Calorific value) Kcal/kg : 6314 (Six thousand three hundred fourteen)

ANALYSIS (ON DRY BASIS)

Ash %	15.85 (Fifteen decimal eight-five)
Volatile Matter %	42.37 (Forty-two decimal three-seven)
Fixed Carbon %	41.78 (Forty-one decimal seven-eight)
Sulphur %	0.63 (Zero decimal six-three)

GCV (Gross Calorific value) Kcal/kg : 6605 (Six thousand six hundred five)

Appendix D: Costing Sheet of Water Treatment System

COSTING SHEET OF WATER TREATMENT SYSTEM (Operation)

Desalinated. (Rs/m^3)			Service water. (Rs/m^3)			Potable system. (Rs/m^3)			Dematerialized water. (Rs/m^3)		
Chemical cost	Electrical cost	Total cost	Chemical cost	Electrical cost	Total cost	Chemical cost	Electrical cost	Total cost	Chemical cost	Electrical cost	Total cost
38.30	**44.55**	82.85	38.30	50.90	89.20	66.44	86.75	153.19	66.44	90.39	**156.83**

Desalinated water	
Chemicals	**Cost** ($Rs./m^3$)
NaoCl	8.04
HCl	6.15
Reductant	5.76
Scale	14.78
NaOH	-
PAC	1.82
PE	1.75
Total	**38.30**

Potable and Deminaralized water	
Chemicals	**Cost** ($Rs./m^3$)
NaoCl	10.57
HCl	9.15
Reductant	8.52
Scale	32.90
NaOH	-
PAC	2.70
PE	2.60
Total	**66.44**