EXERGY (SECOND LAW) ANALYSIS OF STEAM BOILERS IN SRI LANKA

By

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and behalf, it contains no material previously published or written by another person nor material, which to substantial extent, has been accepted for the award of any other acedemic qualification of a university or other institute of higher learning except where acknowledgment is made in the text.

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Abstract

In this study, exergy analysis was carried out for boilers. A sample of 100 Nos. of boilers was selected and input and output streams for each boiler were studied. Exergy and energy balance for each boiler was evaluated and theoretical analysis was carried out using these results.

Variation of exergy efficiency with flue gas temperature and excess air, variation of exergy efficiency with energy efficiency, variation of CO_2 emission with exergy efficiency, variation of cost of steam with exergy efficiency and variation of exergy destruction with excess air and flue gas temperature were presented. The theoretical background for these variations were discussed.

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Acknowledgement

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CHAPTER 1
RESEARCH PROBLEM BEING ANALYZED

The most commonly used indicator for the efficiency of energy conversion process is the ratio of the output of useful energy to the total energy input. This ratio is called first law efficiency. It is based on a quantitative accounting of energy, which reflects recognition of the first law of thermodynamics and the law of conservation of energy.
It is well known that the second law of thermodynamics defines the availability of energy more restrictively than the first law. Principally, first law is silent on the effectiveness with which availability is concerned. Analysis in terms of the second law of thermodynamics more closely describes the effectiveness with which systems or processes use available energy.
This chapter describes the background of the second law analysis or the exergy analysis, CO_2 emission, global warming and how it relates with second law efficiency in steam boiler, exergy based pricing and exergy based taxing for emission, Sri Lankan situation on exergy, and specific objectives of this thesis.

1.1 Background of Exergy

The word "exergy" comes from the Greek words meaning 'form' and 'work' of a thermal system. At the beginning there was no clear nomenclature for exergy analysis and the terms availability, available energy, essergy, utilizable energy, work potential, available work, convertible energy, etc. were used in different countries to refer the term exergy. To improve this situation a workshop on "Teaching Thermodynamic" was held at the University of Cambridge in September 1984. As a result of this three successive drafts of proposed nomenclature have been produced and the final draft was introduced based on that.

The concept of exergy is developed based on the second law of thermodynamics and in practice relies heavily on the use of thermodynamic property entropy. However, while many people express difficulty in grasping the physical signification of entropy, which tends to increase to a maximum in any isolated system, exergy is easier to conceptualize. For example, let us take a container of fuel inside an isolated room. The room is fully insulated. Suppose the fuel burns completely so that finally there is a slightly warm mixture of combustion products and air. According to the first law of thermodynamics the energy at the initial state and the energy at the final state are equal. But the initial fuel-air mixture would be intrinsically more useful than the final warm mixture. For instance the fuel might be used in some device to generate electricity or produce superheated steam, whereas the use to which the slightly warm combustion products can be put would be far more limited in scope. Hence it is observed that the initial potential of energy is very much higher than the final potential. This shows that the initial work potential has been largely destroyed during the process and available energy is existing within the system as generated entropy. Technically we say that the initial energy potential has been largely destroyed due to generation of entropy within the system and generation of entropy leads to system irreversibilities.

The above energy or availability is called exergy and destruction of potential of energy is called exergy destruction.

The basic concepts of exergy analysis can be traced back to the writings of Lord Kelvin and William Thomson in 1852 [19]. In that year Kelvin wrote about ' Sources available to man for the production of mechanical effect' and about the 'Dissipation' and 'Restoration' of mechanical energy. He also presented his monumental work 'On the dynamic theory of heat' to the Royal Society of Edinburgh in the same year. It is sufficient to point out that Kelvin in 1852 had remarkable insights into the area now known as exergy analysis.

George Stephenson invented the world's first steam engine in 1825 and it was run between Berminham and Manchaster. The Sri Lankan railway was established in 1850 and the first trial was made between Colombo and Ambepussa. In 1854 Clausius wrote a very famous paper and introduced the concept of entropy to the world. This shows that the thermodynamics applications date back as far as the theories do.

Exergy analysis has shown to be an efficient tool for process understanding and optimization. During process development, product quality, production capacity, investment costs and operating costs have always been of great importance. However the cost of fossil fuels and the awareness of the environmental impact of the consumption of the non-renewable fossil fuels have increased. Therefore the need for energy efficient processes become more important. In order to achieve savings in primary energy consumption, the potential for improvement of a process needs to be researched.

Usually a process analysis is based on energy and mass balance. However this type of process analysis only shows the energy flows of the process and does not give insight on how the quality of the energy degrades through the process by dissipation. Exergy is a measure for the quality of energy. Decreasing the exergy losses of a process shows a tendency to a lower primary fuel consumption, reducing the operating cost and increasing the process efficiency.

Exergy analysis makes it possible to universally compare different processes and alternative process routes on thermodynamic basis.

1.2 CO_2 Emission and Greenhouse Effect

Energy always radiates to the earth from the sun and the earth reradiates energy back into space. The radiation and reradiation effect, are always balanced and no energy accumulation occurs on the earth surface on a long-term basis. The atmospheric gases such as carbon dioxide, water vapor and other minor gases trap some of this reradiating energy and the temperature of the space increases and tends to temporally stabilizing point. This phenomenon is called "Greenhouse effect".

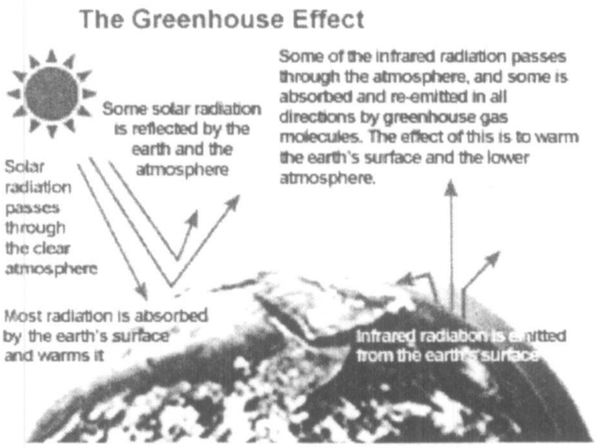


Figure 1.1 The green house effect

Energy trapping in the space due to naturally existing atmospheric gases is named natural greenhouse effect and without this effect temperatures would be much lower than they are now, and lives as known today not be possible. Instead thanks to this natural greenhouse effect the earth's average temperature is maintained at around 60^0F [40].

Some greenhouse gases occur naturally in the atmosphere while others result from human activities. Naturally occurring greenhouse gases include water vapour, carbon dioxide, methane, nitrous oxides and ozone. Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulfurhexafluoride (SF_6) come as a result of human activities.

Generally it is believed that the combustion of fossil fuels and other human activities are the primary reason for the increased concentration of carbon dioxide. Plant respiration and the decomposition of organic matter release more than 10 times the CO_2 released by human activities [40]. But this CO_2 releases have generally been in balance during centuries leading up to the industrial revolution with carbon dioxide absorbed by terrestrial vegetation and oceans.

Methane is emitted during the production and transport of coal, natural gas and oil and also result from the decomposition of organic wastes in municipal solid waste, landfills and the raising of livestock. Nitrous oxide is emitted during agricultural and industrial activities, as well as during combustion of solid waste and fossil fuels.

However, since the beginning of industrial revolution atmospheric concentrations of carbon dioxide have more than doubled and nitrous oxide concentrations have risen by about 15% [40]. These increases have enhanced the heat trapping capability of the earth's atmosphere. Fossil fuels burned are responsible for about 98% of carbon dioxide emissions, 24% of methane emissions and about 18% of nitrous oxide emissions [40].

Mainly global temperature increases due to the greenhouse effect and rising global temperature is expected to rise sea level and change precipitation and other local climate conditions, changing regional climate that could alter forests, crop yields and water supplies. It could also threaten human health and harmful to birds, fish and many other ecosystems. Observations collected over the last century suggest that the average land surface temperature has risen 0.45 - 0.6 ^{0}C [40].

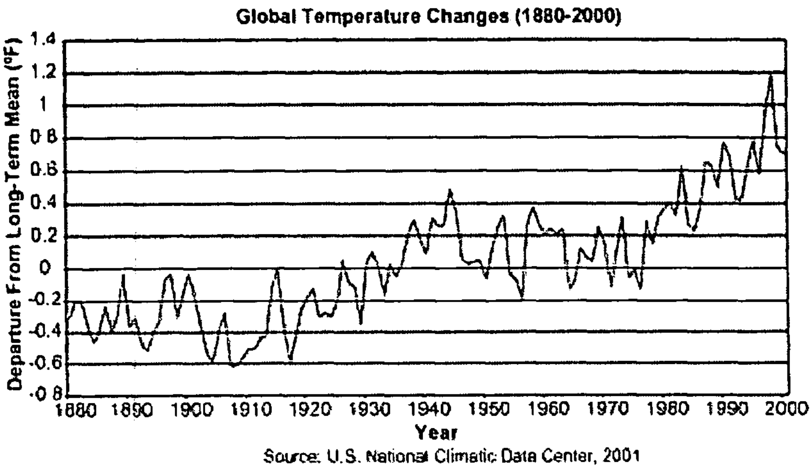


Figure 1.2 Variation of global mean temperature

Sea level has risen worldwide approximately 15 – 20 cm (6 – 8 inches) in the last century [24]. Approximately 2 – 5 cm of rise has resulted from the melting of mountain glaciers and the rest comes from the expansion of ocean water that resulted from Warmer Ocean temperature [40]. Precipitation has increased by about 1% over the world's continents in the last century [40]. High latitude areas are tending to see more significant increases in rainfall while precipitation has actually declined in many tropical areas.

Carbon dioxide (CO_2) is the key greenhouse gas responsible for global warming. Mainly CO_2 comes from burning fossil fuels and about 1440 MT [41] of furnace oil is burnt daily in steam boilers in Sri Lanka and the resultant emission is around 4500 MT per day.

By improving the energy efficiency it can reduce the amount of fuel burning can be reduced resulting in low emission levels.

As exergy is the maximum work potential that can be extracted from a system and exergy efficiency is the ratio between the real exergy output and exergy input, improving the exergy efficiency makes the potential of the source to be used better. Exergy efficiency of a package type steam boiler is around 27% and it implies that there is drastic exergy destruction within the boiler system.

1.3 Energy based Pricing and Exergy based Pricing

The development and application of exergoeconomics have started since 1950s and provided theoretical basis for designing efficient and cost effective energy systems. Large number of optimization methods related to exergoeconomics emerged in the 1980s [19].

Calculation of steam cost is done in normal conventional way by dividing the total cost input by the unit output and thereby the unit cost is obtained. There is no significant error within this calculation and the accounting is also easy. These calculations are based on energy efficiency and if the calculations get involved with exergy-based efficiency the picture is different. The exergy efficiency lies in a very low range than the energy efficiency in a steam boiler and it implies that there is massive amount of exergy destruction leading to less work potential. Thus the exergy-based calculations give the real picture about the energy usage and exergy based pricing gives real cost of usable energy.

Energy efficiency gives an idea about the amount of energy transfer from one state to another and exergy efficiency implies the amount of work potential that can be obtained in each state. The energy efficiency of a package type boiler is in the range of 80% to 85% [31] based on the HHV of the fuel and it can be improved maximum up to around 87% [31] by reducing the losses. The improvements are limited and people never think beyond this.

Exergy efficiency of a boiler is around 27% and comparing the situation in boiler there is huge tendency to improve the exergetic efficiency than the energy efficiency by implementing better energy utilizing systems such as cogeneration, energy cascading, fuel cells, etc. The specific cost based on exergetic efficiency implies the real picture of each thermodynamic system. Without knowing the exergy-based details it is impossible to improve the work potential and also it has not received main attention. Thus exergy-based pricing is very essential to get an idea of the behavior of the process and to implement further improvements as this reflects a more realistic picture and thus a more rational way of costing.

1.4 Exergy based Taxing for Emissions

Burning of fossil fuels give emissions to the environment. Mainly furnace oil is burnt in boilers in Sri Lanka and heat, unburnt carbon and pollutant gases such as CO_2, CO, SO_2, NO & NO_2 are the major emissions.

As we discussed earlier exergetic efficiency of boilers lies in very low levels indicating a large loss of maximum possible work of the source that could have otherwise been obtained. If the efficiency gets increased the fuel consumption gets reduced and the specific emission also gets reduced. Emissions pollute the environment and environmental pollution causes serious damages to human beings and to ecological system. It is impossible to estimate this damages in rupees but however there must be an accounting system for environmental damages.

At present there is a tax system for CO_2 emissions and also regulations for some common pollutants in few countries in the world. But rather than going to tax for direct pollutants it is very important to introduce exergy-based tax or entropy-based tax system. The objective is to reduce the emission by increasing the exergy utilization. The specific emission had to be evaluated reference to the exergy efficiency and the tax can be implemented based on the above figure.

Through these tax methods people will be encouraged to implement higher exergetic efficiency systems and it will result in reduced specific emissions.

1.5 Sri Lankan Situation of Exergy Analysis

Exergy-based analysis is a new concept to Sri Lanka and now it is being introduced to the university syllabus. Around the world, exergy analysis has been used for system optimization and the final results are more realistic than the system design based on first law of thermodynamics. First law of thermodynamics is widely used in analyzing of thermal systems but it does not provide enough information to support a comprehensive system. It measures only the quantities of work and energy and ignores the quality of energy used. It can tell how much energy is needed to perform a particular task, but not how well that energy is used. It can only support bulk allocation arguments. But exergy analysis goes beyond this and provides insights needed to apply energy resources to use, which produce less entropy per unit of useful heat or work.

As an underdeveloped country, we also have to use this type of efficient tools in design stages to minimize energy waste and to achieve development conditions.

Even though energy efficiency is a critical factor to Sri Lanka, one should go beyond energy efficiency, and thus high exergetic efficiency systems are needed for the country. In other words one could obtain a higher work potential from less quentity of energy. Therefore exergy analysis will be a valuable tool for our energy sector for future development.

CHAPTER 2

LITERATURE SURVEY ON EXERGY

Although the basic concepts of the second law analysis have been formulated in the second half of the 18th century, most of the developments of practical applications in this area have been implemented within the last fifty years and are still continuing. Few numbers of books were published during this period and about thousand numbers of researches were conducted and research papers were published. The summary of the most research works conducted during the past can be taken from the Internet. This chapter presents the summary and important data of few papers presented in the past years in international journals.

2.1 Major Researches Conducted and Papers Published

Nomenclature for exergy analysis

T J Kotas, Y R Mayhew, and R C Raichura published this paper on March 1994 at department of engineering, Queen Mary and Westfield College University of London.

The first nomenclature of second law of thermodynamics published by the Rant in 1952. But it was not a complete one for exergy analysis and thus different names were used in different countries. Therefore a workshop on ' Teaching Thermodynamics' was held at Cambridge, England, in September 1984, to prepare a complete nomenclature. As a result of this, a complete draft was prepared and the proposals have been circulated in the UK, USA, Canada and other countries. The final results are presented in this paper. In addition to that it presents the concept of exergy including reference states, concepts of chemical exergy, exergy balance or the Gouy-Stodola relation, loss of exergy and exergetic efficiency, etc.

Exergy analysis – a different perspective on energy

Part I - The concept of exergy

Part II - Rational efficiency and some examples of exergy analysis

A paper was presented on February 1990 by J A McGovern at department of mechanical and manufacturing engineering, Trinity college, University of Dublin, Ireland.

Part I of the paper describes the concept of exergy analysis. Mainly it covers the theory of exergy transfers associated with various systems. It discusses the

- Preliminary definitions related to the words in exergy analysis
- The concept behind work and useful work
- Theory of exergy and exergy functions including chemical exergy
- Exergy analysis in closed systems
- Exergy analysis in open systems, etc.

In Part II of the paper a universal rational efficiency is described and a number of worked examples are presented to illustrate the application of exergy analysis. Those are,

a. Exergy analysis of a hot water boiler
b. Exergy analysis of an air to water heat pump
c. Exergy analysis of a hot air generator for a building

The paper presents some collective data for analysis of chemical exergy.

Table. 2.1 Composition of the specified reference environment

Substance	Mole fraction	Mass fraction
N_2	0.7567	0.7401
O_2	0.2035	0.2275
H_2O_{vap}	0.0303	0.0190
CO_2	0.0003	0.0005
Others	0.0092	0.0129

Thermodynamic analysis of a gas turbine cogeneration plant – a case study

This analysis was done by P S Utgikar an P J Prasada Rao at mechanical engineering department S V regional college of engineering and thchnology, Surat, India, in May 1994.

This was a complete exergy and energy analysis report of a gas turbine cogeneration plant. The capacity of gas turbine was 20 MW and it was run with cogeneration topping cycle. The plant is operating in India and fuelled by heavy oil. The plant performance has been evaluated on the basis of fuel utilization efficiency, power to heat ratio and second law efficiency.

Analysis shows that exergy losses in the combustion chamber of the gas turbine and the heat recovery steam generator with Sankey diagram and Grassmann diagram. The paper presents performance evaluation of the plant with cogeneration system and the results are as follows.

Table 2.2 Performance evaluation of the gas turbine cogeneration plant

Parameter	Full load	Half load
Fuel utilization efficiency	82.6	79.37
Second law efficiency	0.33	0.16
Power – heat ratio	0.33	0.16
Fuel saving ratio	0.35	0.25
Pay back period (Years)	4.77	-

Energy and exergy balance in a gas turbine combustor

This paper was presented by A Datta and K Som at department of power plant engineering, Javapur University, Calcutta, India, in August 1998.

The paper consists of energy and exergy balance in the process of spray combustion in a model tubular gas turbine combustor. A theoretical model of exergy analysis, based on availability transfer and flow availability has been developed to predict the second law efficiency of the combustion process in the gas turbine combustor. The above papers were published in the journal of power and energy during the past years. Mathematical modeling of the gas turbine combustor is presented at the beginning of the paper. The important part is the results and discussion. The paper presents

- Variation of combustion efficiency and second law efficiency with air fuel ratio based on inlet air temperature 600 K and spray angle 80^0

- Variation of combustion efficiency and second law efficiency with inlet air temperature based on air fuel ratio 60 and spray angle 80^0
- Variation of combustion efficiency and second law efficiency with fuel spray cone angle based on air fuel ratio 60 and inlet air temperature 600 K

Exergy analysis of solar – assisted heat pump system

The paper was prepared by Murat Tunc, Mithat Uysal and Akif Özmen and published in applied energy journal, Applied Science Publishers Ltd., England, in 1988.

Mathematical modeling based on exergy analysis of a solar assisted heat pump is given in the first part of the paper and variation of exergetic efficiency with collector area is illustrated in the results. Eleven numbers of different systems have been examined and the results are compared.

Exergy analysis of waste emission

The paper was presented by Marc A Rosen and Ibrahim Dencer of department of mechanical engineering, Ryerson Polytechnic University, 350, Victoria Street, Toronto Ont, Canada, and published in international journal of energy research in 1999.

The paper consists of the relations between several measures of environmental impact and exergy analysis is done by comparing current methods used to assess the environmental impact potential of waste emission and the exergy associated with those emissions. A case study on air pollution limits established by the government of Ontario is presented to highlight the information revealed using exergy. Environmental pollution cost from fossil fuel combustion is also presented with the case study.

A new exergoeconomic approach for analysis and optimization of energy systems

This paper was presented by B Hua, Q L Chen and P Wang, at chemical engineering research institute, South China University of Technology, in October 1996.

The paper consists of a new exergyoeconomic approach to optimize energy systems. It describes the

- Exergoeconomic model of a binary subsystem
- Exergoeconomic analysis and optimization
- Application to optimization of the CGAM problem and results and discussion of the same.

Standard chemical exergy of some elements and compounds on the planet earth

The thesis was prepared by David R Morris and Jan Szargut at department of chemical engineering University of New Brunswick, Fredericton N B Canada.

This is a very valuable document for exergy analysis. The paper presents chemical exergies of 49 elements and some inorganic and organic compounds of those elements. The value for 9 elements are based on the atmosphere as the reference substance, for 27 elements, the values for 27 elements are based on the hydrosphere as the reference substance, the values for 13 elements are based on the lithosphere as the reference substance. Values of the standard chemical exergy of some inorganic compounds in the ideal aqueous solution of unit molarity are also presented.

Exergy – A useful concept

This paper was prepared by Göranwall in Ghalmers University of Technology – Göterborg, Sweden.

The thesis treats the exergy concept and its applications to technical and social systems. This gives the exergy calculation methods, which are based on fundamental theory, and it shows their usefulness in different applications. The paper presents in terms of the conversion of energy and material resources in the Swedish society in 1980. Exergy losses in transformation of material resources and in conversion of various forms of energy into heat are described in detail. A simple method of calculating the exergy of different substances is presented and energy and exergy prices of several common energy forms are compared. Three case studies are included in the paper. One is pulp and paper mill, second one is steel mill and the final case study is Swedish house heating system.

Exergy loss – A basis for exergy taxing

This paper was presented by Gerad Hirs at University of Twente, the Netherlands.

This paper introduces a very special taxing method named Entropy Added Tax (EAT). This is analogous to Value Added Tax (VAT) or Goods and Service Tax (GST). Mainly the paper gives the concept and advantages and disadvantages of EAT.

Entropy Generation Minimization: Ther Method of Thermodynamic Optimization of Finite-Size Syatems and Finite-Time Processes

This book was edited by Adrian Bejan, Frank A. Kulacki

This book presents the field of Entropy Generation Minimization (EGM), the method of thermodynamic optimization of real devices. The EGM method also referred to as " thermodynamic optimization," " thermodynamic design," and " finite time thermodynamics" are thoroughly discussed, and the methods applications to real devices are clearly illustrated. This book places EGM's growth in perspective by reviewing both sides of the field engineering and physics. Special emphasis is given to chronology and to the relationship between the more recent work and the pioneering work that outlined the method and the field.

Few publications in international journals and in the Internet are presented above and apart from this there are more research publications and papers in the world. At present more researches are going on in the University of Twente in the Netherlands and in Chalmers University of Technology in Goteborg Sweden. The details of the above are available in the following web sites.

1. www,thw.utwente.nl and 2. www. exergy.se.

The concept of exergy is not new, but within about past fifty years people have used this theory for analyzing and optimizing systems to achieve maximum productivity and efficiency.

Systems here refers to both technical and social systems. Exergetic efficiency of many systems are very high in countries like Japan and South Korea and we are in far away and also we have not tried to reach these levels.

Though the exergy concept has been used very vastly in the world there is no single research or publication in our country yet. Unfortunately there are many energy managers who do not know even the word exergy. But we have installed, installing and also we are planning industrial zones, export processing zones, large-scale production plants (eg. steel industries, glass industries, etc.) and various types of power plants. This subject is being introduced into university syllabus and we hope there will be warm-up in the near future.

CHAPTER 3

THEORETICAL ANALYSIS

Exergy analysis is based on the second law of thermodynamics according to which complete transformation of heat into work is not possible. Exergy is the maximum work that can be obtained from a given form of energy with reference to the environmental parameters as the dead states. One of the main uses of this concept is in the exergy balance that may be looked upon as an amount of the degradation of energy. The concept of exergy is not new but for a long time it was nearly forgotten but now it is being used in the energy sector due to increasing interest in efficient energy techniques deriving from the problems related to energy use in the society.

This chapter discusses mainly the theories behind the exergy analysis. At the beginning it gives the fundamental concepts behind exergy and then the components of exergy are explained. The formulas for the exergy in fuel, chemical and physical exergy, exergy balance for closed and open systems and exergetic effciency are discussed in the end of the chapter.

3.1 Reference States or Reference Environment

Exergy is not a property of the system but of the system and environment. The environment is the limit to which thermodynamics systems tend towards equilibrium in spontaneous processes. When a system reaches the state of equilibrium with the environment it can no longer produce work that is it does not have exergy.

The reference environment is considered to be so large, that its parameters are not affected by interaction with the system under consideration. It may be used, as the Reference State in the analysis. Depending on the situation the Reference State may be either dead state or restricted dead state as describe bellow.

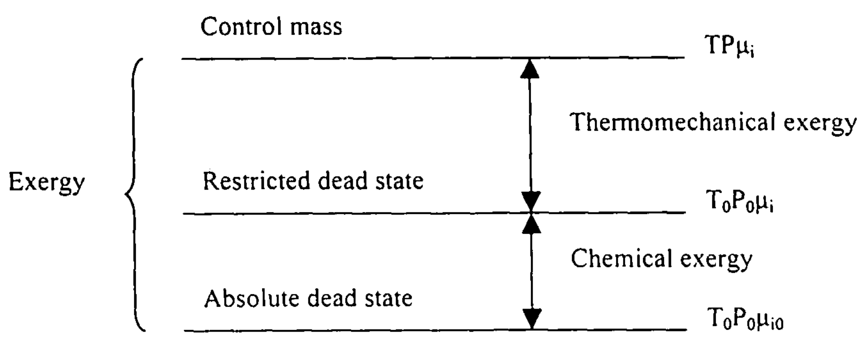
3.1.1 Restricted dead state

The system in thermal and mechanical equilibrium with the surroundings or environment is said to be restricted dead state. In this state the system is not permitted to mix or enter into chemical reaction with the surroundings and the maximum amount of work obtained is called "Thermomechanical exergy" [24].

The environmental state is defined by the actual pressure and temperature and denoted by P_0 and T_0. In general, 1 atm and 298.15 K is taken as the restricted dead state and it is always free from internal irreversibilities [24].

3.1.2 Absolute dead state

Absolute dead state is achieved when the system is in thermal, mechanical and chemical equilibrium with the surrounding or environment. Thus the concentration difference between the system at restricted dead state and the surroundings at absolute dead state could be used to produce a certain quantity of work called the "Chemical availability or Chemical exergy" [24]. At this stage there can be no spontaneous change within the control mass or within the environment.



(Subscript i denotes difference chemical species)

Fig 3.1 Control mass, dead states and exergy

3.2 Fundamental Concepts

As we discussed earlier the term exergy is defined, as the maximum work potential of a material or form of energy in relation to its environment. This concept is based on the thermodynamic property called entropy and the second law of thermodynamics. Combining the first law and the second law of thermodynamics, Exergy balance is developed.

In the late 1800s Clausius investigated the equilibrium condition for an isolated system. He knew that the total energy of the system was a constant and he wanted to determine whether or not there would be a change of state in the isolated system. He had shown that a change of state might occur but could not formulate a method by which the change could be predicted. If the system is in equilibrium then no change would occur. It could be especially helpful if there was a system property that would denote whether or not the system was in equilibrium.

3.2.1 Clausius inequality

When a system passes through a complete cycle a perpetual motion machine is

$$\oint \frac{\delta Q}{T} \leq 0$$

possible unless

where δQ represents the energy received in a heat interaction in a part of the system boundary during a portion of the cycle and T is the corresponding absolute temperature at that part of the boundary [7]. The integral is to be performed over all parts of the boundary and the entire cycle. The equality sign applies only for internally reversible operations and the inequality sign, in the presence of irreversibilities.

3.2.2 Entropy

Entropy is introduced by showing that for a control mass $\int \frac{\delta Q}{T}$ has the same value between two states when the integral is evaluated for any internally reversible process between the states. This means that the value of the integral represents the difference in some property. This property is called entropy, entropy is denoted by 'S' [7].

3.2.3 Exergy, anergy and energy

As discussed earlier exergy is the maximum work that can be extracted from a given form of energy reference to the environment. The maximum implies that there is some energy that cannot be extracted. Any form of energy can be categorized into two areas, the first part being made up of the convertible forms and the other the unconvertible remainder. The name exergy is for the part consisting of convertible forms and the name anergy for the unconvertible part. All forms of mechanical energy i.e. kinetic and potential energy and mechanical work and also electrical energy consists of pure exergy because they are in principle totally convertible to any other energy form. In contrast internal energy and heat involve both exergy and anergy and the internal energy of the environment consists solely anergy. The higher the proportion of exergy in any form of energy, the more valuable it is from the technical and economical point of view.

3.2.4 Irreversibility

Anergy takes place in any form of heat or internal energy due to system entropy reference to the environment. When the energy is transferring from the form of high temperature to low temperature, the quantity of energy remains constant but the anergy gets increased at low temperature than its initial high temperature state. On the other hand the exergy gets reduced or destroyed. This destruction takes place due to system irreversibilities and irreversibilities are developed due to creation of entropy within the system boundary. At the reference environment or dead state the exergy gets completely destroyed and the system will consist solely anergy or entropy.

The irreversibilities or creation of entropy within the system destroys the exergy and this is caused by

- Temperature difference while transferring heat
- Free expansion of a system
- Difference of Gibbs energy of the components and the products during a chemical reaction.

3.2.5 1st Law of thermodynamics

Now we realize the concept of exergy and the irreversibility. Technical people and energy managers always think about energy conservation. Do we need to conserve energy, what does the 1st law of thermodynamics say? It says that energy cannot be destroyed and only possibility is to convert it into any other forms. That means energy conversion is possible from form to form or energy transfer is possible from state to state. But according to the 2nd law of thermodynamics the available energy gets destroyed while energy is transferring from state to state. Now we realize that the energy conservation is not needed but exergy conservation is essential.

According to the above definitions the 1st law of thermodynamics can be illustrated as follows.

1st Law : The sum of exergy and energy remains constant during each process [1].

3.2.6 2nd Law of thermodynamics

If a process were reversible the exergy would remain constant, if it is irreversible some exergy is converted to anergy, anergy cannot be converted to exergy [1].

3.3 Components of Exergy

Energy is available in different forms and it can be transferred to any other forms in many ways. For example energy is available as work, kinetic energy, potential energy, electricity, heat energy, chemical energy or material stream. In form to form the exergy analysis is different. Exergy can be associated in different forms within single system but the amount of exergy is calculated using different formulas and finally it can be added together to evaluate the total exergy.

3.3.1 Exergy transfer with work interaction

Four types of exergy are associated for work interaction and those are

- Mechanical work
- Kinetic exergy
- Potential exergy and
- Electricity

The exergy transfer with work interaction is associated with work transfer rate or shaft power. Because exergy is defined as the maximum work potential, it is equivalent to exergy in every respect.

(a) Exergy associated with potential energy

The potential energy of a body with respect to an arbitrary level in the earth's gravitational field is fully convertible to useful work.

(b) Exergy associated with kinetic energy

Macroscopic kinetic energy is fully convertible to work only if it's exact distribution in space can be described and quantified.

(c) Exergy associated with electrical energy

Electrical energy is totally convertible to any other energy form and it consists of pure exergy.

3.3.2 Exergy transfer with heat interaction

Let a control mass initially at the dead state be heated or cooled at constant volume in an interaction with some other system. The heat transfer experienced by the control mass is Q. The subscript zero is denoted the initial state and f denotes the final state. An increase in exergy is realized by heating to increase the temperature from T_0 to T_f or by cooling to decrease the temperature from T_0 to T_f. The exergy associated with the final state equals the maximum work extractable from the combined system of control mass and environment as the mass is returned to the dead state. Then the exergy transfer rate can be calculated by the following formula.

$$E = \iint_{f}^{0} \left(1 - \frac{T_0}{T_f}\right) Q \cdot dA$$

Where A is the heat transfer area [1].

3.3.3 Exergy transfer associated with material stream

Kinetic exergy and potential exergy are not much appearing in thermodynamics analysis. So it is neglected in general and major contribution comes from heat energy appeared in different forms. There are two types of heat energy associated in thermodynamics systems and those are

- Heat energy associated in control mass (eg. surface of boiler, steam distribution pipes, hot water tanks, etc.)
- Heat energy associated in material stream (eg. flue gas flow, steam flow, hot air, etc.)

Exergy in material stream is divided into two as follows.

- Physical exergy
- Chemical exergy

(a) <u>Physical exergy</u>

Physical exergy is the work obtainable by taking the substance through reversible processes from its initial state temperature T and pressure P to the state determined by the temperature T_0 and the pressure P_0 of the environment. Physical exergy components can be calculated from the following formula.

$$E_{ph} = (H - H_0) - T_0(S - S_0)$$

Where H is denoted by enthalpy and S is the entropy [27]. The physical exergy can be split into temperature and pressure components and also the pressure component is called the mechanical component. So physical exergy is named thermomechanical exergy.

(b) <u>Chemical exergy</u>

Exergy of a system denotes the maximum work that can be obtained when the system is allowed to come into equilibrium with the surroundings. The state of the surroundings is often called the dead state. Two types of dead states come into play. The system in thermal and mechanical equilibrium or physical equilibrium with the surroundings is said to be in "restricted dead state". In this state the system is not permitted to mix or enter into chemical reaction with the surroundings and the maximum amount of work obtained is called physical exergy or thermomechanical exergy as we discussed above.

The second one called the absolute dead state is achieved when the system is in thermal, mechanical and chemical equilibrium with the surroundings. Thus the concentration difference between the system at restricted dead state and the surroundings at absolute dead state could be used to produce a certain quantity of work called "chemical exergy".

It is important to note that chemical exergy plays a dominant role in exergy analysis in processes involving mixtures of chemical substances or chemical reactions and should not be ignored.

For the calculation of chemical exergy of the reference gases which form together the reference atmosphere, the work for getting the components at the standard pressure from the partial pressure of the Reference State has to be determined. This is done by the following formula.

$$E_{ch} = RT_0 \ln\left(P_0 / P_{00} \right)$$

Where - P_{00} is the partial pressure of the components in the Reference State[27].

The above equation can be expressed as

$$E_{ch} = RT_0\, y_i \ln (y_i/y^e_i) \qquad [28]$$

Where

y_i and y_i^e represent the mole fraction of component i in the mixture and in the environment

3.4 Exergy in Fuels

Consider a chemical reaction of a hydrocarbon fuel of $C_\alpha H_\beta$

$$C_\alpha H_\beta + (\alpha + \beta/4)O_2 \longrightarrow \alpha CO_2 + \beta/2H_2O$$

The component of physical exergy can be obtained from the following formula [27].

$$E_{ph} = \left\{h_f + \left(\alpha + \frac{\beta}{4}\right)h_{O_2} - \alpha h_{CO_2} - \frac{\beta}{2}h_{H_2O}\right\}(T_0P_0) - T_0\left\{S_F + \left(\alpha + \frac{\beta}{4}\right)S_{O_2} - \alpha S_{CO_2} - \frac{\beta}{2}S_{H_2O}\right\}at(T_0P_0)$$

The component of chemical exergy can be obtain [27]

$$E_{ch} = RT_0 \ln\left\{\frac{(y_{O_2})^{\alpha+\frac{\beta}{4}}}{(y_{CO_2})^{\alpha}(y_{H_2O})^{\frac{\beta}{2}}}\right\}$$

Where

S_{O_2}, S_{CO_2}, S_{H_2O}, S_f, Denotes the entropy of O_2, CO_2, H_2O and fuel respectively

h_{O_2}, h_{CO_2}, h_{H_2O}, h_f, Denotes the enthalpy of O_2, CO_2, H_2O and fuel respectively

y_{O_2}, y_{CO_2}, y_{H_2O}, Denotes the mole fraction of O_2, CO_2, and H_2O in the environment respectively

Then the total exergy represent [27]

$$E_{fuel} = E_{ph} + E_{ch}$$

The following component of the physical exergy formula represent the higher heating value of the fuel [27]

$$HHV = \left\{h_f + \left(\alpha + \frac{\beta}{4}\right)h_{O_2} - \alpha h_{CO_2} - \frac{\beta}{2}h_{H_2O}\right\} \text{ at } (T_0 . P_0)$$

Therefore the exergy formula can be represented as follows [27].

$$E_{fuel} = HHV - T_0\left\{S_F + \left(\alpha + \frac{\beta}{4}\right)S_{O_2} - \alpha S_{CO_2} - \frac{\beta}{2}S_{H_2O}\right\}at(T_0P_0) + RT_0 \ln\left\{\frac{\left(y_{O_2}\right)^{\alpha+\frac{\beta}{4}}}{\left(y_{CO_2}\right)^{\alpha}\left(y_{H_2O}\right)^{\frac{\beta}{2}}}\right\}$$

Or using standard chemical exergy it can be represent as follows [27].

$$E_{fuel} = HHV - T_0\left\{S_F + \left(\alpha + \frac{\beta}{4}\right)S_{O_2} - \alpha S_{CO_2} - \frac{\beta}{2}S_{H_2O}\right\}at(T_0P_0) + \left\{\alpha E^{ch}_{CO_2} + \frac{\beta}{2}E^{ch}_{H_2O} - \left(\alpha + \frac{\beta}{4}\right)E^{ch}_{O_2}\right\}$$

3.5 Exergy Balance for Total System

It can be defined two types of systems in thermodynamic analysis. Those are

- Closed systems
- Control volumes

3.5.1 Exergy balance for closed system

$$E_2 - E_1 = \int_1^2\left(1 - \frac{T_0}{T_B}\right)\delta Q - \left\{W - P_0\left(V_2 - V_1\right)\right\} - T_0\sigma$$

Where $\int_1^2\left(1 - \frac{T_0}{T_B}\right)\delta Q$ - Exergy transfer accompanying heat

$W - P_0\left(V_2 - V_1\right)$ - Exergy transfer accompanying work

$T_0\sigma$ - Irreversibility due to internally entropy generation [27]

3.5.2 Exergy balance for control volume

$$E_2 - E_1 = \int_1^2\left(1 - \frac{T_0}{T_B}\right)\delta Q - \left\{W - P_0\left(V_2 - V_1\right)\right\} + \sum m_i a_{fi} - \sum m_e a_{fe} - T_0\sigma$$

Where $\sum m_e a_{fe}$ - Total input exergy

$\sum m_i a_{fi}$ - Total output exergy [27]

3.3 Exergetic Efficiency

Engineers frequently use efficiencies to judge the performance of devices and processes. Many of these expressions are based on first law of thermodynamics or

energy efficiencies. Also useful are measures of performance that take into account limitations imposed by the second law of thermodynamics. Efficiency based on second law analysis is named second law efficiency or exergetic efficiency. The exergetic efficiency is a very useful measure for the thermodynamic quality of a technical process. This efficiency can be defined in different ways and the most useful definition is as follows [22].

$$\psi = \left(\frac{\text{Exergy out in products}}{\text{Exergy inpput to the system}} \right)$$

3.4 Cost of Steam

Cost of steam is calculated based on the prices of input materials, operation & maintenance costs and the steam production. If the boiler efficiency is around 80% - 85%, it can be obtained about 12.5 kg to 13.5 kg of steam burning one kg of furnace oil when it is operated at 10 barg. As we discussed earlier energy is vastly degraded or destroyed within the boiler due to temperature difference between the combustion mixture and the steam. Therefore the cost of steam based on rational efficiency is much higher than its cost based on energy efficiency. Exergy is the theoretically usable energy and comparing with energy analysis exergy based costing is very essential to get the actual picture of any thermal system.

The exergy-based unit cost of steam can be calculated by using the following formula [27].

$$C_S = \frac{C_f \{m_f a_f\} + C_w m_w a_w + C_e a_e}{m_S a_s}$$

Where

$m_f a_f$ - Exergy of fuel input

$m_S a_s$ - Exergy output through steam

a_e - Exergy of electricity input

$m_w a_w$ - Exergy input through feed water

C_w - Cost of feed water

C_e - Cost of electricity

C_f - Cost of fuel

C_s - Cost of steam

3.5 Radiation and Convection Losses in Cylindrical and Flat Surfaces

There are few empirical formulas for calculation of convective heat transfer of a heat body and the following formulas [42] are used for this analysis. Radiation heat transfer is taken from the Stefan Boltzman formula.

$$Q = UA(T_s - T_a)$$

$$U = U_R - U_C$$

Where

U - Overall heat transfer coefficient

U_R - Radiative heat transfer coefficient and

U_C - Convective heat transfer coefficient

$$U_R = \sigma\xi \frac{(T_s^4 - T_a^4)}{(T_s - T_a)}$$

Where σ - Stefan Boltzman constant

ξ - Emissivity of the surface

T_s - Surface temperature of the body

T_a - Ambient temperature

$$U_C = \frac{B(T_S - T_a)^{0.25}}{D^{0.25}}$$

Where D - Length of the significant dimension of the structure (mm)

B - Constant depending on structure geometry

Values of B & D for some common surfaces [42].

Table 3.1 Values of B and D for some common surfaces

Surface	D	B
Vertical planes & large cylinders	Height	1.35
Horizontal planes facing upward	Side	1.35
Horizontal planes facing downward	Side	0.60
Horizontal cylinders and small vertical cylinders	Diameter	1.15

CHAPTER 4
METHODOLOGY

Mode of collection of data and measurements and their accuracy are very important considering the final results of any analysis. It was used very accurate instruments for collection of measurements and it was taken nearly one year's time for the measurements in various industries and those are presented in the appendices. To evaluate the exergy balance, the method is to calculate the exergy input and output separately, so that it is necessary to collect all the inputs and outputs of the system separately.

This chapter presents the method of selection criteria of the sampling size and the type of the samples, instruments used and specimen calculation for one set of sample. The measurements were taken from the industries and samples were selected according to the type of industries, configuration of boilers, size of the boilers and types of the burners.

4.1 Data Collection

There are about 1600 furnace oil fired boilers operating in Sri Lanka in different capacities in various industries. Mainly the boilers are used for process heating and very little in power generation in Sri Lanka. The measurements were taken in these industries and incorporated to the analysis.

Boiler tuning and flue gas analysis is one of the major activities of Energy & Environmental Management Centre of the NERD Centre. It was completed over 100 numbers of individual exercises during the year 2000 and 2001 and these data was taken for this analysis. The sampling size is 100 and the sample was decided based on the following factors.

- Different industries
- Different loads
- Different types of burners
- Different types of boiler configurations, etc.

4.1.1 Different industries

There are various types of industries and manufacturing organizations in Sri Lanka and out of them the data were collected from the following industries.

- Consumer product manufacturing
- Food and beverages manufacturing
- Tobacco processing
- Textile and textile processing
- Latex and rubber products manufacturing
- Manufacturing of paper products

4.1.2 Different loads

There is not much effect to the operation of the boilers depending on the type of industries but the capacities of the boilers vary according to the steam requirements, which is mainly dependent on the process. In some industries the specific thermal energy contribution to the product is very little compared to material and other costs involved. Component of the fuel cost is not highlighted compared to the others in the annual reports. Due to these reasons, people are not much worried about the operation and maintenance of boilers and thus the losses can be considerably high.

Process steam requirements are varied due to type of the product and also due to size of the process plant. Therefore it was greatly helpful to select the boilers in different capacities by selecting different types of industries. Depending on the output, the fuel consumption and the size of the burners and boilers vary. Due to these reasons the amount of losses in the areas such as blowdown, surface emission, flue gas, etc. vary very much. In some industries the boilers are not fully utilized due to high capacities of the boilers comparing to the process requirements. Therefore the frequency of the on and off operation is high. Due to these reasons the overall efficiencies get reduced and ultimately output gets reduced.

4.1.3 Configurations of boilers

There are about 1600 numbers of steam boilers operating in industries in Sri Lanka and over 80% consume furnace oil as their fuel. Therefore this study has focussed mainly for furnace oil fired boilers but the calculation procedures are common to any type of fuel.

Boilers are categorized into two main groups according to their configuration. Those are

1. Water tube boilers
2. Fire tube boilers

Water tube boilers are mainly used in power generation processes.

There are few water tube boilers operating in Sri Lanka for power generation and processes requirements. Two nos. of 83 MWe water tube boilers are operating in Kelanithissa power plant and it is run with furnace oil of viscosity 1000 sec. and the generation capacity of the power plant is 50 MWe. Four numbers of water tube boilers are operating in Pelwatta and Sewenagala sugar factories and these are fueled with both baggase and furnace oil and those are operating for both power generation and process heat applications.

Seven numbers of water tube boilers are operating in Kabool Lanka, Thulhiriya for process heating and out of them one is operating with saw dust and others are operating with furnace oil. Two numbers of water tube boilers are operating in the Nestle factory, Pannala, only for process heating and the capacities are 10 ton each and both the boilers are fuelled with furnace oil too. Apart from these few water tube boilers operating in the field, there are few in different capacities, and are mainly in garment industries.

Fire tube boilers are common in Sri Lanka and widely used in the industries for process heating applications and operating in below 20 barg. Most of the boilers are operating in 10-barg pressure and there are few numbers operating in 17 barg and 20 barg. Furnace oil is the common fuel being used in the field, firewood and sawdust are used in few boilers. One boiler is operating with producer gas which is taken from the output of the charcoal gasifier in Bieco – Link factory Griulla and another one is being converted to producer gas in a DC mill named S A Silva and Sons in Loluwagoda. In addition to this there operate few boilers below 5 barg in par-boiling industries and paddy husk and firewood are the major fuels for these.

4.1.4 Different types of burners

Whatever the configuration of boilers the combustion is mainly dependent on the type of fuel and the type of burners. As it was discussed earlier furnace oil is the major energy source for boilers in Sri Lanka. Furnace oil is available in different viscosity in the country and it varies from 500 Redwood sec. to 3500 Redwood sec. Common types in the market are 500 sec, 800 sec, 1000 sec and1500 sec. Whatever the fuel viscosity the heat capacity is in a constant range and the average HHV is 43 MJ/kg [35].

(a) Furnace oil combustion

Furnace oil is categorized according to the type of viscosity and the furnace oil 1000 Redwood sec and 1500-sec are widely used in Sri Lanka. Before the combustion, fuel should be atomized. Proper atomization is a must to make a proper air-fuel mixture and there are three major types of fuel atomization. Those are

- Rotary cup atomization,
- Pressure jet atomization
- Twin fluid atomization.

(b) Rotary cup atomization

A cone type cup is rotated with high speed (around 3000 – 5000 rpm) horizontally and the fuel is supplied inside the cup. Due to the high speed the fuel is slipped to the tip of the cup. High velocity air is blown through the outer surface of the cup and this air takes the fuel at the tip of the cup and gets atomized. After atomization the fuel is fired by external sources and secondary air is supplied to the flame separately for proper combustion.

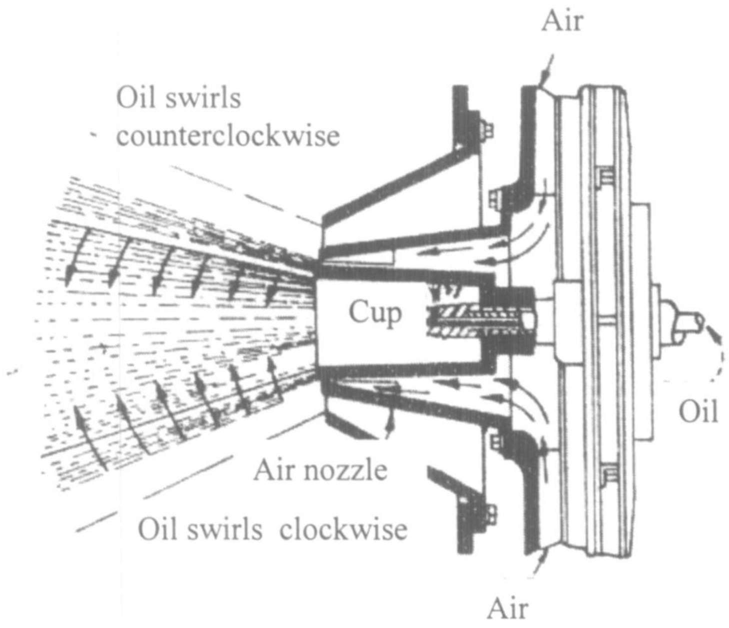


Figure 4.1 Rotary cup burner

The following parameters mainly affect the combustion in rotary cup burners.

- Fuel preheating temperature
- Quantity and the velocity of the primary air
- Speed and the surface condition of the rotary cup
- Rates of fuel supply to the cup, etc.

Fine adjustments are essential in the above area to achieve better performance of the combustion and there is possibility to adjust all the parameters above in this type of rotary cup burners.

(b) Pressure jet atomization

Fuel is pressurized upto about 300 to 400 psi and blown through a small orifice to the atmosphere. Due to the sudden change of pressure the fuel gets expanded at the atmosphere and separated into particles. This is named pressure jet atomizing. The viscosity of the fuel is maintained by preheating the fuel and the average viscosity of the fuel that should be maintained is in the range of 100 sec [31] when atomizing. The equivalent preheating temperature to maintain the viscosity is varied with the type of fuel. As an example furnace oil 1000 sec should be preheated upto around 100 ^{0}C and it is around 115 ^{0}C for furnace oil 1500 sec [31].

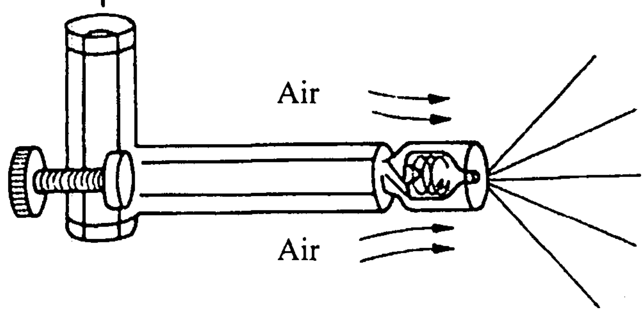


Figure 4.2 Pressure jet atomizer

Atomizing depends on the fuel pressure, viscosity and the condition of the nozzle in these type burners. Fuel pressure can be controlled easily by regulating the fuel pump and viscosity can be maintained uniformly keeping the fuel preheating temperature in a constant range. But the conditions of the nozzles get varied in time to time while the burner is in operation. Therefore frequent replacements of the nozzles are necessary in these burners. Therefore the atomization of this type burners are far limited.

(c) Twin fluid atomization

Twin fluid atomizers are designed to spray a mixture of oil and air or a mixture of oil and steam. The fuel is generally introduced into the high velocity air stream in discrete jets. These are based on the spray nozzle that has emerged as the most popular mechanism of oil droplet preparation. These customarily operate with oil pressure less than 100 psi and more often less than 30 psi. The air pressure may vary from 3 - 15 psi in the medium air pressure, it may be 15 psi or more in high air pressure burners. The dry steam pressure may vary from 25 – 175 psig. The nozzles get wear frequently in this type of burners too. But by regulating the other parameters such as fuel preheating temperature, fuel pressure, compressed air pressure, etc. the combustion efficiency can be maintained at higher levels.

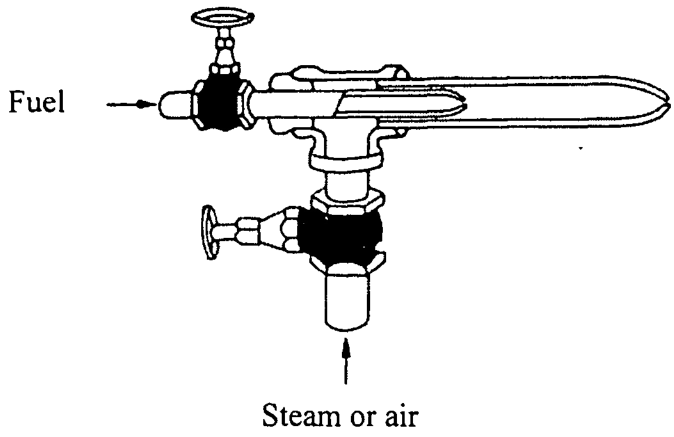


Figure 4.3 Twin fluid atomizer

In addition to the proper atomization the correct air-fuel ratio is needed for proper combustion. If the air supply is less, the fuel gets burnt partially and if the air supply is high, complete combustion occurs, but higher amount of exergy gets wasted through the flue gas. Therefore it is essential to maintain the correct amount of combustion air to achieve maximum possible efficiency.

The smoke number (opacity or suspended particulate matter) in the flue gas is a parameter that can decide the condition of the combustion. If the smoke number is zero, it implies that the combustion is complete and if it is greater than zero the combustion is incomplete. All the measurements for this analysis were taken when the smoke number was zero.

4.1.5 Fuel consumption

Steam flow meters are not installed in most of the boilers in Sri Lanka and only indicator is the fuel consumption. Unfortunately fuel is also not metered in most organizations but the daily consumption is available by measuring the level difference of stock tanks. Therefore the hourly consumption is predicted through these figures and taken for the analysis.

4.2 Sampling Size

The sampling size of this analysis is 100 and it was selected as mentioned above. If the sampling size is large the accuracy of the results is high, but there are limitations to collect information from the samples.

1. The instruments are limited in Sri Lanka for analysis of boilers and also those are very expensive, mainly the flue gas analyzers. The hiring facilities are available but due to the above reasons, the per-day chargers are also high. Therefore collecting the measurements is impossible without having financial support.
2. Energy & Environmental Management Department of the NERD centre is involved in boiler tuning and flue gas analysis in industries. So the data of boiler and flue gas analysis were collected from the E&EMC of the NERD centre. The E&EMC of the NERD centre carries out flue gas analysis only on request of the management of industries. Therefore limited numbers of analysis are carried out per year and thus the sample size was limited up to 100.

4.3 Instruments Used

4.3.1 Flue gas analyzer

Flue gas analyzer is equipped with Electro chemical type sensors, which are calibrated at the factory.

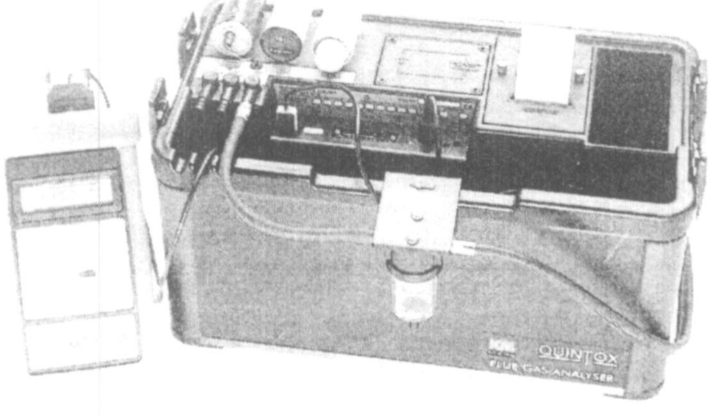


Figure 4.4 Flue gas analyzer

In addition to that on line calibration facilities are available in each sensor. Ambient O_2 concentration, which is equivalent to 20.9% by volume is taken as reference point for calibration of O_2 sensor and 0 % by volume for other sensors such as CO, NO, NO_2 and SO_2.

Make - Kane May International Limited
Swallowfied, Welwyn Garden City, Hertfordshine AL71JG, England
Model - KM 9106
SR Number - 52698311

4.3.2 Other instruments used

- Digital thermometer with thermocouples
- Infrared thermometer
- Measuring tapes
- Conductivity meter

Kane International Limited

Kane House • Swallowfield • Welwyn Garden City • Hertfordshire AL7 1JG • England
Telephone +44 01707 375550 • Facsimile +44 01707 393277

ANALYSER CALIBRATION REPORT

Instrument: KM9106 *Serial No:* 52698311

Parameter(s)	Signal Input(s)	Instrument Reading(s)		Equipment
Temperature	0 °C	-0.9		Temperature Simulator
	100 °C	99.6		EH/T/109
	1000 °C	999.2		
Oxygen (O_2)	0 %	0.1		Using CO test gas
	5.09 %	5.2		BOC Alpha standard gas
Carbon Monoxide (CO)	0 ppm	0		In ambient air
	990 ppm	990		BOC Alpha standard gas
Nitric Oxide (NO)	0 ppm	0		In ambient air
	1006 ppm	1006		BOC Alpha standard gas
Sulphur Dioxide (SO_2)	0 ppm	0		In ambient air
	1560 ppm	1560		BOC Beta standard gas
Nitrogen Dioxide (NO_2)	0 ppm	0		In ambient air
	180 ppm	180		BOC standard certified gas
Hydrocarbon	0 %	N/F		In ambient air
(Methane)	2.6 %	N/F		BOC standard certified gas
Pressure	0 mBar	N/F		Dead weight tester
	100 mBar	N/F		EX/C/100
Carbon Monoxide (CO)	0 %	N/F		In ambient air
[6CO]	3.58 %	N/F		BOC standard certified gas
Measured Flow Rate	ltrs/min	2.1		TL529
Measured Pump Suction	mBar	593		EX/C/147

Signed: D. Nutt

Calibration Results

Test Method: **Temperature:** The temperature input is subjected to a known and traceable voltage simulating a thermocouple input. The references voltages are taken from International Tables - BS4937 (1973)

Gas: The gas input is subjected to a known and traceable value of a Certified gas mixture

Pressure: The pressure input is subjected to a known and traceable pressure using a dead weight tester

Measurement Uncertainties: The uncertainty assigned to the above measurements is 1°C for temperature, ± 2% for gas measurements and 0.05% for pressure

4.4 Method of Analysis

Exergy inputs and exergy outputs of each boiler were estimated by using standard exergy formulas. Both chemical exergy and physical exergy were considered for this analysis. All the formulas and method of calculations is presented in the chapter 3. Exergy inputs of a boiler take place through fuel, feed water, combustion air and electricity (blowers, feed water pumps, fuel preheating, etc.). Steam is the useful exergy output and exergy gets lost through the other areas such as flue gas, blow down, surface emission, etc. Ash production is very much less in furnace oil fired boilers compared to the other fuels such as saw dust, wood, paddy husk, etc. Thus the losses in this are is neglected. If the combustion is incomplete the unburnt carbon particles are emitted through the flue gas or can deposit inside the boiler tubes. Considerable amounts of exergy can be wasted in this mode. But all the measurements were taken when the smoke number was at zero and it can be assumed that the combustion is complete.

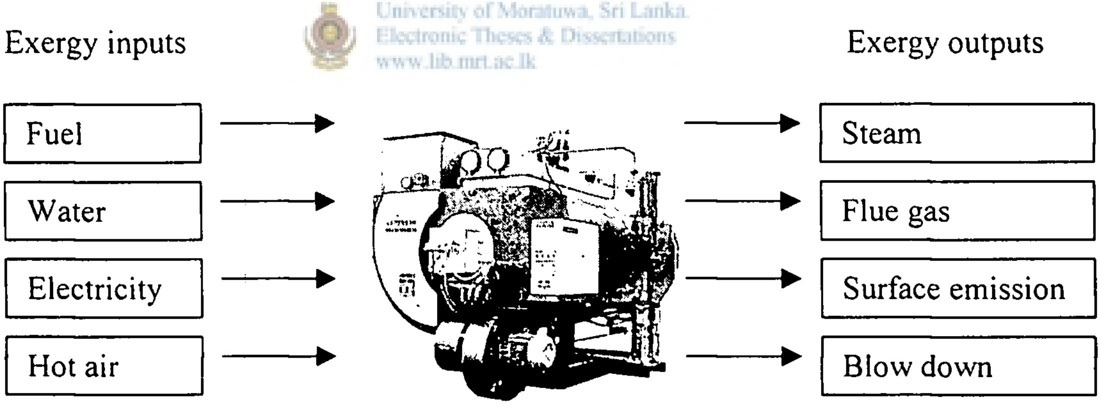


Figure 4.5 Exergy input and exergy output streams of boiler

4.5 Case Study Analysis - Boiler System

4.5.1 Data and measurements

(A) Data

Boiler make - Danks of Netherton

Capacity - 5448 kg / hr at 150 psi

Burner control - Modulate automatic control pressure jet atomize

(B) Measurements

Fuel used - Furnace oil 1000 sec.

Fuel consumption - 5270 lt. / day (5005.68 kg/day)

Water consumption - 65700 lt. / day

Power consumption of blown motor - 5.5 kW

Power consumption of fuel pre heating system - 12 kW

Consumpation air - 1.38 m^3/sec. @ 30°C

Water treatment cost - Rs. 1150 / day

Flue gas temperature - 241°C

Table 4.1 Average flue gas measurement

Parameter	Measurements
Oxygen percentage	7.8
CO_2 percentage	10.0
CO percentage	0.0275
SO_2 percentage	0.077
NO percentage	0.032
NO_2 percentage	Negligible
Flue gas temperature °C	241
Excess air percentage	60

i. Details of water

Table 4.2 Water quality data

Parameter	TDS ppm	Hardness ppm
Feed water	72	44
Makeup water	96	54
Boiler water	1500	less than 4

ii. Boiler dimensions

Length - 15'

Diameter - 8'

iii. Surface description

Table 4.3 Surface temperatures of boiler

Parameter	Surface Color	Surface Temperature (^{0}C)
Cylinder	Light blue	37
Back side	Silver	96
Burner side	Silver	160

Fuel oil pre heating temp - 120°C

Fuel pump pressure - 20 bar

Feed water temperature - 80°C

iv. Feed water treatment cost

Feed water treatment cost - Rs. 1150.00 / day

4.5.2 Composition analysis of fuel

Percentage composition of fuel (Gravimetric basis)

C = 84.0
H = 14.0
S = 2.0

4.5.3 Calculation

(a) <u>Calculations of exergy input to boiler</u>

i. Exegry in fuel

Composition weight basis

C - 84.0

H - 14.0

S - 2.0

Composition of the elements in mole basis

C - 84/12 = 7

H - 14/1 = 14

S - 2/32 = 0.0625

Combustion reaction (Stoichiometric)

$$(C_7H_{14} + 0.0625\ S) + 10.5625\ O_2 \longrightarrow 7CO_2 + H_2O + 0.0625SO_2$$

Exergy of fuel can be divided is to two parts

i. Chemical exergy
ii. Phiysical exerge or flow exergy

<u>*Chemical exergy*</u>

$$E_{fuel} = HHV - \mathrm{T}_0\left\{S_F + \left(\alpha + \frac{\beta}{4}\right)S_{O_2} - \alpha S_{CO_2} - \frac{\beta}{2}S_{H_2O}\right\}at(\mathrm{T}_0\mathrm{P}_0) + \left\{\alpha E^{ch}_{CO_2} + \frac{\beta}{2}E^{ch}_{H_2O} - \left(\alpha + \frac{\beta}{4}\right)E^{ch}_{O_2}\right\}$$

Applying the above equation to stoichiometric combustion equation

$$E_{fuel} = HHV - \mathrm{T_O}\{ \mathrm{S_F} + 10.5625\mathrm{S_{O2}} - 7\mathrm{S_{CO2}} - 7\mathrm{S_{H2O(l)}} - 0.0625\mathrm{S_{SO2}} \}$$

$$+ 7E^{ch} + 7E^{ch} + 0.0625E^{ch} - 10.5625E^{ch}$$

$$= 43.7 \times 10^3 \times 100 - 25 \{ 360 + 10.5625 \times 205.03 - 7 \times 213.69$$

$$- 7 \times 69.95 - 0.0625 \times 130 \} + \{7 \times 19870 + 7 \times 900 + 0.0625$$

$$\times 313400 - 10.5625 \times 3970 \}$$

$$E_{fuel} = 44.797 \text{ MJ / kg of fuel}$$

Physical exergy

$$E = (h - h_o) - T_o(S - S_o)$$

Fuel comes to the boiler at T = 30°C and heated up to 120°C heating is done by electrical heaters. So will take T = 30°C for exergy calculation and electrical load will add separately.

Enthalpy of fuel

$$\begin{aligned}(h_2 - h_1) &= (h_{30} - h_{25}) \\ &= C_p\Delta T \\ &= C_p(303 - 298) \\ &= 1.2 \times 5 \\ &= 6 \text{ KJ/ Kg}\end{aligned}$$

Entropy change between 30°C and 25°C is negligible

∴ Physical exergy = 6 kJ/ kg of fuel

Total exergy input through fuel = 44.797 MJ/ kg of fuel

ii. *Exergy of the feed water*

Exergy of water also can be divided in to two categories

Chemical exergy

Physical exergy

Chemical exergy

$$\begin{aligned}e^{ch}_{H2O(l)} &= 900 \text{ kJ / k mole} \quad [28] \\ &= 50 \text{ kJ / kg}\end{aligned}$$

Physical exergy

$$e^{ph} = (h - h_o) - T_o(S - S_o)$$

Water input to the boiler at T = 80°C

$$\begin{aligned}(h - h_o) - T_o(S - S_o) &= (h_{80} - h_{25}) - 25(S_{80} - S_{25}) \\ &= (334.9 - 104.8) - 298(1.075 - 0.367) \\ &= 19.61 \text{ kJ/ kg}\end{aligned}$$

$$\begin{aligned}\text{Total exergy } e^{ch} + e^{ph} &= 50 + 19.61 \\ &= 69.12 \text{ KJ/ kg} \\ &= 189.2 \text{ MJ / hr}\end{aligned}$$

iii. *Exergy in combustion air*

Physical exergy

$$(h - h_o) - T_o (S - S_o)$$

Combustion air supply at T = 30°C

$$= (h_{30} - h_{25}) - 25(S_{30} - S_{25})$$
$$= (130.26 - 128.34) - 537(0.60296 - 0.59945) \text{ Btu / lb}$$
$$= 0.082 \text{ KJ/ kg}$$
$$= 0.395 \text{ MJ/ hr}$$

iv. *Exergy in electricity input*

Fuel preheating - 12 kW

Blower - 5.5 kW

Water pumping - 7 x 1/3 kW

(The pump is operate 1/3 of full operating period)

Total - (12 + 5.5 +7/3) x 3600 kJ/ hr

- 19.83 x 3600 kJ/ hr

- 342.2 kJ / kg of fuel

(b) <u>Calculation of exergy outputs</u>

i. *Exergy loss through Boiler cylinder surface*

$$U_R = 5.57 \times 10^{-8} \times 0.92 \frac{310^4 - 303^4}{(310 - 303)}$$
$$= 6.00 \text{ W/ m}^2\text{K}$$

$$U_C = \frac{B (T_s - T_a)^{0.25}}{D^{0.25}}$$

$$= \frac{1.2 (310 - 303)^{0.25}}{2438.4^{0.25}}$$
$$= 0.277 \text{ W /m}^2\text{K}$$

$$U = 6 + 0.277$$
$$= 6.277 \text{ W / m}^2$$

$Q_{cylinder}$ $= UA (T_s - T_a)$

$= 6.277 \times 21.35 (310 - 303)$

$= 938 W$

Exergy $= Q (1 - T_o/T)$

$= 938 (1 - 25/37)$

$= 304.2 W$

Similarly

Exergy loss through burner side surface

= 1418.5 W

Exergy loss through back side surface

= 1504.5 W

Total surface loss = 304.2 + 1418.5 + 1504.5

= 3227.2 W

= 55.69 kJ/ kg of fuel

ii. *Exergy loss through boiler flue gas*

Table 4.4 Stack composition in dry basis

Parameter	Composition Mole basis	Composition Weight basis	Percentage weight
O_2	7.8	249.6	8.27
CO_2	10.0	440.0	14.69
CO	0.0275	0.77	0.025
SO_2	0.078	4.99	0.166
NO	0.023	0.69	0.023
N_2	82.07	2297.96	76.75

Flue gas temperature - 241 ^0C

Percentage carbon in dry flue gas = 14.69 x 12/44 + 0.025 x 12/28
= 4.0 + 0.011
= 4.01 %

Percentage carbon in fuel = 84%

∴ Weight of dry flue gas = 84/4.01
= 20.95 kg/ kg of fuel

∴ Corresponding fuel for the above flue gas

= 2994.05 / 20.95

= 142.91 kg

∴ Corresponding H_20 Production
= 10 H_2O mole

∴ Mole fraction of elements in flue gas.

Table 4.5 Mole fraction of stack composition

Parameter	mole	Mole fraction (%)
O_2	7.8	7.1
CO_2	10.0	9.1
CO	0.0275	0.025
SO_2	0.078	0.071
NO	0.023	0.021
N_2	82.07	74.61
H_2O	10.0	9.1
Total	110.0	100

iii. Calculation of chemical exergy in flue gas

$$e^{ch} = RT_o \{ 7.8 \ln X_{O2}/X^e_{O2} + 10 \ln X_{CO2}/X^e_{CO2} + 10 \ln X_{H2O}/X^e_{H2O}$$
$$+ 0.0275 \ln X_{CO}/X^e_{CO} + 0.078 \ln X_{SO2}/X_{SO2} + 0.023 \ln X_{NO}/X^e_{NO}$$
$$+ 82.07 \ln X_{N2}/X^e_{N2} \}$$ (Refer chapter 3 for original formula)

$= 8.315 \times 298 \{ 7.8 \ln 0.071/0.2035 + 10 \ln 0.091/0.0003$

$+ 10 \ln 0.091/0.0303 + 0.0275 \ln 0.0025/0.00025$

$+ 0.078 \ln 0.0071/7.75 \times 10^{-7} + 0.023 \ln 0.0021/1.26 \times 10^{-6}$

$+ 82.07 \ln 0.746/0.7567\}$

= 147662.74 kJ/ 142.91 kg of fuel

= 1033.26 kJ / kg of fuel

iv. *Physical exergy in flue gas*

$(h - h_o) = (h_{241} - h_{25})$

$= 7.8(h_{241} - h_{25})_{O2} + 10(h_{241} - h_{25})_{Co2} + 10(h_{241} - h_{25})_{H2O}$

$+ 0.0275(h241 - h25)_{CO} + 0.78(h_{241} - h_{25})_{SO2}$

$+ 0.023(h_{241} - h_{25})_{No} + 80.73(h_{241} - h_{25})_{N2}$

$= 7.8 \times 65232 + 10 \times 8939 + 10 \times 7422 + 0.0275 \times 6350$

$+ 80.73 \times 6326 + 0.078 \times 9420 + 0.023 \times 6488$

= 5081.8 KJ/ kg of fuel.

$T_o(S - S_o) = T_o(S_{241} - S_{25})$

$= 25 \{ 7.8(S_{241} - S_{25})_{O2} + 10(S_{241} - S_{25})_{Co2}$

$+ 10(S_{241} - S_{25})_{H2O} + 0.0275(S241 - S25)_{CO}$

$+ 0.078(S_{241} - S_{25})_{SO2} + 0.023(S_{241} - S_{25})_{No}$

$+ 82.07(S_{241} - S_{25})_{N2} \}$

$= 298 \{ 7.8(221.5 - 205.1) + 10(236.1 - 213.8)$

$+ 10(207.6 - 188.8) + 0.0275(213.6 - 197.7)$

$+ 82.07(207.5 - 191.6) + 0.078(23.5) + 0.023(16.3) \}$

= 3850.3 kJ / kg of fuel

= 5081.8 – 3850.3

= 1231.5 kJ/kg of fuel

Total exergy output through flue gas $= e^{ch} + e^{ph}$

= 1231.5 + 1033.26

= 2264.8 kJ/ kg of fuel

v. *Exergy loss through blow down*

Percentage blow down = $\dfrac{(B \times M)}{(A - B)}$

Where

A - Maximum TDS maintained, ppm

B - Feed water TDS, ppm

M - Percent makeup water expressed as a percentage of total evaporation (total evaporation - condensate return)

Percent blow down = 5.04% of steam production

Feed water input = Steam production + blow down

= 65700 kg/ day

let steam production be - $\aleph$

$$\aleph + \frac{5.04\,\aleph}{100} = 65700$$

$$\aleph = 2606 \text{ kg/ hr}$$

Amount of blow down = 131.5 kg / hr

Physical exergy of blow down water

$= (h - h_o) - T_o(S - S_o)$

$= (763 - 104.8) - 298 \times (2.138 - 0.367)$

= 130.44 kJ /kg

= 17153.12 kJ/hr

= 82.25 kJ / kg of fuel.

Let flash steam generated due to blow down be χ

$\therefore\ 131.5 \times 336.4 = \chi \times 1052.3 + (131.5 - \chi) \times 40.94$

$\chi \times 1011.36 = 138\,(336.4 - 40.94)$

χ = <u>38.42 kg /hr</u>

Chemical exergy of flash steam.

e^{ch} = 900 kJ / K mole [28]

= 50 kJ / kg

e^{ch} = 50 x 38.42

= 1921 kJ/ hr

= 13.4 kJ/ kg of fuel

Total Exergy = $e^{ch} + e^{ph}$

= 1921 + 17153.12

= 19.0 MJ / hr

= 133.5 kJ/kg of fuel

vi. *Exergy out put in steam*

Steam Production = $\frac{65700}{24} - 131.5$

= 2606.5 kg/hr

e^{ph} = $(h - h_o) - T_o(S - S_o)$

= (112778 - 104.9) - 298 (6.586 - 0.3674)

= 819.95 kJ / kg

= 2137.22 MJ / hr.

e^{ch} = 900 kJ / k mole [28]

= 50 kJ / kg

= 130.3 MJ / hr

Total Exergy of steam

$e^{ch} + e^{ph}$ = 130.3 + 2137.22

= 2267.5 MJ/hr

(c) Results

i. *Exergy input*

Table 4.6 Exergy inputs to the boiler

Parameter	Exergy in kJ / kg of fuel	Exergy in MJ / hr
Fuel	44797.00	9344.84
Water	907.15	189.2
Combustion air	1.89	0.395
Electricity	342.20	71.38
Total	46048.24	9605.82

ii. *Exergy output*

Table 4.7 Exergy output from the boiler

Parameter	Exergy in kJ / kg of fuel	Exergy in MJ / hr
Steam	16842.64	2267.5
Blow down	179.5	19.0
Flue gas	2348.19	489.76
Boiler surface	55.69	11.62
Total	19426.00	2787.88

Exergy destroyed = exergy in - exergy out

= 9605.82 – 2787.88

= 6817.94 MJ / hr

Percentage exergy destroyed

= 6817.94 / 9605.82

= 70.97 %

Exergy efficiency $= \frac{2267.5}{9605.82}$

= 23.6 %

Exergy based costing of steam

C_F $= \frac{\text{Cost of fuel}}{\text{Exergy in fuel}}$

= 16.5/44797

= 0.036 Cts/kJ

C_W

Water treatment = 1.75 Cts/kg

Capital cost = 0.02 Cts/kg

Total cost = 1.77 Cts/kg

Total salary = 25500 Rs / Month (3 Operators + 1 Forman)

= 35.50 Rs/hr

Unit cost of electricity = Rs. 7.00 (Including unit charge, fixed charge, demand charge and taxes)

C_E = 7.00 Rs / kWh

= 0.194 Rs / kJ

Cost of steam

C_S = [0.036 x 9344.84 x 10^3 + 1.77 x 2737.5 + 0.194 x 71.38 x 10^3 + 35.50] / 2267.5 x 10^3

= 1.57 Ctc/ MJ of steam

(c) Energy Balance

i. Energy input to the boiler

Fuel = 208.6 kg /hr

= 208.6 x 42.6

= 8886.36 MJ/hr

Water Temp @ 80^oC

$= \frac{65700}{24} \times 4.192 \times (80 - 30)$

= 573.78 MJ/hr

Elect = 19.83 x 3600 x kJ/hr

= 71.38 MJ /hr

ii. Energy output from the boiler

Surface loss = (938 + 1918 + 5012) W

= 7868 W

= 28.32 MJ/hr

Stack loss = 23.2 kg / hr of fuel

= 23.2 x 1.50 x (241 - 30)

= 5.38 MJ/kg of fuel

= 1123.0 MJ/hr

Blow down loss

From earlier figures

Percentage of blow down = 5.04 % of Steam production
= 131.5 kg/hr

Q = 131.5 (Δh)
= 131.5 (336.4 - 40.94)
= 91.4 MJ/ hr

Energy of Steam = 2606 x Δh
= 7249 MJ/hr

Miscellaneous = 1039.8 MJ/ hr

$$\eta = \frac{\text{Energy in useful product}}{\text{Energy input}}$$

$$= \frac{7249}{(8886.36 + 573.78 + 71.38)}$$

$$= \underline{76.34\ \%}$$

iii. *Energy based costing of steam*

$$\text{Cost of fuel} = \frac{\text{Cost of fuel}}{\text{Energy in fuel}}$$

= 16.5/42600

= 0.038 Cts/kJ

Water treatment cost = 1.75 Cts/kg

Capital cost = 0.02 Cts/kg

Total cost = 1.77Cts/kg

Total salary = 25500 Rs / Month (3 Operator + 1 Forman)

= 35.50 Rs/hr

Unit cost of electricity = Rs. 7.00 (Including unit charge, fixed charge, demand charge and taxes)

= 7.00 Rs / kWh

= 0.194 Rs / kJ

$= (0.038 \times 8886.36 \times 10^3 + 1.77 \times 2737.5$

$+ 0.194 \times 71.38 \times 10^3 + 35.50) / 7249 \times 10^3$

$= 0.049$ Cts / kJ of steam

(d) *Summary*

Table 4.8 Exergy and energy balance of the boiler

Description	Exergy balance (MJ / hr)	Energy balance (MJ / hr)
Input		
Fuel	9344.84	8886.36
Water	189.2	573.78
Combustion air	0.395	-
Electricity	71.38	71.38
Output		
Surface loss	11.62	28.32
Stack loss	489.76	1123.00
Blow down	19.0	91.40
Steam	2267.5	7249.00
Miscellaneous	-	1039.8
Exergy destroyed	6817.94	0

Exergy Balance

Table 4.9 Exergy balance of boiler

Description	Exergy balance (MJ / hr)	Percentage share
Input		
Fuel	9344.84	97.280
Water	189.2	1.970
Combustion air	0.395	0.004
Electricity	71.38	0.746
Output		
Surface loss	11.62	0.12
Stack loss	489.76	5.10
Blow down	19.0	0.20
Steam	2267.5	23.60
Exergy destroyed	6817.94	70.98

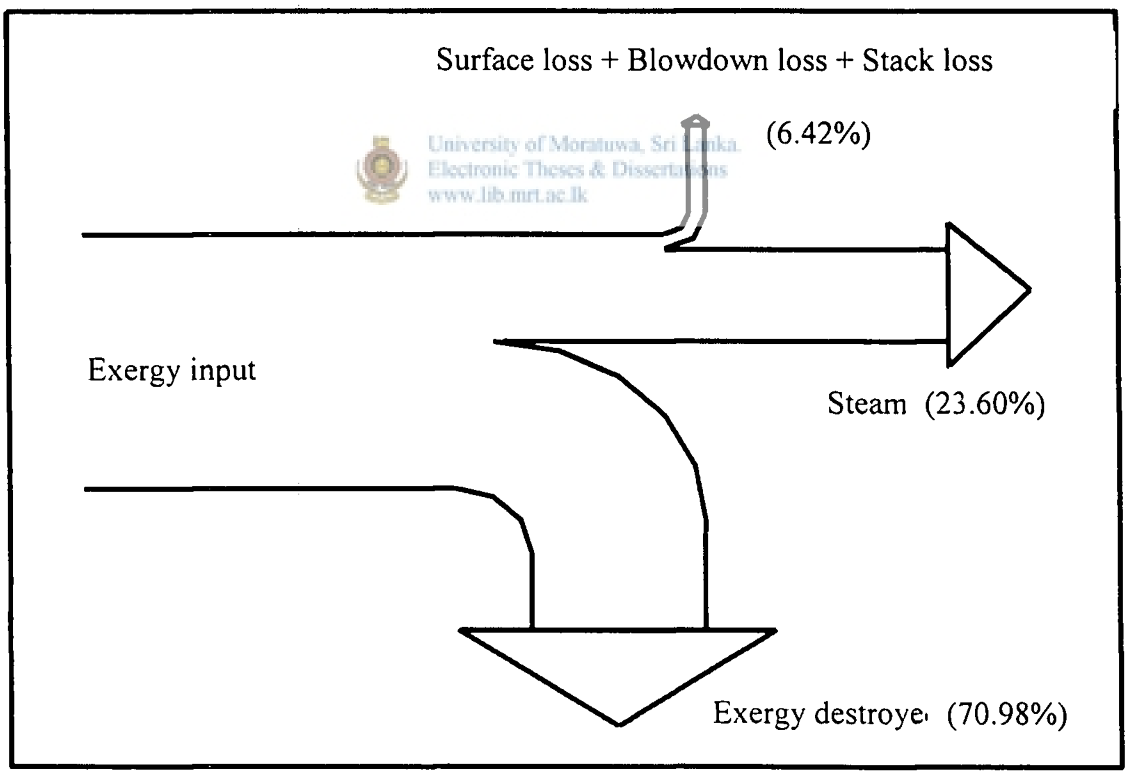


Fig 4.6 Sankey diagram for exergy balance of the boiler

Energy Balance

Table 4.10 Energy balance of the boiler

Description	Energy balance (MJ / hr)	Percentage share
Input		
Fuel	8886.36	93.23
Water	573.78	6.01
Combustion air	-	-
Electricity	71.38	0.75
Output		
Surface loss	28.32	0.29
Stack loss	1123.0	11.78
Blow down	91.4	0.96
Steam	7249.0	76.05
Miscellaneous	1039.8	10.92

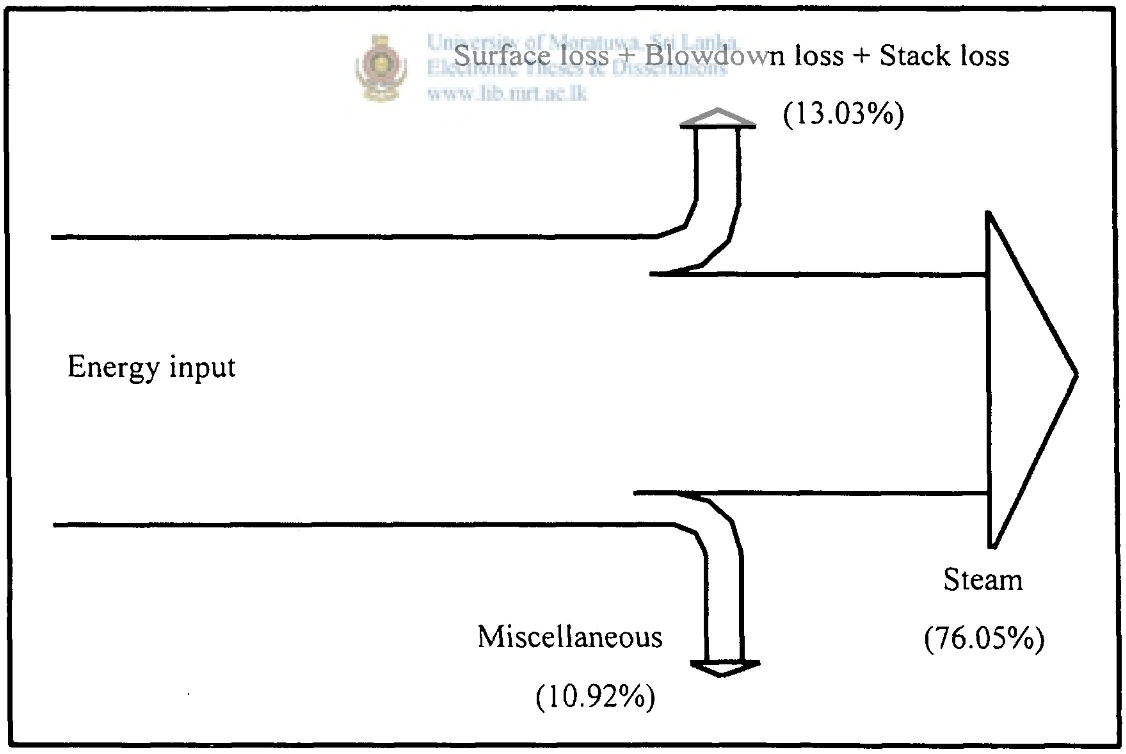


Fig 4.7 Sankey diagram for energy balance of the boiler

CHAPTER 5
ANALYSIS OF RESULTS

Steam is the useful product that is given by the boiler. The output of boiler varies from boiler to boiler and it depends on the efficiency of the system. Efficiency means both energy and exergetic efficiency. The efficiencies very due to the losses, which occur in the following areas.

- Blow down
- Surface emission
- Flue gas loss
- Exergy destruction

According to the details given in 4.5 in the previous chapter, calculations were performed for 100 numbers of boilers and the results are tabulated in the appendices.

The exergy losses, which occur through blow down, surface emission, stack emission and exergy destruction are discussed in the first part of the analysis.

- Variation of exergy loss with TDS of blowdown water,
- Variation of exergy destruction with exergy loss in flue gas,
- Variation of exergy destruction with flue gas temperature at different exces air levels,
- Variation of percentage exergy loss in flue gas with flue gas temperature at different excess air levels

are looked into in this chapter.

In addition to the variation of exergy losses of the system, the second part of the chapter discusses about the exergy efficiency of the boiler and variation of exergy efficiency with flue gas temperature at different excess air levels and energy efficiency. Comparison of cost of steam with exergy efficiency, variation of CO_2 emission with exergy and energy efficiency and variation of CO_2 emission with percentage flue gas losses are discussed at the end of this chapter.

5.1 Exergy Losses through Blowdown

Blowdown is needed to maintain the required total dissolved solids (TDS) level in a boiler. Maintaining TDS level is essential to achieve the maximum efficiency. The boiler tubes will be covered with scales, when the TDS level becomes high in boiler water and the result is poor heat transfer. Due to this reason stack temperature will increase and ultimately the exergy losses will increase.

If the rate of blow down is increased to reduce the TDS in boiler water, the sludge formation on the fire tubes will be reduced, but ultimately more exergy loss will occur through blowdown. Therefore blowdown should be controlled to minimize the exergy loss. TDS of feed water varies from place to place in Sri Lanka and generally TDS of boiler water should be maintained between 3000 - 3500 ppm [17] in package type low-pressure boilers.

In addition to the TDS, hardness of the feed water should be maintained in the minimum level possible. Normally softeners are maintained to control the hardness in feed water. However reference to the analysis the percentage exergy losses through the blowdown vary from 0.02% to 0.2% in 100 numbers of samples and the mean value is 0.09 %.

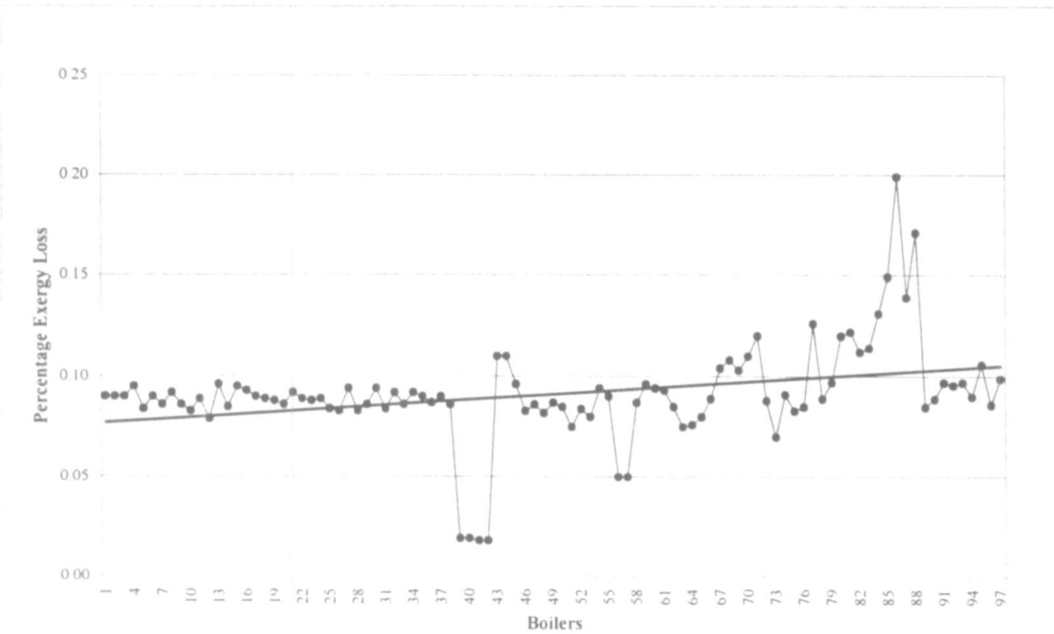


Figure 5.1 Variation of percentage exergy loss in blow down

According to Fig 5.1 the percentage blowdown loss is almost constant in each boiler. There are two extreme points in the fig 5.1. The percentage exergy loss of one set of sample is at 0.02%. This is because of the less amount of TDS present in boiler water. The condensate is totally collected to the feed water tank in this steam network and makeup water consumption is very small and TDS of feed water is maintained at low level. Thus the blowdown rate is very small and exergy loss is minimum. Maintaining this condition is possible if the total system consumes steam indirectly. But most of the plants consume both direct steam and indirect steam together. Due to this reason makeup water is taken to the boilers and TDS level of the boiler water is significant and the average blowdown loss is in the range of 0.09%. Comparing the above-mentioned situation (collection of condensate totally) there is an average exergetic efficiency improvement potential of 0.07%. In addition to the direct improvement of the exergetic efficiency, the lifetime of the boiler also gets improved due to maintaining of water quality in a better range. But this area is not properly evaluated yet. The percentage exergy loss in the other extreme point is around 0.2% and this is because of maintaining TDS in feed water at higher levels (around 2800 ppm).
By maintaining water quality in a better range it can minimize the exergy losses. The recommended values of different parameters are given in the following table.

Table 5.1 Recommended levels for different parameters in feed water and boiler water [13]

Parameter	Amount
Boiler water	
Total Desolved Solid (TDS) -ppm	3500
Hardness – mg / l	1000
pH	10 – 11
Feed water	
Total Desolved Solid - ppm	50
Hardness – mg / l	10
pH	8.5 – 9.5

By maintaining the above figures, the rate of blowdown can be maintained in the range of 1.5 % of total steam production and the resultant exergy loss is 0.08 %.

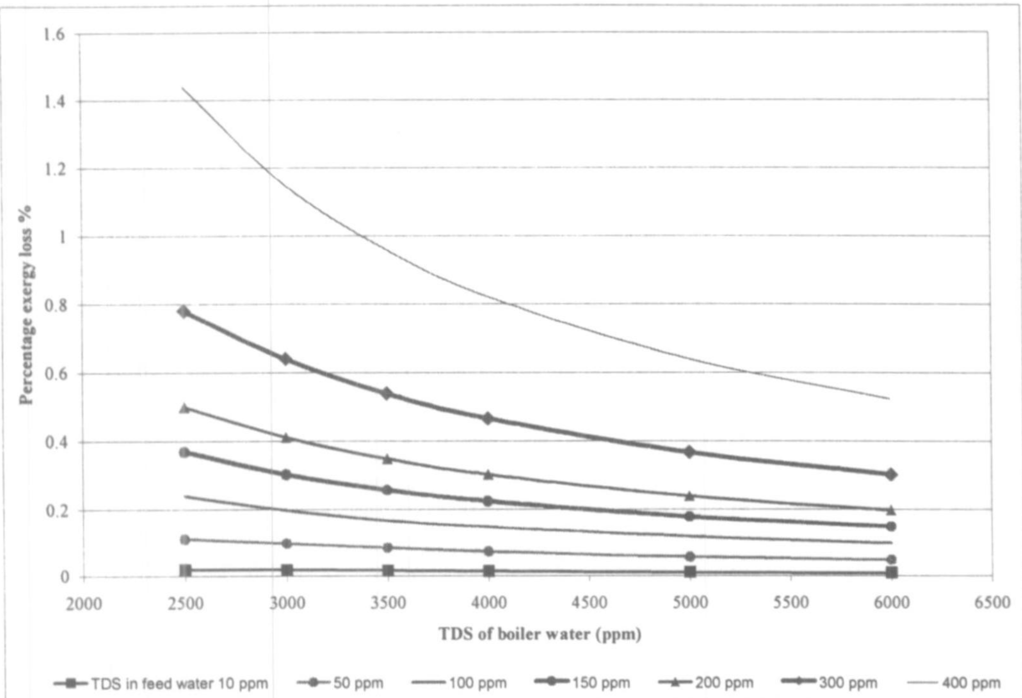


Figure 5.2 Variation of exergy loss with TDS of blowdown water

The above figure 5.2 gives the variation of exergy loss with amount of TDS level present in the boiler water. Reference to the figure, both the exergy and energy losses are reduced with increase of TDS level and the rate of reduction also gets reduced with increase of amount of TDS. In addition to that the exergy losses are always less than the energy losses.

5.2 Exergy Losses Through Surface Emission

Radiation and convection are the two modes that create surface losses. The emission through these two modes depends on the surface temperature, surface area, condition of the surface and wind velocity. In general, boilers are operated inside a boiler room and the average wind velocity is almost constant everywhere and it is around 1.5 m/s. The surface area depends on the capacity of the boiler but the surface condition (the surface emissivity) is almost constant and in average the surface emissivity is in the range of 0.85 [35]. Figure 5.3 below shows the variation of exergy loss through the surface emission. The percentage exergy loss varies between 0.05% and 0.94 % and in average the variation is almost constant and it is around 0.3% of the total.

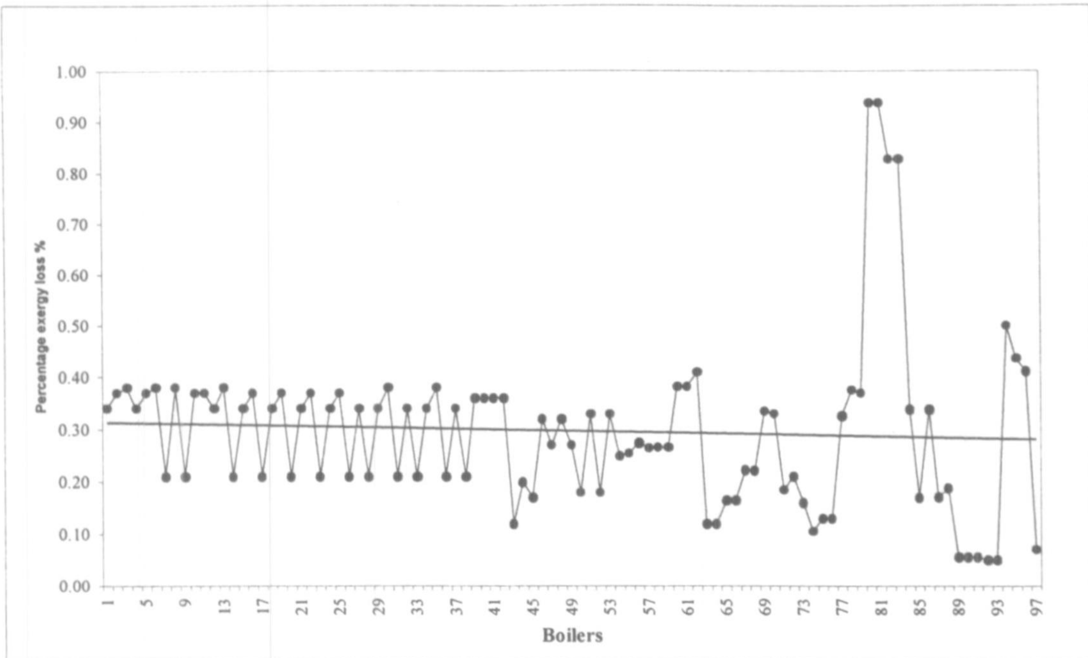


Figure 5.3 Variation of percentage exergy loss through surface emission

There are possibilities to reduce the existing exergy loss through the surface emission by reducing the surface temperatures of the boilers. It is better if it is possible to bring the surface temperature closer to the ambient. But the insulation cost will get increased while reducing the surface temperature. Therefore there should be a compromise between these two factors and as a rule of thumb it can be said that the surface temperature should be in the range of 50 ^{0}C more than the ambient. By maintaining these figures the exergy loss can be reduced up to 0.05 %.

5.3 Exergy Losses in the Flue Gas

Flue gas losses depend on the temperature and the level of excess air. The exergy in flue gas is calculated using the following formula.

$$E_x = (H - H_0) - T_0(S - S_0) + a^{ch}$$

$$a^{ch} = RT_0 \sum y_i \ln\left\{ y_i / y_i^e \right\}$$

y_i y_i^e represents the mole fraction of the species in the flue gas and the environment respectively.

When the level of excess air in the flue gas is fixed then the mole fraction remains constant. Therefore the chemical exergy in flue gas also remains constant. If we plot the exergy loss of flue gas with temperature while the excess air level remaining constant, the plot will follow the pattern identical to variation of enthalpy & entropy with temperature.

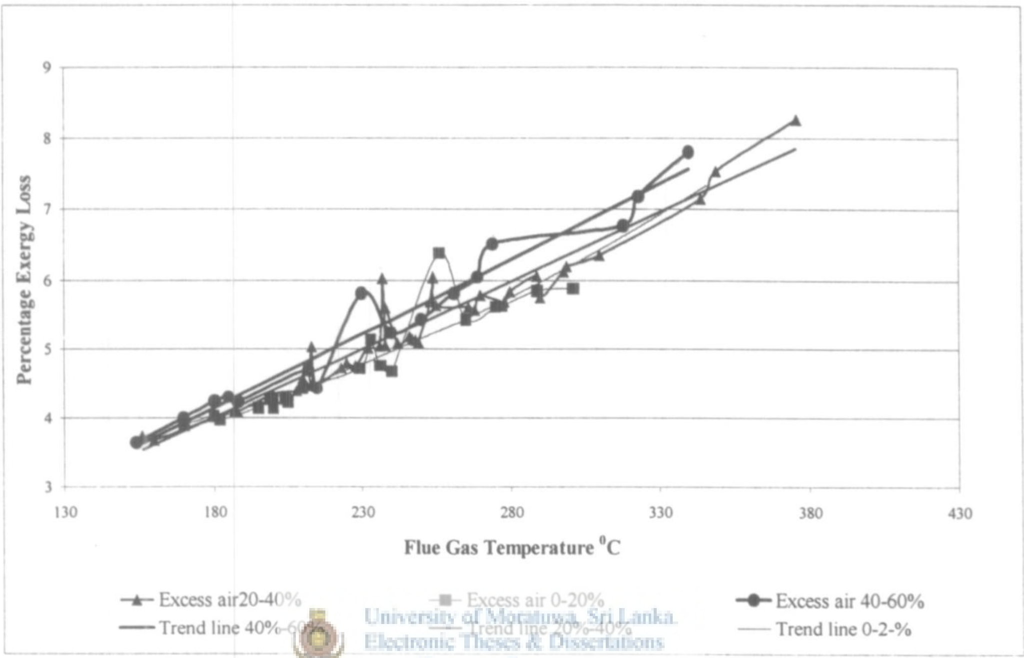


Figure 5.4 Variation of percentage exergy loss in flue gas with flue gas temperature at different excess air levels

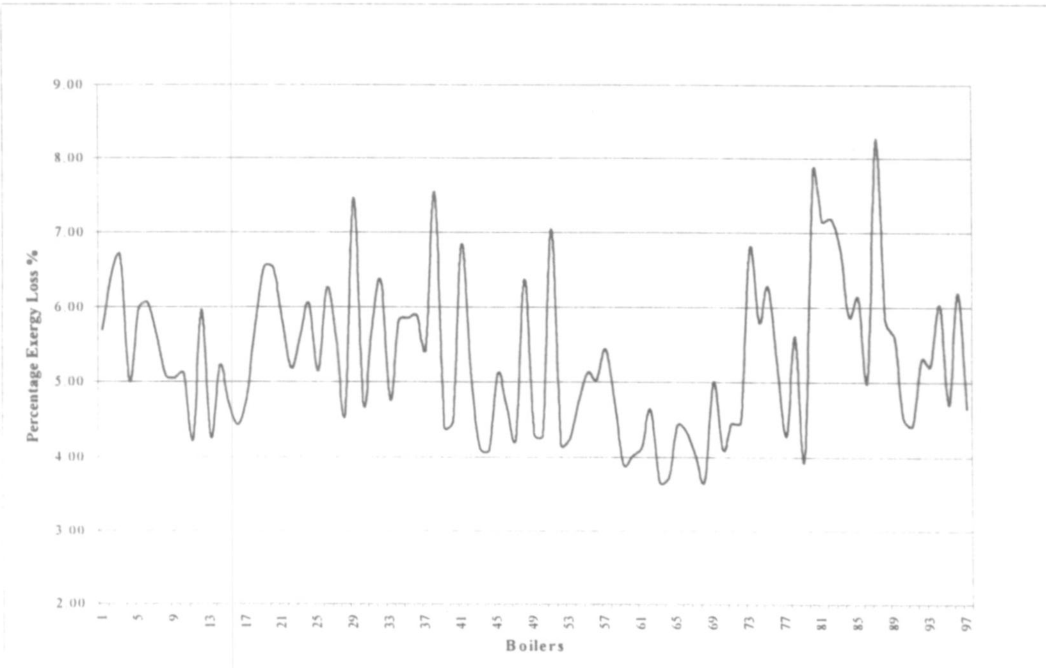


Figure 5.5 Variation of percentage exergy loss in flue gas

According to the measurements taken from the industries the flue gas temperature varies between 160^{0}C and 349^{0}C. The excess air level varies between 4.5% and 194 %. The exergy loss of the flue gas varies between 3.65 % & 8.27 % and the average is 5.31%. All the variations are given in the following figures graphically.

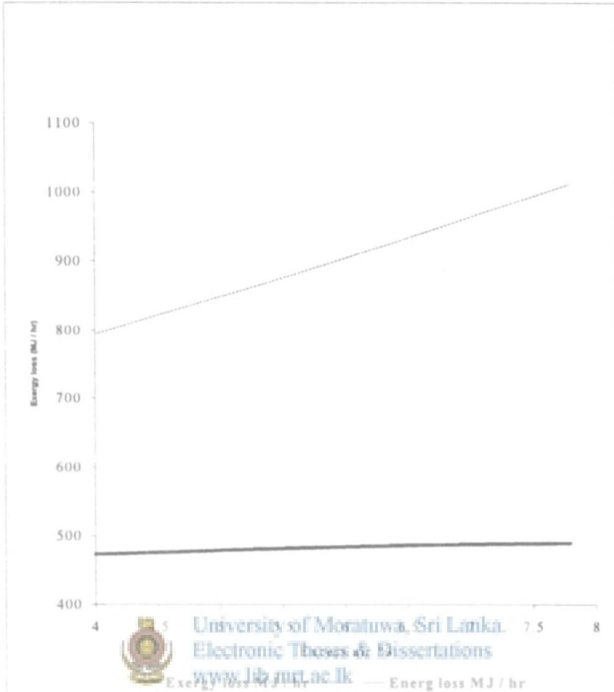


Figure 5.6 Variation of exergy and energy loss in flue gas with excess air at constant flue gas temperature

Reference to the figure 5.6 given above the exergy loss gets increased with increase of excess air level but the variation is very, very small. That means the increase of excess air is not much affected to the thermodynamics irreversibilities associated in the flue gas.

Quality of the flue gas is a measure of the combustion and the heat transfer. If the flue gas temperature is high more exergy is lost through the stack. Excess air is essential for proper combustion but again exergy loss occurs with increase of the amount of excess air. The recommended excess air level for an oil-fired boiler is in the range of 17 % to 22 % [31]. This amount is mainly provided

1. To achieve proper combustion
2. To maintain proper turbulence inside the combustion chamber and fire tubes.
3. To maintain an even flame.

The flue gas temperature gets increased due to

1. Poor heat transfer (The heat transfer gets reduced due to scale or soot formation in the boiler tubes)
2. High excess air
3. Combustion of higher amount of fuel oil than the rated allowable limit.

Therefore by implementing a proper operation and maintenance program, the flue gas temperature can be maintained at a low level. But the temperature reduction should be limited to 180 ^{0}C [13]. This limit is named the acid dew point and below this limit H_2SO_4 will form due to condensation of SO_2 present in the flue gas. H_2SO_4 acid is a heavily corrosive media and it will badly affect the stack and its accessories.

According to this there should be an optimum limit for flue gas parameters in oil fired boilers.

1. Flue gas temperature 180^{0}C [13]
2. Excess air level 17 % - 22 % [31]

The equivalent O_2 concentration is 3.5 % - 4.0 %. If the combustion is complete the equivalent CO_2 concentration is 13.25 % - 12.9 % and the reference other parameters are as follows.

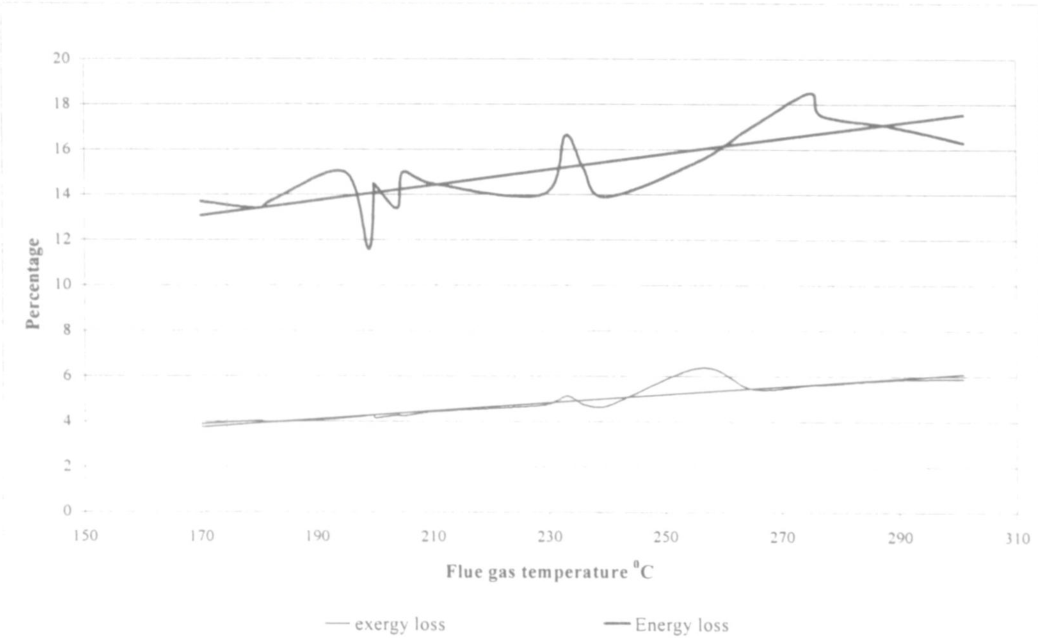


Figure 5.7 Variation of energy and exergy loss in flue gas with flue gas temperature at excess air 0-20%

CO ppm - 50

NO ppm - 310

NO_2 ppm - 0

SO_2 ppm - 970

Reference to the above parameters the exergy loss in the flue gas becomes 3.4 % in any steam boiler and it is not dependent on the capacity of boilers.

The figure 5.7 and 5.8 give the variation of exergy loss and energy loss with flue gas temperature at constant excess air level.

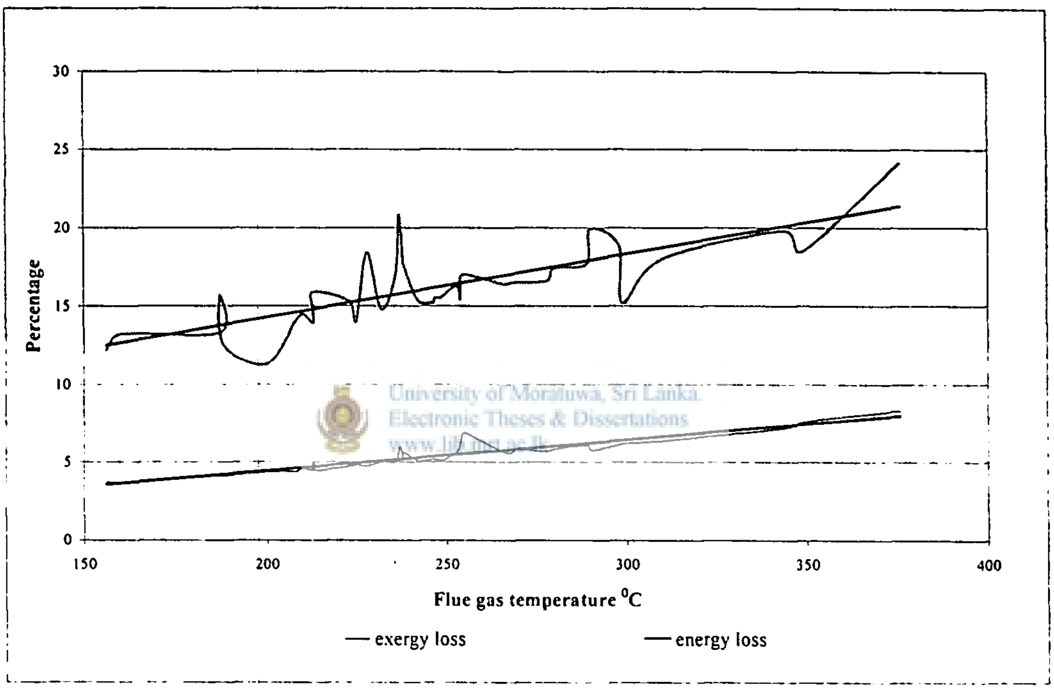


Figure 5.8 Variation of energy and exergy loss in flue gas
with flue gas temperature at excess air 20-40%

Reference to the above figures the exergy loss is always less than the energy loss. The rates of increase of exergy loss with increase of flue gas temperature is also less than the proportional increase of energy loss. It is clear that the increase of flue gas temperature does not much affect the rate of thermodynamic irreversibilities associated with the flue gas. But the effect is significant.

Variation of exergy loss with energy loss in flue gas follows a linear relationship. Exergy loss is always lower than its energy loss and approximately energy loss is three times greater than the exergy loss in terms of MJ. The following figures illustrate the variation pattern.

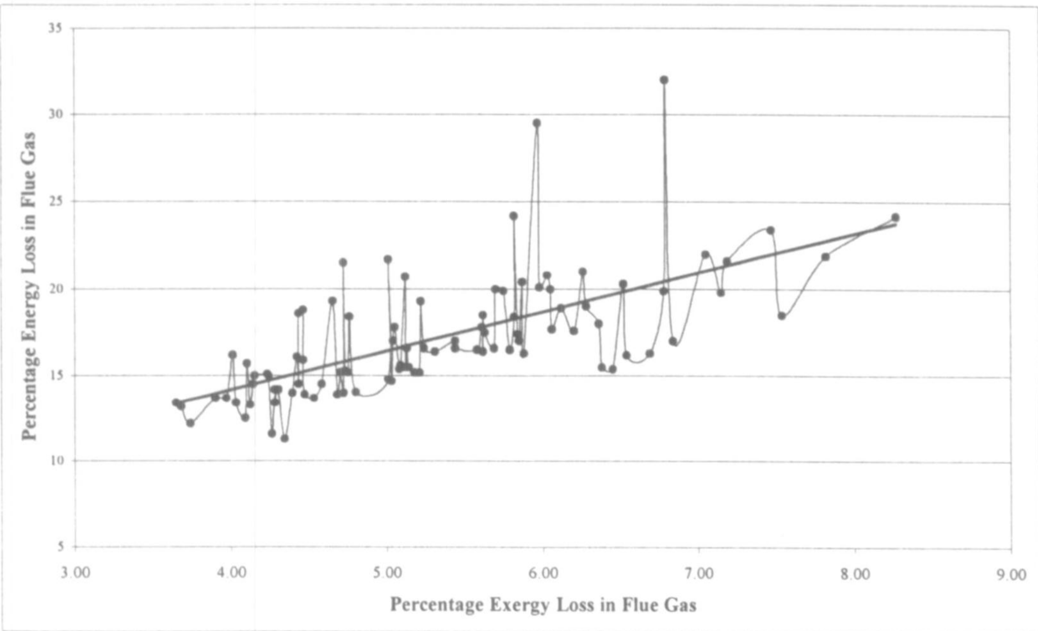


Figure 5.9 Variation of exergy loss with energy loss in flue gas

The approximate variation can be given by the following formula.

Energy loss = 2.7 x Exergy loss + 132

Percentage energy loss = 2.3 x Percentage Exergy loss + 5.2

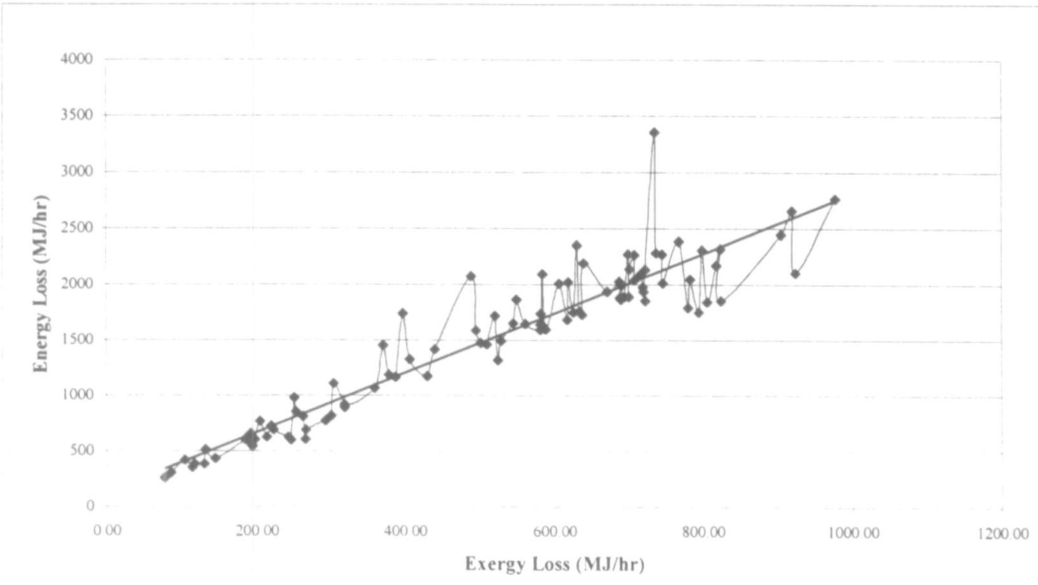


Figure 5.10 Variation of exergy loss with energy loss in flue gas

5.4 Exergy Destruction

Exergy means the maximum work potential that can be extracted from a given system. Comparing the same energy quantity at the high and low temperature, the work potential or the exergy gets reduced with reduction of temperature from high range to low range. In a boiler system this situation always happens.

The exergy of input fuel is at a higher level, the temperature of the combustion products is in the range of 1200 ^{0}C[36] and the energy in this mixture transfers to steam which is in low temperature. Mainly low-pressure boilers are operated in 10 barg and the equivalent steam temperature at this pressure is 180^{0}C [35]. There is a rapid temperature reduction in this process and due to this reason exergy is destroyed rapidly. Apart from the temperature variation, the irreversibilities in combustion reaction also cause exergy destruction.

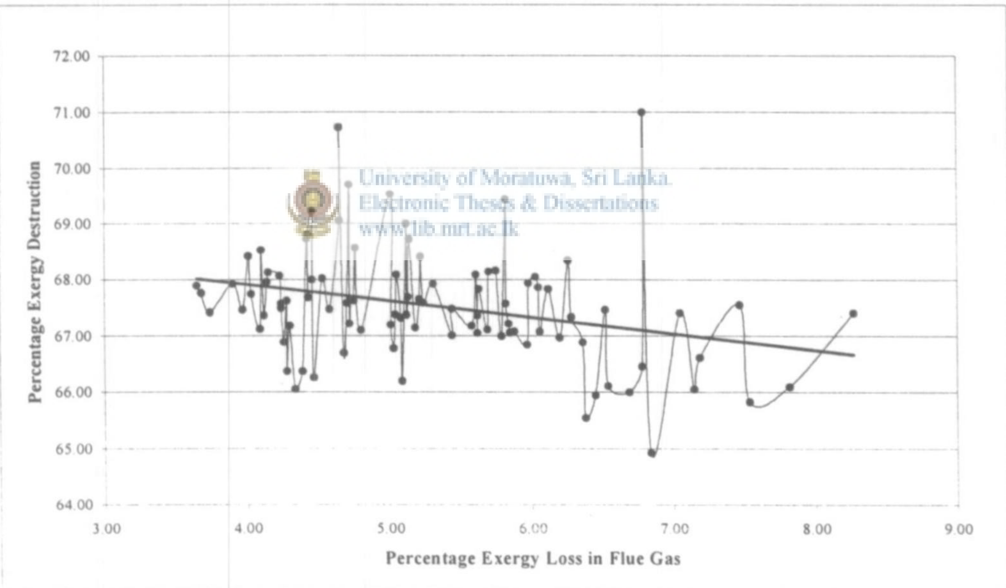


Figure 5.11 Variation of exergy destruction with exergy loss in flue gas

Figure 5.11 gives the variation of exergy destruction with percentage exergy losses in flue gas. Reference to the figure the exergy loss through the flue gas gets reduced with increase of percentage exergy destruction. The previous analysis gives that the percentage exergy losses through the blowdown and surface emission is very small and is in a constant range. When the flue losses are low, that means there are more exergy remaining in the combustion chamber to transfer to steam. While transferring exergy from combustion products to steam, exergy gets destroyed rapidly due to sudden temperature reduction between the two states. If the flue losses are high, less

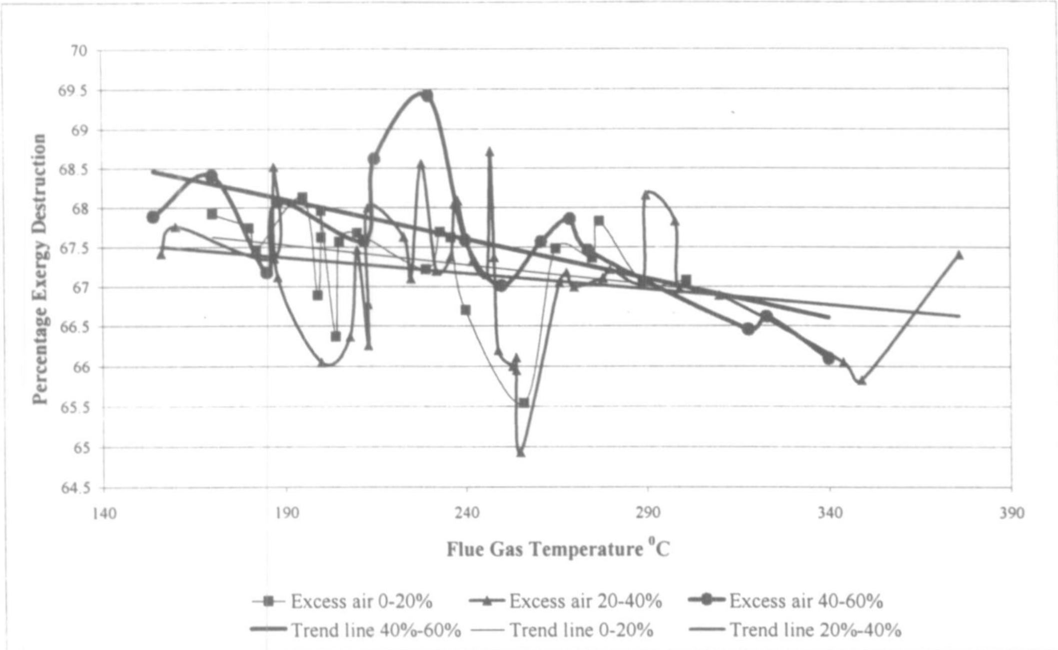


Figure 5.12 Variation of exergy destruction with flue gas temperature at different excess air levels

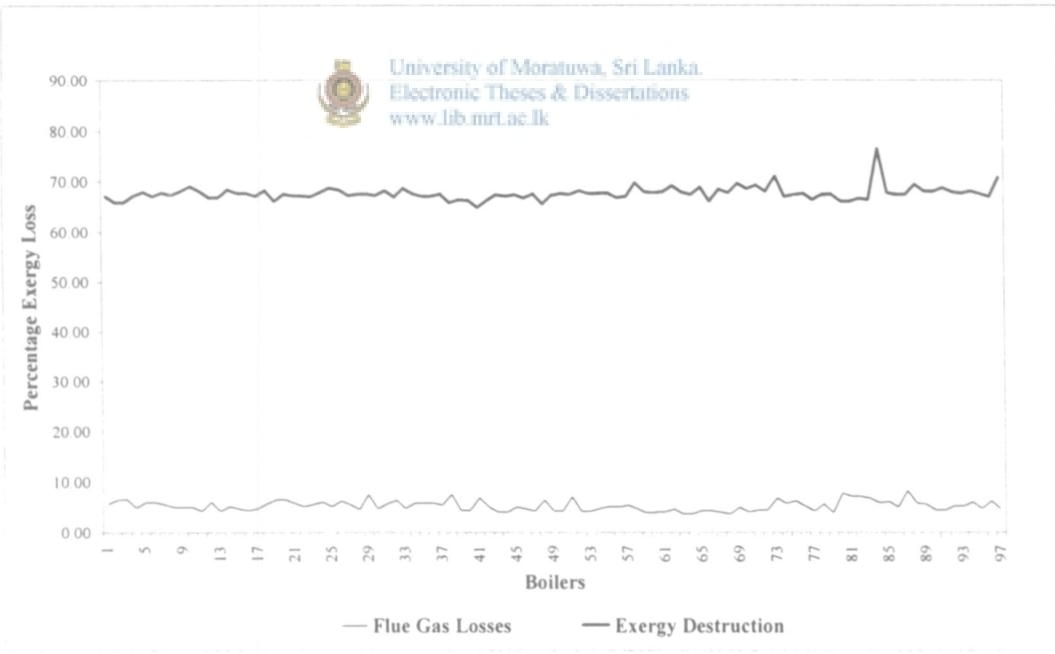


Figure 5.13 Variation of percentage exergy destruction and percentage exergy loss in flue gas

amount of exergy transfers to steam and thus the exergy destruction is less, but the exergy loss at the flue is high. Reference to these there are limitations to get the maximum exergetic efficiency.

According to the above figures the percentage exergy destruction gets reduced with increase of flue gas temperature and also the exergy destruction increases with increase of excess air while the flue gas temperature is constant. This phenomenon gives a very good result.

1. Exergy destruction gets reduced with increase of flue gas temperature.
2. Exergy destruction gets increased with increase of amount of excess air at constant flue gas temperature and this effect is reduced with increase of flue gas temperature.
3. The level of excess air does not affect the exergy destruction when the flue gas temperature is around 310^{0}C and beyond this limit the exergy destruction gets reduced with increase of excess air.

Therefore the amount of excess air is very important in exergy analysis of boilers and should be maintained at the minimum possible limit.

Though the exergy destruction gets reduced with increase of flue gas temperature the combined loss of exergy destruction and exergy loss through flue gas gets increased and also it increases with increase of excess air. The variation is given in the following figure.

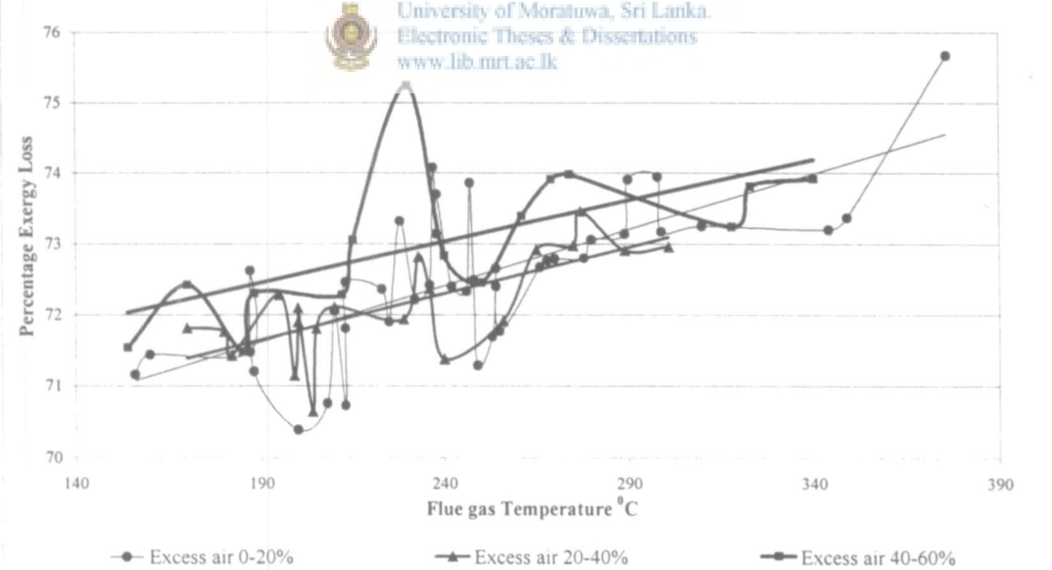


Figure 5.14 Variation of percentage exergy destruction + percentage exergy loss in flue gas with flue gas temperature at different excess air levels

5.5 Exergetic Efficiency

Efficiency is the measure of system performance. The ratio between useful output to total input is taken as the efficiency. Considering a steam boiler the real output or the useful output is given through the steam, and flue gas, blow down and surface emission are the other outputs, which are present as losses. The inputs are given through fuel, electricity, feed water, combustion, etc. In general efficiency means the energy efficiency. As mentioned earlier, the ratio between the quantity of energy stored in the steam and energy inputs through number of input streams gives the efficiency. In average the energy efficiency is in the range of 80 % - 85 % [31] for package type low-pressure boilers.

Exergy means the real work output that can be extracted from a given form of energy. According to this analysis the work output of the steam is in a very low level compared to the work input. Therefore the exergetic efficiency is very low comparing the energy efficiency in package type low-pressure steam boilers.

According to the 1st law of thermodynamics energy is always conserved. The input energy is always equal to the outputs. Therefore one can make a balance between input and output energy. But in the case of exergy analysis inputs are not equal to the outputs. Exergy exists in steam, blow down water, flue gas and surface emission. Compared to the input exergy, the quantity of output exergy is less. That means some amount is disappeared. This destruction takes place due to generation of entropy within the system and this reaction is named exergy distruction.

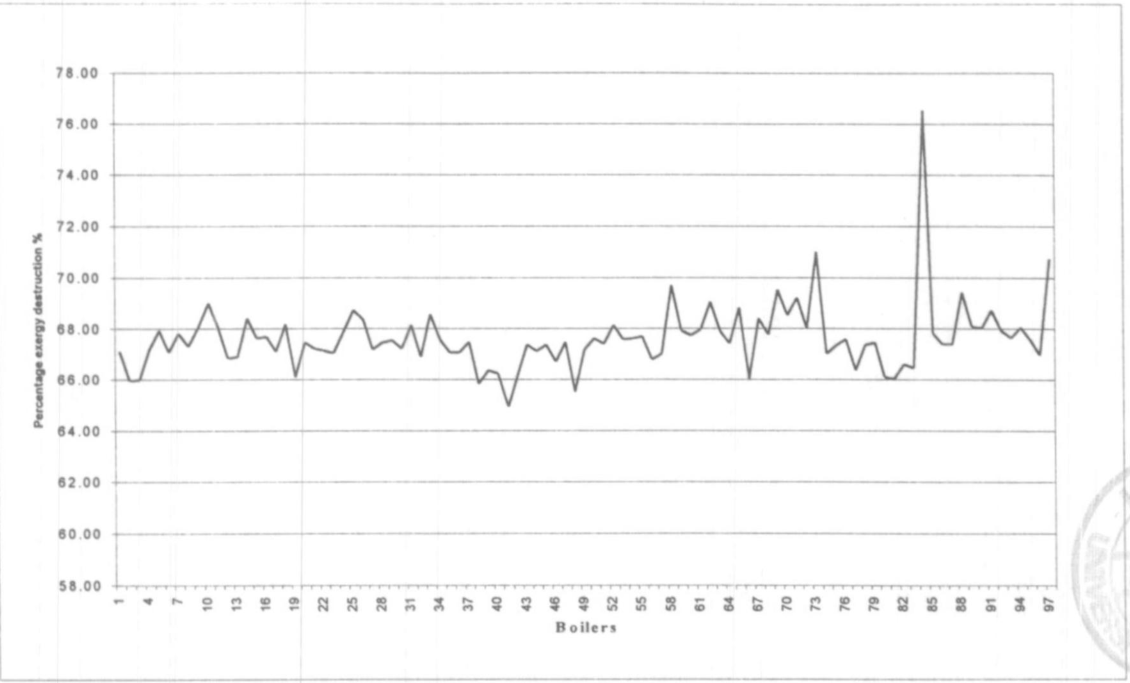


Figure 5.15 Variation of percentage exergy destruction in boilers

Exergy destruction is mainly dependent on the temperature difference between the combustion mixture and the products. Steam temperature gets varied with variation of the steam pressure and this analysis is based on 10 barg steam. The steam temperature is 180 ^{0}C at 10 barg [35] and the temperature of the combustion mixture is in the range of 1200 ^{0}C [36]. Due to these temperature variations the average exergy destruction is in the range of 67.63 % in package type low-pressure steam boilers. The average exergy loss through the flue gas is 5.31 % and it is in the range of 0.39 % for both surface emission and blowdown. Depending on the above figures the average exergetic efficiency becomes 26.6 % in most of the boilers. The analysis gives that the exergetic efficiency varies between 17.12 % and 28.9 %. Out of them 96 % are operating between 24.5% and 28.9 %. The average is 26.89 %.

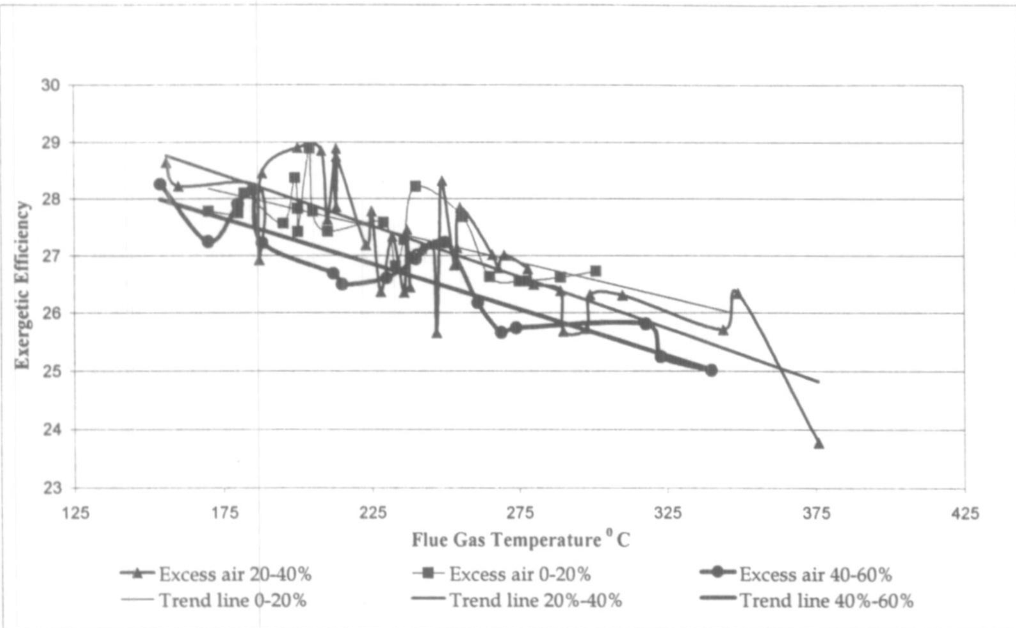


Figure 5.16 Exergetic efficiency with flue gas temperature at different excess air levels

According to this analysis the minimum possible exergy losses in a boiler should be within the following limits.

Percentage exergy loss through blowdown - 0.08 %

Percentage exergy loss through flue gas - 3.4 %

Percentage exergy loss through surface emission - 0.05 %

With reference to these limits the percentage exergy destruction is 67.1 % and the exergetic efficiency is 28.0 %. This is the maximum possible exergetic efficiency that can be taken by maintaining the optimum running condition in a boiler.

Apart from the above, the efficiency can be increased by preheating the combustion air before feeding to the combustion. According to Figure 5.17 below the amount of contribution to the exergetic efficiency is very small. But the contribution amount to the energy efficiency is significant.

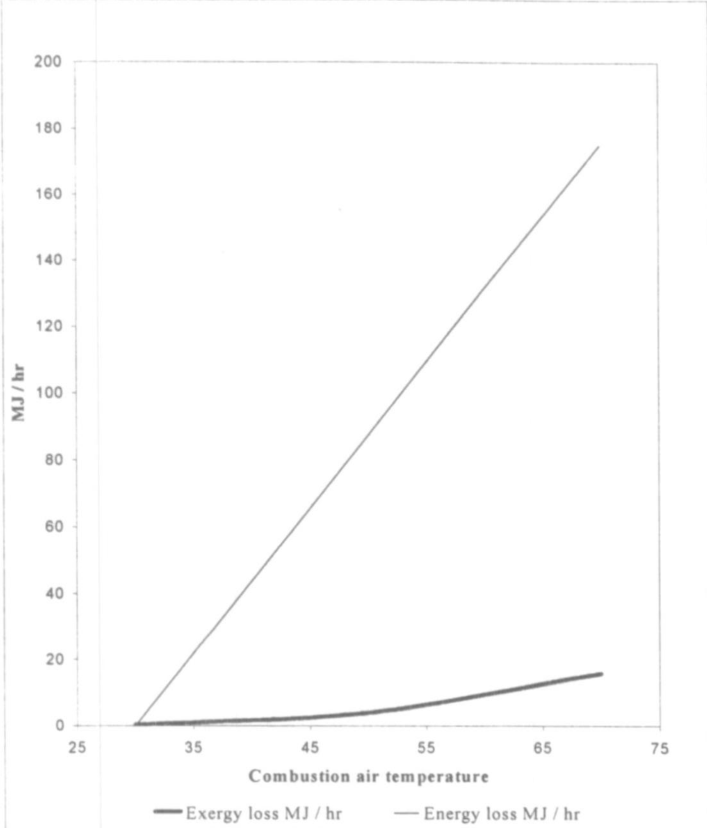


Figure 5.17 Variation of input exergy in combustion air with combustion air preheating temperature

5.6 Variation of Exergetic Efficiency with Energy Efficiency

Reference to the following figure 5.18, it is clear that there is a relationship between energy efficiency and exergetic efficiency.

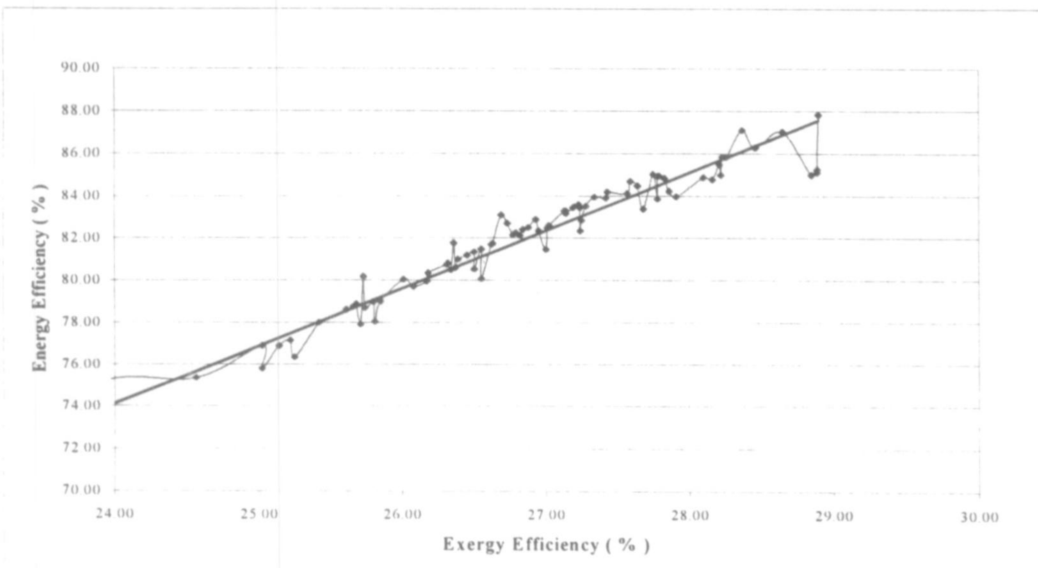


Figure 5.18 Variation of exergetic efficiency with energy efficiency of boilers

With increase of exergetic efficiency, the energy efficiency also gets increased, and the relationship can be illustrated by the following formula.

$$\varepsilon = 0.36\,\eta + 3.0$$

Where, ε – Exergetic efficiency η – Energy efficiency

5.7 Cost of Steam Vs Exergetic Efficiency

Cost analysis is very essential in any system. The specific cost of any product is a measure of the system performance and also it is helpful to compare the existing system with others.

The variation of specific cost of steam with exergetic efficiency is illustrated in the following figure. Reference to the figure the specific cost of steam gets reduced with increase of exergetic efficiency. That is due to increase of output with increase of exergetic efficiency. The steam cost varies between 1.36 Rs./MJ and 1.78 Rs./MJ based on the exergetic efficiency and the average is 1.49 Rs./MJ. The equivalent average cost of steam based on energy efficiency is 0.52 Rs./MJ. This implies that the cost of steam based on exergetic efficiency is approximately three times higher than the cost of steam based on energy efficiency. The cost of steam is based on the number of input parameters as describe bellow.

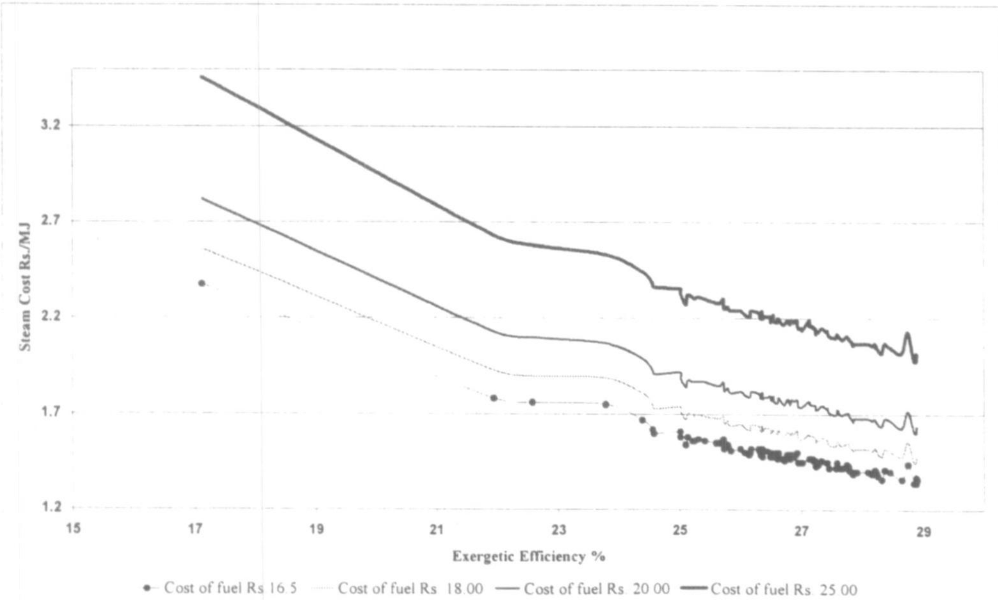


Figure 5.19 Variation of steam cost with exergetic efficiency

5.7.1 Type of fuel

Various types of fuel are used in steam boilers. Furnace oil, diesel, firewood, saw dust, bagasse, paddy husk and electricity are widely used in Sri Lanka. Furnace oil is the most popular fuel for steam boilers and very little quantity of coal is used in steam engine operated locomotives in Sri Lanka. As far as the world is concerned, coal and LNG are widely used in steam generation.

Calorific values of fuels vary with the type of fuel. As an example the higher calorific value of the furnace oil is in the range of 43 MJ/kg [35] and it is 19.5 MJ/kg for dry sawdust. The efficiency of boilers also varies with the type of fuels due to variation of combustion properties. The overall energy efficiency of the furnace oil fired package type boilers are in the range of 80 % - 85 % [31] and it varies between 60 % - 70 % [31] in wood or saw dust fired low pressure steam boilers.

The configuration of the burners also varies with the type of fuel and due to this reason the combustion properties get varied. The prices are also different from type to type and the prices mainly depend on the availability and transportability. Therefore it is clear that the cost of steam varies with the type of fuel.

5.7.2 Cost of electricity.

Electricity is widely used in the area of fuel pre-heating, fuel atomizing, air blowing and water pumping in steam boilers. Apart from that very little quantity is used in the control unit. Fuel is pressurized through an electrically operated fuel pump in pressure jet atomizing burners and the rotary cup is driven by an electric motor in rotary cup atomizing burners. Generally compressed air is used in twin fluid atomizing burners and the compressors are energized by electricity.

The cost of electricity mainly depends on the following.

- Tariffs system
- Energy consumption
- Amount of self-generation, etc.

(a) Tariff system

At present the Ceylon Electricity Board has introduced seven numbers of tariff systems for industries in Sri Lanka. The customer can select one of them and basically the selection is carried out according to the energy consumption. Industrial time of day tariff charges according the peak and off peak consumption and industrial purpose I_2, I_3, S_2 and S_3 have fixed rate charge per unit consumption. Apart from that demand charge and monthly fixed charge is included to the electricity bill and the rates are different from tariff to tariff.

(b) Electricity consumption

The electricity consumption pattern and the quantity are different from organization to organization. Some factories are operated 24 hours and some are operated during the daytime only. The unit charge for peak hours is higher than the off peak hours in time of day tariff. In Earlier days the peak hour consumption was met by the self-generation in most of the organizations due to less generation cost. At present the unit costs for both self-generation and peak hour grid electricity are almost equal due to higher fuel prices. A fixed charge is included in any type of tariff system and depending on the number of unit consumed the amount contribution to the unit cost from fixed charge varies. The maximum demand varies due to both power factor and unit consumption and this amount also contributes to the unit cost.

As far as the average unit cost is concerned, it varies from organization to organization. Therefore the average cost of grid electricity was taken for this analysis as Rs. 5.70 per kWh.

5.7.3 Cost of water treatment

Boiler water treatment can be separated into two main categories.

a. Primary treatment
b. Feed water treatment

(a) Primary treatment or pretreatment

Water is taken from different sources. Rivers, wells, ponds, lakes, rain etc. are the main sources in Sri Lanka and the water is in different qualities in each source.

Depending on the quality of water it should be treated upto recommended conditions before used. This is called the primary treatment or pre treatment.

(b) Boiler feed water treatment

Pre treated water also contains dissolved or suspended impurities, which may cause trouble. Concentrations of impurities in fresh water vary from about 30 to over 2000 parts per million.

The principal substances are calcium and magnesium carbonates and sulphates, and in smaller amounts, silicon salts. Salts of sodium, potassium, aluminium, iron and manganese may be present, and both mineral and organic acids too.

The carbonates and sulphates mentioned above cause temporary and permanent hardness. They have the characteristic of reacting with soap to form insoluble curds, inhibiting its detergent effect. Both precipitates as scale when heated, carbonate scale being softer and more like sludge than sulphates scale. Silica produces a very hard complex scale, which is very difficult to remove. Other materials may increase the scale bulk by entrainment. This may lead to the composition of complex scales or sludge deposits.

Dissolved oxygen or CO_2 may cause corrosion in the boiler water, excessively high alkalinity, dissociation of steam in contact with hot surfaces and acid water. Both oxygen and carbon dioxide are highly soluble in cold water.

It is recognized that the presence of contaminants will promote carry-over. Total solids, alkalinity and organic matter are all important. Any increase, which leads to support film formation, will greatly increase the tendency of moisture to carry over with the steam either continuously in small quantities or intermittently in large quantities.

Because of the above facts it is always necessary to treat the water further before using to generate steam.

Water treatment cost is mainly dependent on the quality of water and type of chemical used. If the quality is so bad the amount of chemicals needed is high and the result is higher water treatment cost. There are different types of chemicals in the market in different brands and the cost varies from type to type. In addition to the above the transport cost of water or the pumping cost and the maintenance cost of these equipment are incorporated to the cost of water treatment. Therefore evaluation of water treatment cost is very complex and it varies from organization to organization. So, an average figure was estimated and introduced to the analysis.

In addition to the cost of water treatment, life cycle cost of the plant, operation and maintenance cost, etc. should be incorporated. But these figures also vary with type of equipment, output, operation and maintenance, etc. Unfortunately I was not possible to collect the data to evaluate the above figures in this analysis.

5.8 CO_2 emission Vs Exergetic Efficiency.

Exergetic efficiency is mainly dependent on the exergy destruction and exergy losses through the flue gas. As we discussed earlier exergy destruction occurs due to rapid temperature reduction between the combustion products and steam. Exergy loss through the flue gas mainly depends on the excess air and the flue gas temperature. If the excess air level is high the exergy loss is also high and it leads to reduce exergetic efficiency. If the combustion of fuel is complete the amount of CO_2 emission gets increased but ultimately the efficiency is increased. According to the figure below the CO_2 emission (kg/MJ of useful exergy) is reduced while the exergetic efficiency is increased. This shows that the increase of steam output is higher than the amount of CO_2 emission with respect to the increase of exergetic efficiency.

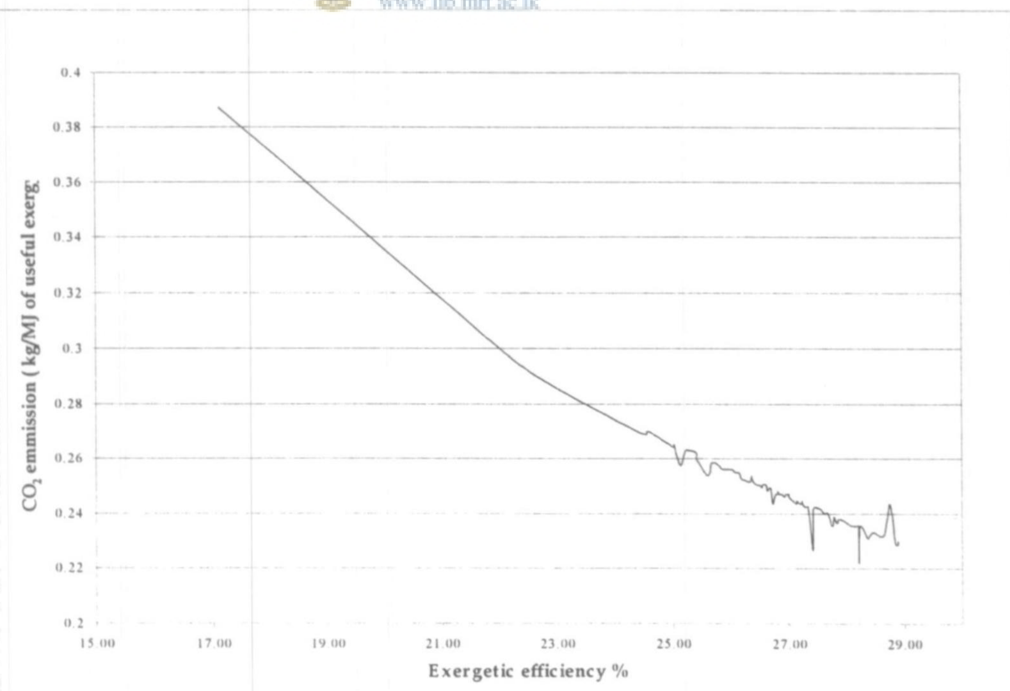


Figure 5.20 Variation CO_2 emission (kg/MJ of useful exergy) with exergetic efficiency

The relationship between exergetic efficiency and the CO_2 emission can be given by the following formula.

$$\mathbf{CO_2\ emission\ (kg/MJ\ of\ useful\ exergy) = 6.5 / \varepsilon}$$

Where ε – Exergetic efficiency of the boiler

5.9 CO_2 emission Vs Energy Efficiency

According to the previous analysis, the energy efficiency of a steam boiler is higher than its exergetic efficiency. Therefore the specific CO_2 emission reference to the useful energy (kg/MJ of useful energy) is very much less than the specific CO_2 emission reference to the useful exergy.

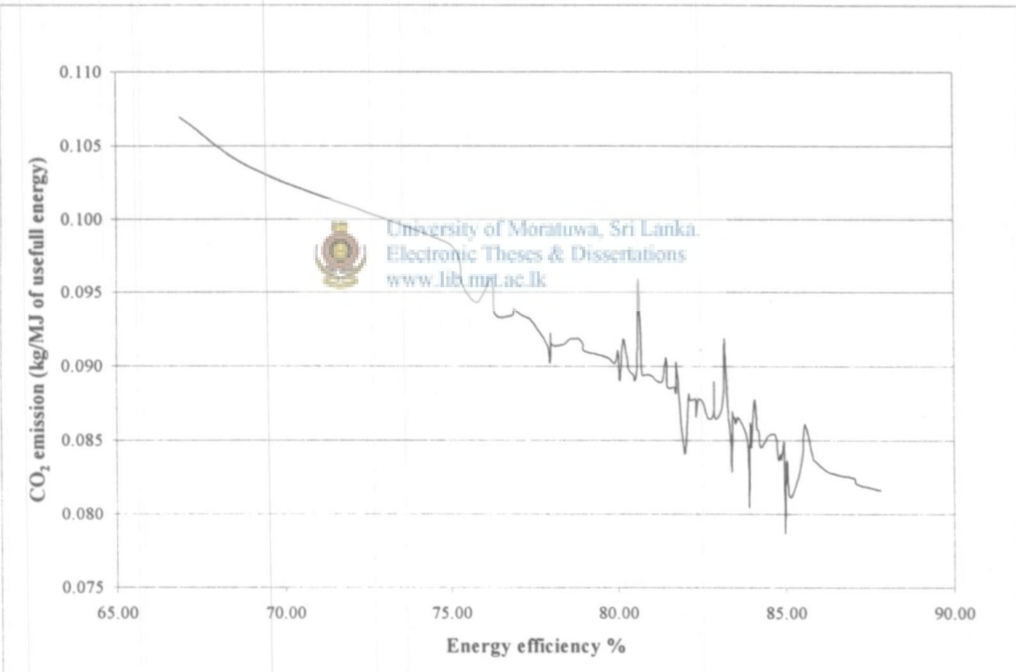


Figure 5.21 Variation CO_2 emission (kg/MJ of useful energy) with energy efficiency

The pattern of the variation of the CO_2 emission with energy efficiency is the same as its variation with exergetic efficiency. But the relationship is somewhat different and can be illustrated as follows.

$$CO_2 \text{ emission (kg/MJ of useful energy)} = 9.2 / \eta$$

Where η – Energy efficiency of the boiler

According to the previous analysis it is clear that the variation pattern of specific CO_2 emission with exergetic efficiency and energy efficiency is similar to the variation pattern of specific steam cost with exergetic efficiency.

5.10 CO_2 emission Vs Percentage Exergy Loss in Flue Gas

Amount of CO_2 emission is equivalent to the amount of fuel used in the burner. According to the following figure the specific CO_2 emission reference to the steam output is getting increased with increase of percentage exergy loss in flue gas.

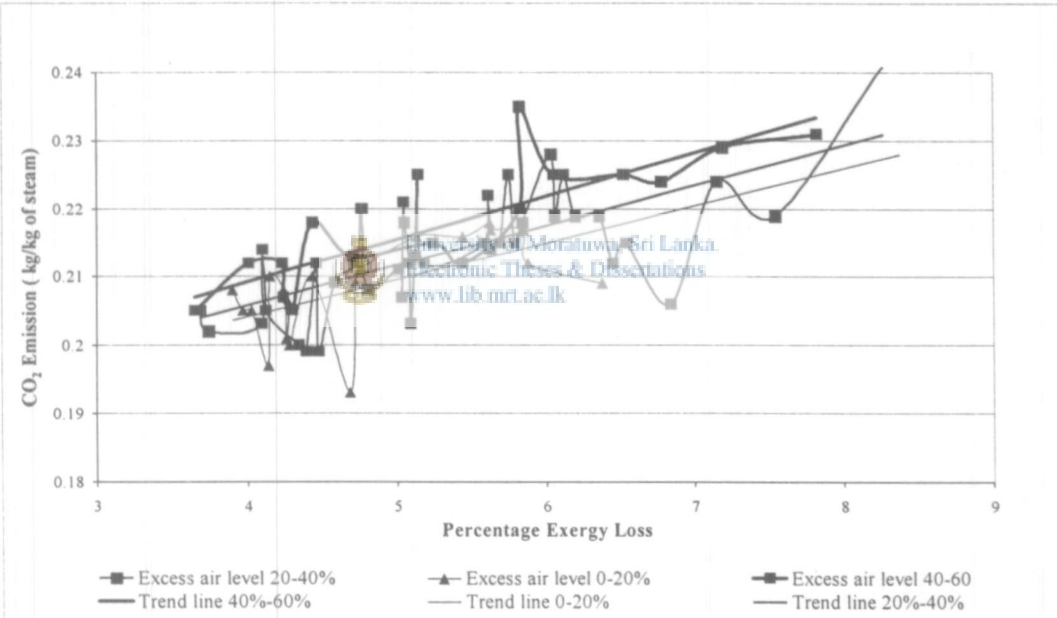


Figure 5.22 Variation of CO_2 emission with percentage exergy loss in flue gas at different excess air level

Due to the increase of exergy loss, the exergetic efficiency gets reduced and the steam output will be reduced.

Apart from that, the figure 5.22 indicates that the specific CO_2 emission reference to the steam output is getting increased with increase of excess air while the percentage exergy loss remaining constant. Reference to the exergy analysis to keep the flue gas loss at constant level, it is necessary to reduce the flue gas temperature while increasing the excess air. That means there is an inverse relationship between flue gas temperature and excess air when the flue gas loss is constant. However, according to the figure 5.22 CO_2 emission (kg/h of steam) is getting increased with increase of excess air at constant flue loss. Reference to the previous analysis the exergy loss through the blow down and the surface emission is in a constant range. To increase the specific CO_2 emission (kg/kg of steam), the only possibility is to reduce the exergetic efficiency, but the exergy losses through surface emission, blow down and flue gas are constant at this instance. Therefore the exergy destruction has to be increased. Reference to this the following results can be predicted.

1. To maintain the exergy loss through flue gas in constant level, the temperature of flue gas should be reduced while increasing the excess air.
2. The exergy destruction will increase with increase of amount of excess air while the exergy loss through the flue gas remaining constant.
3. Exergy losses through flue gas get reduced with reduction of both flue gas temperature and excess air.

CHAPTER 6
EXERGETRIC EFFICIENCY IMPROVEMENT POTENTIAL

Exergetic efficiency of a package type steam boiler is somewhat lower than its energy efficiency. Mainly the exergy gets destroyed thtough system irreversibility and according to this analysis the average destruction is around 67.3%. In addition to this, exergy is lost through flue gas, surface emission and blowdown in different quantities. According to the analysis it is possible to increase by about 2.17% on average by reducing the existing losses and comparing the average exergy destruction, the potential is very small.

The exergetic efficiency of a steam boiler can be improved in two ways as mentioned below.

- By reducing the existing losses in various streams.
- By implementing better energy efficient systems.

This chapter presents the details of exergy improvement potential, all the results are illustrated pictorially.

6.1 Potential Improvement of Exergy Efficiency by Reducing the Existing Losses in Boilers

As discussed in section 5.6 the exergetic efficiency can be improved maximum up to 28.0% by reducing the existing losses without changing the configuration. It is impossible to extract the total losses and there are limitations to reduce it. These limitations are based on the operation and maintenance of the boilers and accessories.

The exergy losses of a steam boiler occur through blowdown, surface and flue gas and some amount of exergy gets destroyed by the system irreversibility. But without changing the configuration exergy distortion cannot be minimized to a certain limit. According to the analysis the average losses are in the range of,

Blowdown	-	0.09 %
Surface emission	-	0.3 %
Flue gas loss	-	5.31 %

By maintaining the boiler accessories and operating parameters properly, the losses of the above areas can be reduced up to the following limits.

Blowdown - 0.08 %

Surface emission - 0.05 %

Flue gas loss - 3.4 %

and the average total improvements is in the range of,

Blowdown - 0.01 %

Surface emission - 0.25 %

Flue gas loss - 1.91 % and the total improvements is 2.17 %

The following figure illustrate both the percentage losses and the improvements.

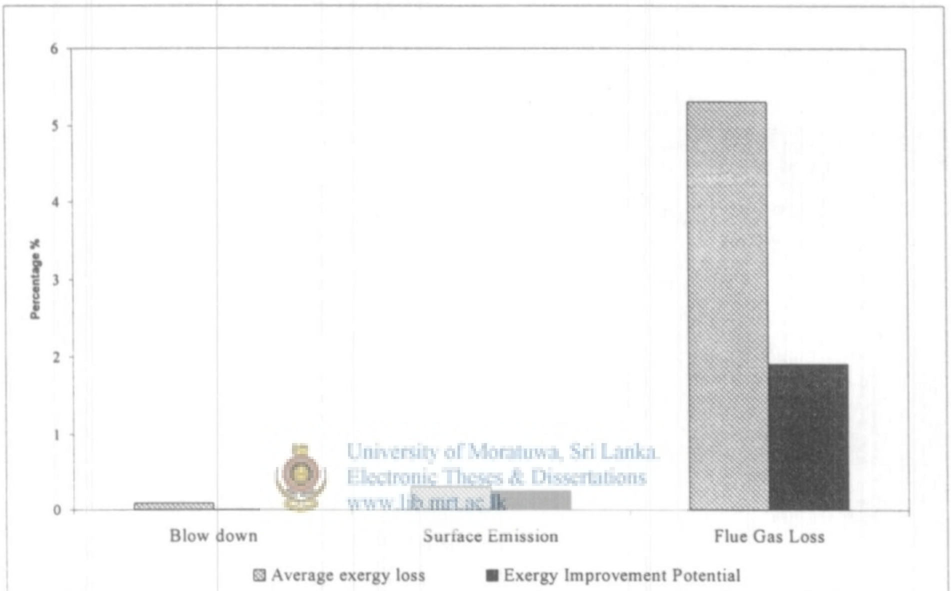


Figure 6.1 Average exergy losses and exergy improvement potential in different areas

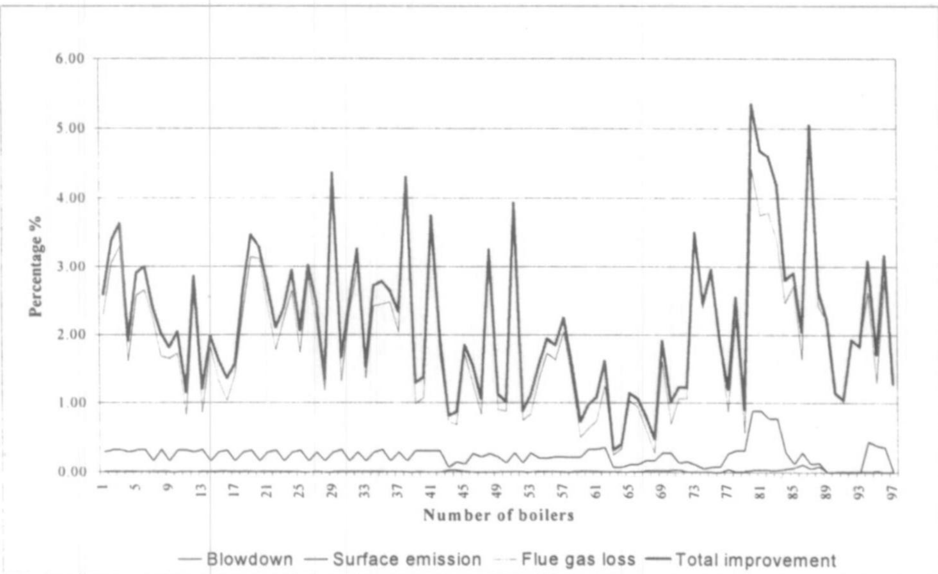


Figure 6.2 Exergetic improvement potential in oil fired boilers

The total average exergetic improvement potential is in the range of 2.17 % from the total exergetic input. Reference to the 1998 energy balance published by the Energy Conservation Fund, the total furnace oil consumption is in the range of 524.2 thousand metric ton per annum. According to the above figures there is potential to save 11.4 thousand metric tons of furnace oil per annum. This is equivalent to 492×10^3 GJ of exergy per annum and the corresponding reduction of CO_2 emission is 36 thousand metric tons per annum.

6.2 Improvement of Exergy Potential by Implementing Better Energy Efficient System.

We discussed the possibility to improve the exergy potential by reducing the losses in the existing systems in the above section. In addition to that the potential of exergy can be improved by implementing efficient energy utilization systems. As we discussed earlier, the exergy distruction due to system irreversibility can be reduced by this way. There are number of methods to improve the exergetic potential in steam boilers.

6.2.1 Cogeneration

The concept of cogenaration is based on the principle of thermal cascading which consists of generation of power on site where a substantial fraction of waste heat produced is recovered to satisfy the heating demand of the end user. There is thus a considerable enhancement of the overall conversion efficiency. The average exergetic efficiency of a cogeneration system is in the range of 33 % [18] of total inputs.

6.2.2 Thermal power plant (Steam turbine based)

Electricity is generated through a steam turbine in this type of power plants. Steam is produced in a boiler and feed in to the turbine. The overall exergetic efficiency is in the range of 40 %[18] of total input.

6.2.3 Thermal cascading

Suppose there is a large industrial complex with various sub-sectors and the energy requirement of the above sectors is different. As an example an industrial complex and its energy requirements can be defined as follows.

Table 6.1 Variation of temperatures in different processes

Process	Required temperature level ^0C
Metallurgical treatment process	>1700
Ceramic furnace	1700 – 1200
Steam cracking	1200 – 900
Catalytic chemical reactions	900 – 600
Dehydration, distillation process	600 – 200
Drying, textiles etc.	200 - 80

At present these various thermal energy sources providing heat at different levels are almost independent of each other and it is illustrated in the following figure.

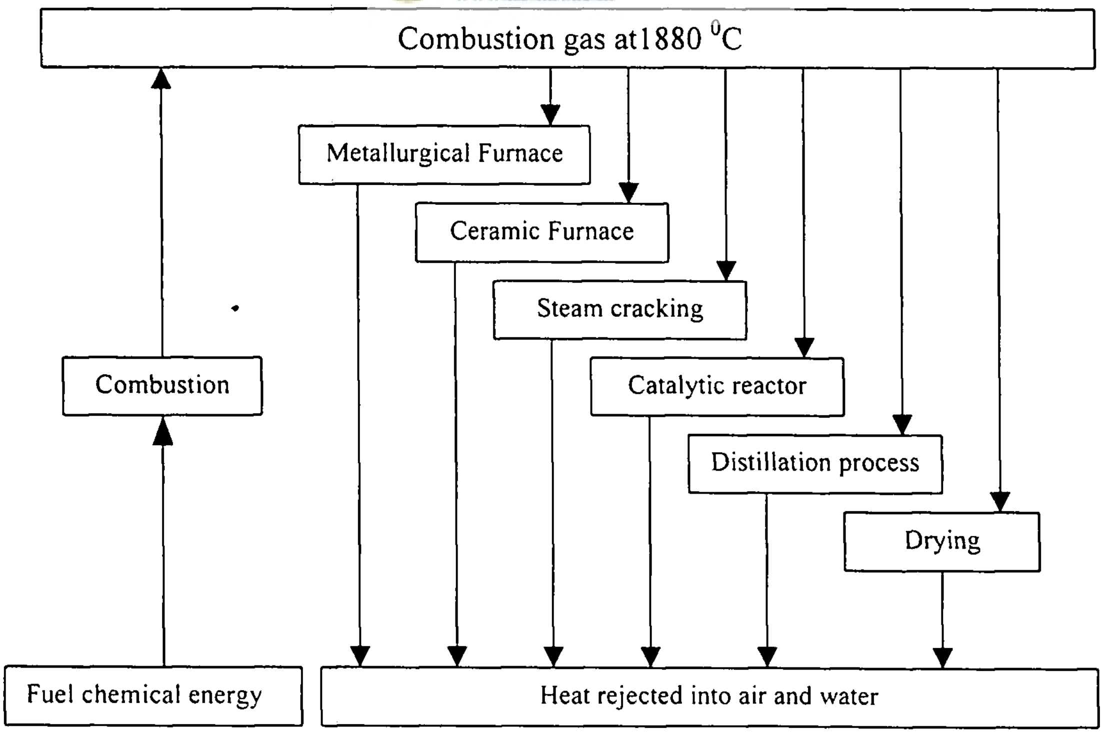


Figure 6.3 Heat provided at different levels for different processes

Fuel is burnt and hot combustion gas is sometimes used directly in some equipment or used indirectly through heat carrying fluids, mainly superheated steam at high temperatures, between 100 and 500 ^{0}C or water at low temperature between 50 and 150 ^{0}C. The ideal way of using energy would be to link all the operation in a thermal cascade so that the heat flux leaving one equipment becomes the input to the next. The maximum thermal potential of heat can be extracted by using it at the appropriate level in specific equipment.

But in practice the maximum interconnections of various exchangers and machines are difficult to carry out because of various factors. Particularly the quantity and the temperature levels should match and their management is quite complex especially if one wants to modify existing facilities. The locations of the equipment pose another constraint.

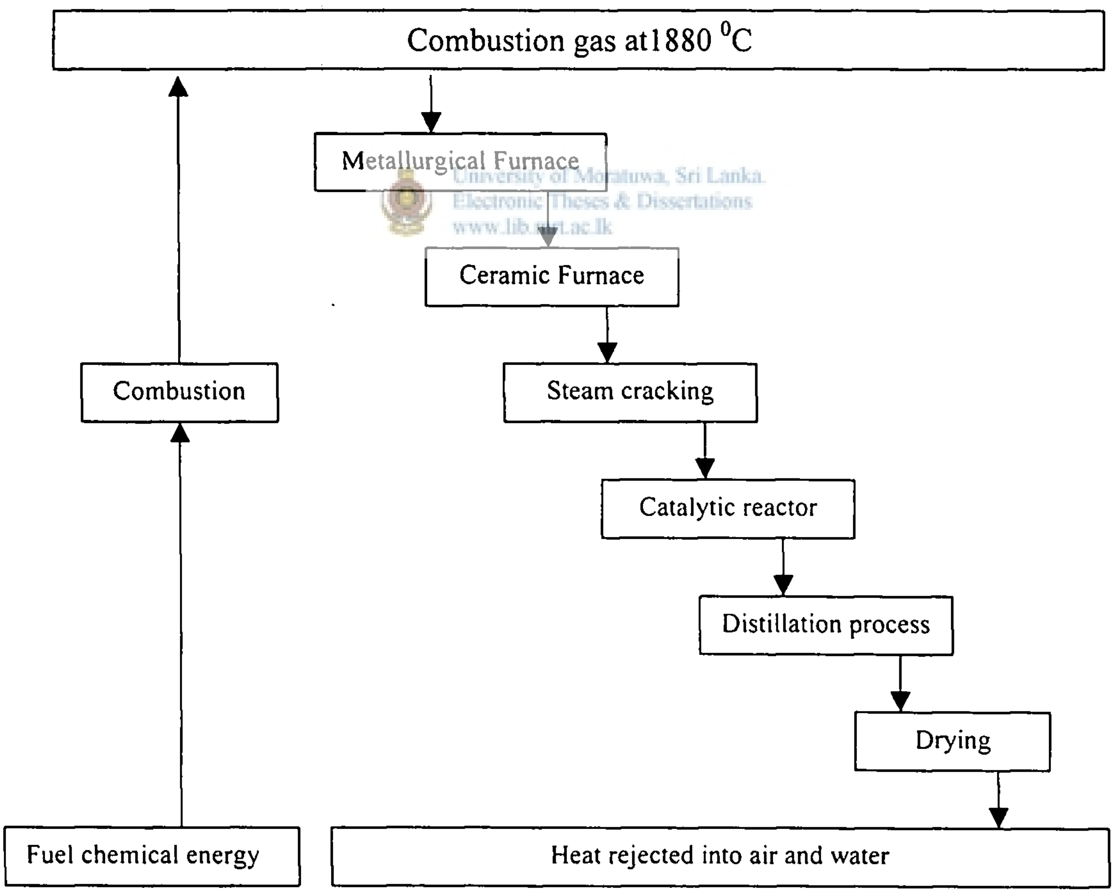


Figure 6.4 Optimum cascading of thermal energy in industries

CHAPTER 7
CONCLUSION

Exergy analysis is a technique at the forefront of applied thermodynamics research where by systems that utilize energy are assessed in the light of the second law of thermodynamics. All forms of energy transfer and transport can be represented by equivalent exergy transfers which are, in fact, the quantities of work that could be produced from the same types of energy transfer or transport by perfect thermodynamics device, free to interact with a specified reference environment. It is a fundamental physical law that energy is conserved. But conventional energy analysis can only account for where energy is distributed or lost from systems of interest. Exergy analysis can highlight where energy is used inefficiently.

Exergetic efficiency or the rational efficiency is a very useful measure for the thermodynamic quality of a technical process. In the case of steam boilers, exergetic efficiency is always less than the energy efficiency. This is mainly due to rapid exergy destruction taking place within the boilers. The exergy destruction takes place due to rapid temperature reduction between combustion products and the steam. On average, exergetic efficiency of a steam boiler is three times less than the energy efficiency and it can be evaluated using the following formula.

$$\varepsilon = 0.36\eta - 3.0$$

Where ε - Exergetic efficiency
η - Eneregy efficiency

Flue gas loss gets increased with increase of both amount of excess air and flue gas temperature. But the effect of increasing excess air is not much significant in comparison to the increase of flue gas temperature. As an example, the reduction of exergetic efficiency is around 0.5%, when increasing the excess air level by 60%. But by increasing the flue gas temperature by 50 ^{0}C at constant excess air level, the exergetic efficiency is reduced by 1%.

The other losses, which occur through surface emission and blowdown are very small. The blowdown loss is in the range from 0.02% to 0.2% and the surface emission varies between 0.05% and 0.94%. The average of the above parameters are 0.09% and 0.3% respectively and the improvement potential in this area is negligible.

Mainly the exergy loss of a boiler occurs through the exergy destruction due to rapid system irreversibility. It is impossible to reduce the irreversibility rate without changing the configuration of a boiler and the system. But the existing losses in the other streams such as flue gas, blow down and surface emission can be minimized to a certain limit by adjusting the existing operating parameters to optimum condition. The maximum possible exergetic efficiency that can be taken by maintaining the above parameters to the optimum condition is 28.0%. The improvement potential of the existing exergetic efficiency varies between 0% to 6.5% from total inputs. The average improvement potential is 2.2%. The savings are equivalent to 11.4 thousand metric tons of furnace oil per annum in Sri Lanka and the corresponding reduction of CO_2 emission is 36 thousand metric tons per annum.

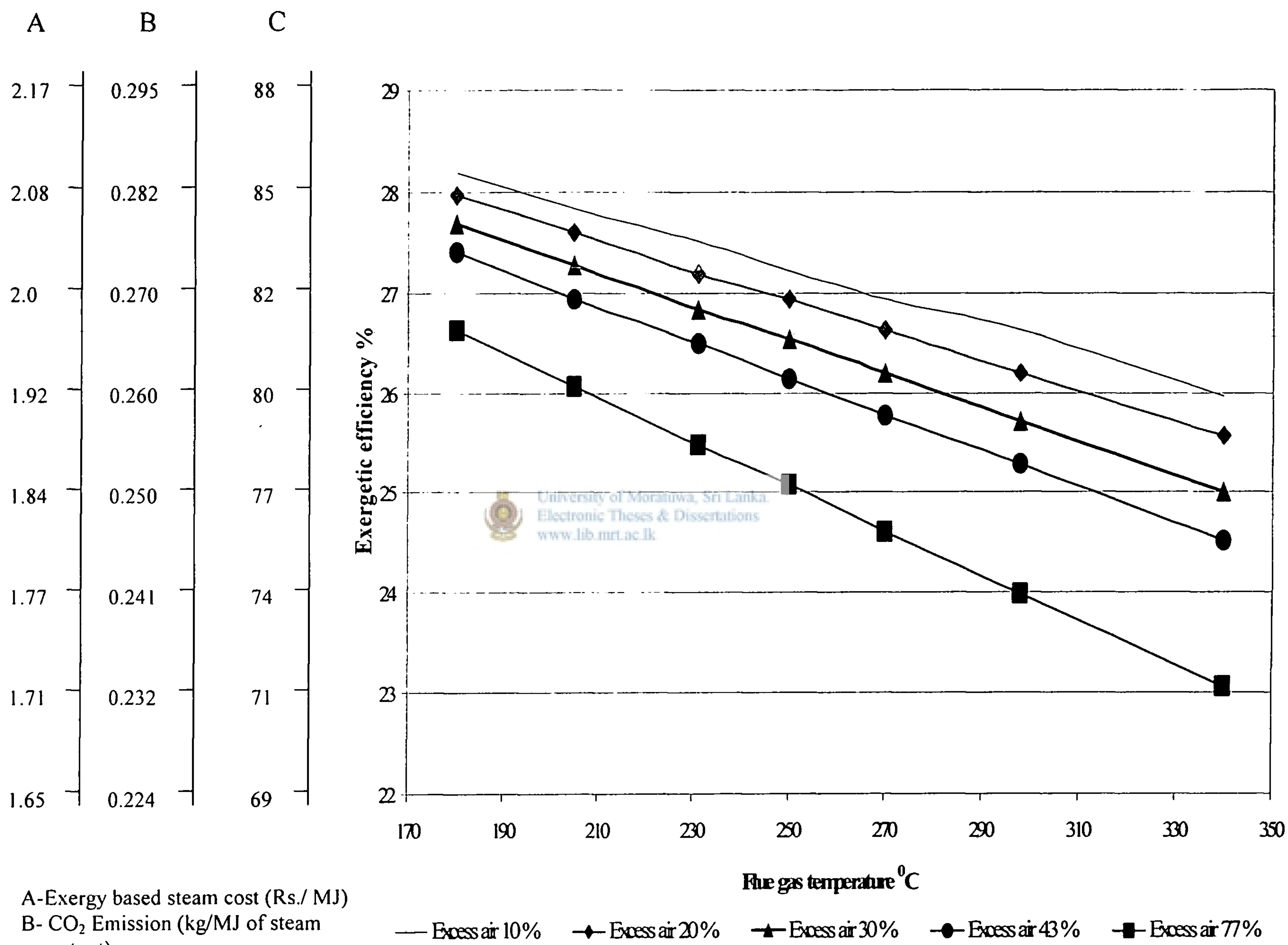
The specific CO_2 emission (kg/MJ of useful exergy) is reduced with increase of exergetic efficiency. This shows that the increase of steam output is higher than the amount of CO_2 emission with respect to the increase of exergetic efficiency. This behavior follows the following formula.

$$CO_2 \text{ emission (kg/MJ of useful exergy)} = 6.5/\varepsilon$$

Where ε - Exergeic efficiency

The steam cost varies between 1.36 Rs./MJ and 1.78 Rs./MJ based on the exergetic efficiency and the average is 1.49 Rs./MJ. The equivalent average cost of steam based on energy efficiency is 0.52 Rs./MJ. This implies that the cost of steam based on exergetic efficiency is approximately three times higher than the cost of steam based on energy efficiency.

As we discussed earlier there are few parameters, which directly effect to the exergetic efficiency. Flue gas parameters such as excess air and flue gas temperature, blow down parameters and surface emission are the major parameters. Variation of exergetic efficiency with such parameters is illustrated in the following figures.



A-Exergy based steam cost (Rs./ MJ)
B- CO_2 Emission (kg/MJ of steam output)
C- Energy efficiency %

Figure 7.1 Variation of exergetic efficiency with excess air and flue gas

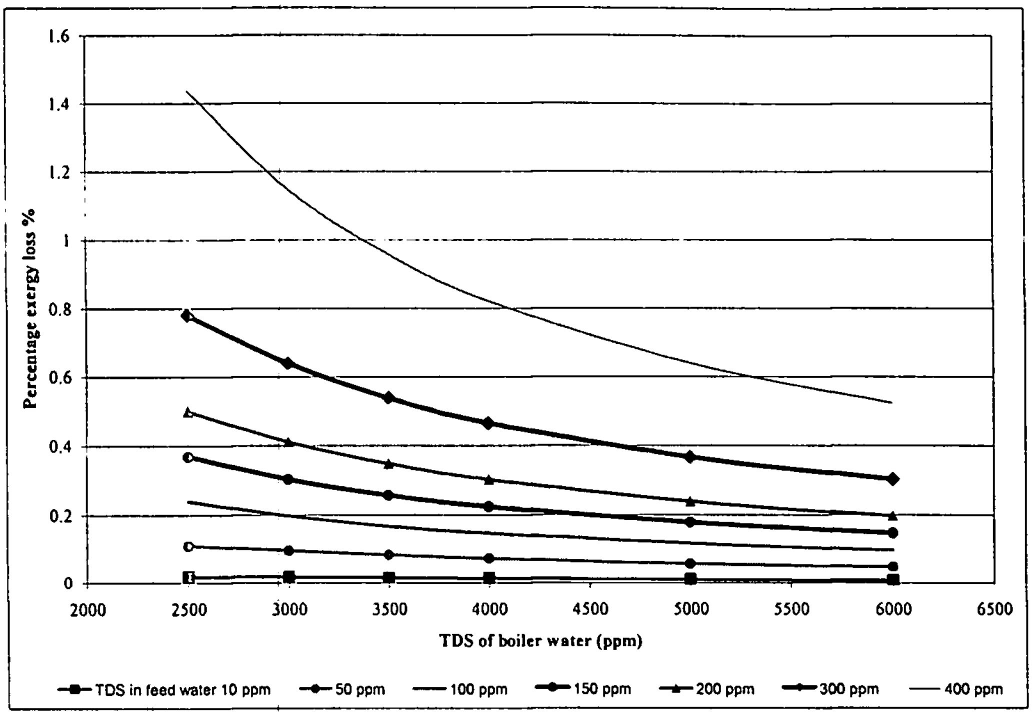


Figure 7.2 Variation of exergy loss with TDS in feed water and and blow down water

To prepare these figures, it was assumed that the surface emission is constant in each boiler and it is taken as 0.05%. Exergetic efficiency varies with variation of TDS levels of boiler and feed water. As a bench mark it was taken that the TDS of such parameters as 3500 ppm and 50 ppm respectively and the corresponding loss is equivalent to 0.08%.

If the blowdown parameters are different, the corresponding losses can be taken from figure 7.2 and the correction would be made accordingly. As an example if the TDS levels of feed water and blowdown water are 100 ppm and 3000 ppm respectively and the level of excess air is 77% and flue gas temperature is 310 ^{0}C, reference to figure 7.2 the actual blow down loss is 0.2%. Difference between recommended value and the actual value is -0.12% (0.08% - 0.2%). The exergetic efficiency taken from the figure 7.1 is 25.0 % but the actual efficiency is 24.88 % (0.12% less than the direct reading)

In addition to the above, the cost of steam, CO_2 emission and the energy efficiency corresponding to the exergetic efficiency can be directly taken from figure 7.1.

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APPENDIX A
DATA & MEASUREMENTS

Organization : CU

Table 01
Details of Boilers

Parameter	Boiler No. 01	Boiler No. 02	Boiler No. 03	Boiler No. 04
Type	Horizontal, 3-pass fire tube	Horizontal, 3-pass fire tube	Horizontal, 3-pass fire tube	Horizontal, 3-pass fire tube
Capacity	8200 kg/hr @17bar	8200 kg/hr @17bar	8200 kg/hr @17bar	7000 kg/hr @17bar
Fuel Consumption	295 ltr/hr	295 ltr/hr	295 ltr/hr	295 ltr/hr

Table 02
Details of Burners

Parameter	Boiler No. 01	Boiler No. 02	Boiler No. 03	Boiler No. 04
Type	Rotary cup	Rotary cup	Rotary cup	Rotary cup
Blow Motor	15 kW	15 kW	15 kW	7.5 kW
Heater	12 kW	12 kW	12 kW	10 kW
Fuel preheating temperature ^0C	80	80	80	80
Pump Motor	22 kW	22 kW	22 kW	8.5 kW

Table 03
CUB – 1 Measured on 5th July 1997

Parameter	Boiler No. 01		
	Trial 1	Trial 2	Trial 3
Combustion Efficiency	83.4	83.2	83.2
O_2 Percentage	4.3	4.3	4.3
CO_2 Percentage	12.7	12.7	12.7
CO ppm	5.0	6.0	6.0
NO ppm	208	210	214
NO_2 ppm	0	0	0
SO_2 ppm	810	860	840
Flue Gas Temperature ^0C	278	278	278
Excess Air Percentage	26	26	26
Smoke No.	0	0	0

Table 04
CUB – 2 Measured on 5th July 1997

Parameter	Boiler No. 02		
	Trial 1	Trial 2	Trial 3
Combustion Efficiency	84.6	84.6	84.6
O_2 Percentage	4.3	4.2	4.3
CO_2 Percentage	12.6	12.6	12.7
CO ppm	30	48	60
NO ppm	281	190	198
NO_2 ppm	0	0	0
SO_2 ppm	953	990	985
Flue Gas Temperature ^0C	254	254	254
Excess Air Percentage	26	25	26
Smoke No.	0	0	0

Table 05
CUB –3 Measured on 5th July 1997

Parameter	Boiler No. 03			
	Trial 1	Trial 2	Trial 3	Trial 4
Combustion Efficiency	83.7	83.7	83.8	83.7
O_2 Percentage	5.6	5.6	5.6	5.5
CO_2 Percentage	11.6	11.6	11.8	11.7
CO ppm	57.0	58.0	58.0	58.0
NO ppm	190	200	205	185
NO_2 ppm	0	0	0	0
SO_2 ppm	990	929	982	1010
Flue Gas Temperature ^0C	252	253	253	253
Excess Air Percentage	32	32	32	32
Smoke No.	0	0	0	0

Table 06
CUB – 1,2,3&4 Measured on June 1998

Parameter	CUB-1		CUB-2		CUB-3		CUB-4	
	High Fire	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire	Low Fire
Combustion Efficiency	83.6	85.2	79.9	81.1	82.3	84.5	82.5	87.1
O_2 Percentage	2.9	4.7	9.4	10.8	4.9	7.3	3.1	4.1
CO_2 Percentage	13.8	12.3	8.6	7.6	12.1	10.2	13.5	12.7
CO ppm	152	60	48	38	68	50	120	70
NO ppm	252	200	198	170	210	180	248	228
NO_2 ppm	0	0	0	0	0	0	0	0
SO_2 ppm	1090	670	630	621	730	670	1040	649
Flue Gas Temperature ^0C	289	232	251	212	289	218	277	168
Excess Air Percentage	15	28	78	108	28	55	17	25
Smoke No.	1	0	0	0	0	0	1	0

Table 07
CUB – 3&4 Measured on 23rd July 1999

Parameter	CUB-3		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	85.3	84.6	85.4	82.2
O_2 Percentage	2.4	4.9	4.8	5.5
CO_2 Percentage	14.8	12.1	12.2	11.6
CO ppm	260	30	60	55
NO ppm	260	244	265	280
NO_2 ppm	0	0	0	0
SO_2 ppm	1000	660	710	820
Flue Gas Temperature ^0C	167	212	184	238
Excess Air Percentage	13	30	30	34
Smoke No.	1	0	0	0

Table 08
CUB – 2 Measured on 23rd July 1999

Parameter	Before Tuning		After Tuning	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	79.3	85.2	84.9	85.6
O_2 Percentage	13.0	4.1	7.0	3.9
CO_2 Percentage	5.9	12.7	10.9	12.8
CO ppm	320	80	110	90
NO ppm	110	220	238	198
NO_2 ppm	0	0	0	0
SO_2 ppm	630	968	840	990
Flue Gas Temperature ^0C	154	206	148.0	191
Excess Air Percentage	156	22	47	22
Smoke No.	0	0	0	0

Table 09
CUB – 1,3&4 Measured on 5th October 1999 (Before tuning)

Parameter	CUB-1		CUB-3		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	70.5	78.4	88.4	84.7	80.7	80.0
O_2 Percentage	14.5	8.4	0.3	2.0	10.0	7.5
CO_2 Percentage	4.8	9.4	15.7	14.4	8.3	10.1
CO ppm	600	190	1600	1090	160	200
NO ppm	138	142	195	243	144	165
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	480	798	1120	1070	688	888
Flue Gas Temperature ^0C	193	254	167	237	187	247
Excess Air Percentage	210	60	2	10	80	20
Smoke No.	0	0	2	1	0	0

Table 10
CUB – 2 Measured on 5th October 1999 (After Tuning)

Parameter	CUB-1		CUB-3		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	84.7	82.4	85.5	84.4	85.6	83.1
O_2 Percentage	5.4	4.1	2.4	2.8	5.4	5.0
CO_2 Percentage	11.7	12.7	14.0	13.7	11.6	12.0
CO ppm	110	80	260	270	90	80
NO ppm	198	267	188	239	185	248
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	998	970	1020	1010	881	790
Flue Gas Temperature ^0C	2.2	268	187	226	185	240
Excess Air Percentage	32	23	13	15	32	28
Smoke No.	0	0	1	1	0	0

Table 11
CUB – 1,2&4 Measured on 15th December 1999 (Before Tuning)

Parameter	CUB-1		CUB-2		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	78.4	80.1	81.8	83.8	81.0	79.7
O_2 Percentage	12.9	5.6	9.7	5.6	10.4	9.1
CO_2 Percentage	6.0	1.7	8.5	12.0	7.9	8.9
CO ppm	350	40	10	20	10	10
NO ppm	77	190	199	271	103	128
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	210	1043	666	917	220	300
Flue Gas Temperature ^{0}C	217	290	227	254	231	274
Excess Air Percentage	162	32	86	31	100	77
Smoke No.						

Table 12
CUB – 1,2&4 Measured on 15th December 1999 (After Tuning)

Parameter	Boiler No. 01		Boiler No. 02		Boiler No. 04	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	83.1	82.6	82.9	84.8	85.0	83.6
O_2 Percentage	5.5	4.6	8.4	4.2	6.2	5.1
CO_2 Percentage	1.8	12.3	9.6	12.6	11.1	11.9
CO ppm	20	30	20	20	10	10
NO ppm	210	184	143	264	170	223
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	200	143	21	186	194	155
Flue Gas Temperature ^{0}C	216	280	218	246	225	266
Excess Air Percentage	32	28	78	25	42	32
Smoke No.						

Table 13
CUB – 1,2&4 Measured on 9th August 2000 (Before Tuning)

Parameter	CUB-1		CUB-2		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	65.0	80.0	86.0	84.5	79.0	82.0
O_2 Percentage	16.6	7.9	4.8	4.3	13.0	4.4
CO_2 Percentage	3.2	9.8	12.2	12.5	5.9	12.4
CO ppm	760	90	80	95	1600	88
NO ppm	67	139	212	286	118	280
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	288	841	865	941	369	1008
Flue Gas Temperature ^{0}C	215	269	210	247	206	308
Excess Air Percentage	389	60	29	26	166	27
Smoke No.	2	2	0	0	0	0

Table 14
CUB – 1&4 Measured on 9th August 2000 (After Tuning)

Parameter	CUB-1		CUB-4	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	83.5	83.5	85.5	82.0
O_2 Percentage	6.5	4.8	5.5	4.4
CO_2 Percentage	10.8	12.2	11.7	12.4
CO ppm	92	58	66	70
NO ppm	130	210	223	267
NO_2 ppm	0	0	0	0
SO_2 ppm	800	1037	870	1008
Flue Gas Temperature ^0C	210	268	170	307
Excess Air Percentage	38	30	32	27
Smoke No.	1	1	0	0

Table 15
CUB – 1,3&4 Measured on 4th January 2001 (Before Tuning)

Parameter	CUB - 1		CUB - 3		CUB - 4	
	Low Fire	High Fire	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	82.0	76.6	86.0	86.0	80.0	82.0
O_2 Percentage	7.1	10.3	6.3	2.6	11.6	3.8
CO_2 Percentage	10.4	8.0	11.0	13.8	7.0	12.9
CO ppm	200	400	100	200	300	300
NO ppm	165	137	219	268	134	232
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	883	627	292	563	627	920
Flue Gas Temperature ^0C	246	292	198	229	223	311
Excess Air Percentage	51	97	43	14	126	22
Smoke No.	1	1	0	0	0	0

Table 16
CUB – 1&4 Measured on 4th January 2001 (After Tuning)

Parameter	CUB – 1		CUB - 4	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	85.0	82.0	81.6	82.0
O_2 Percentage	3.2	4.1	4.7	3.8
CO_2 Percentage	13.4	12.6	12.2	12.9
CO ppm	100	100	100	300
NO ppm	158	198	197	232
NO_2 ppm	0	0	0	0
SO_2 ppm	1130	1128	630	920
Flue Gas Temperature ^0C	251	310	228	311
Excess Air Percentage	18	25	28	22
Smoke No.	0	0	0	0

Table 17
CUB – 1,3&4 Measured on 2nd May 2001 (Before Tuning)

Parameters	CUB - 1		CUB - 3		CUB -4	
	Low fire	High fire	Low fire	High fire	Low fire	High fire
Combustion Efficiency	79.0	81.6	83.8	83.0	87.0	83.7
O_2 Percentage	13.1	7.8	4.9	3.6	1.2	1.8
CO_2 Percentage	5.8	9.9	12.0	13.1	14.9	14.4
CO ppm	610	180	40	60	9490	3250
NO ppm	128	137	221	253	143	246
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	480	815	943	1072	1118	1114
Flue Gas Temperature ^0C	205	161	252	289	225	301
Excess Air Percentage	171	60	31	20	6	9
Smoke Number	0	0	0	0	1	2

Table 18
CUB – 1&4 Measured on 2nd May 2001 (After Tuning)

Parameters	CUB – 1		CUB - 4	
	Low fire	High fire	Low fire	High fire
Combustion Efficiency	84.0	83.0	85.5	81.5
O2 Percentage	5.2	4.1	4.8	5.7
CO2 Percentage	11.5	12.6	12.2	11.5
CO ppm	170	120	450	425
NO ppm	171	183	193	238
NO2 ppm	0	0	0	0
SO2 ppm	988	1082	892	950
Flue Gas Temperature ^0C	231	265	227	349
Excess Air Percentage	31	25	29	37
Smoke Number	0	0	0	0

Table 19
Boiler Dimensions

Parameter	Boiler No. 01	Boiler No. 02	Boiler No. 03	Boiler No. 04
Length (feet)	20	20	20	16
Diameter (feet)	12	12	12	10

Table 20
Boiler Surface Temperature – ^0C

Parameter	Boiler No. 01	Boiler No. 02	Boiler No. 03	Boiler No. 04
Cylinder Side	52	55	58	48
Back Side	178	182	180	210
Burner Side	89	88	78	70

Table 21
TDS of Water - ppm

Parameter	Boiler No. 01	Boiler No. 02	Boiler No. 03	Boiler No. 04
Feed Water	50	50	50	50
Boiler Water	3000	3200	3100	3220

Feed water temperature: 78 ^0C

Organization : BL

Table 22
Boiler Data

Parameter	BLB 1
Type	Horizontal, 3 – pass fire tube package
Capacity	10 Tons/hr
Fuel Consumption	250 ltrs / hrs

Table 23
Burner Data

Parameter	BLB 1
Type	Rotary cup modulate control
Blow Motor	11 kW
Heater	12 kW
Fuel preheating temperature	80 ^0C
Water Pump	11 kW

Table 24
BLB-1 Measured on 30th November 2000 (Before Tuning)

Parameter	Burner Positions					
	Low flame	20% from low flame	40% from low flame	60% from low flame	80% from low flame	High flame
Combustion Efficiency	87.5	86.6	86.0	85.3	83.9	83.1
O_2 Percentage	2.7	4.6	5.2	5.6	7.2	8.0
CO_2 Percentage	13.7	12.3	11.8	11.5	10.4	9.7
CO ppm	200	400	300	300	200	300
NO ppm	259	228	210	197	191	192
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	813	864	849	823	732	623
Flue Gas Temperature ^0C	192.6	199.8	208.2	217.3	227.2	228.8
Excess Air Percentage	15	28	33	37	52	62
Smoke No.	1	0	0	0	0	0

Table 25
BLB-1 Measured on 30th November 2000 (After Tuning)

Parameter	Burner Positions					
	Low flame	20% from low flame	40% from low flame	60% from low flame	80% from low flame	High flame
Combustion Efficiency	87.3	87.0	86.1	85.8	85.4	84.4
O_2 Percentage	4.0	4.0	4.4	4.3	4.8	5.9
CO_2 Percentage	12.8	12.8	12.4	12.5	12.1	11.3
CO ppm	200	200	200	200	200	200
NO ppm	253	220	211	210	197	198
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	834	646	923	936	881	821
Flue Gas Temperature ^0C	192.2	196.7	212.6	221.0	225.5	232.5
Excess Air Percentage	22	22	26	26	30	39
Smoke No.	0	0	0	0	0	0

Table 26
BLB-1 Measured on 23rd April 2001 (Before tuning)

Parameters	Burner Positions					
	Low flame	20% from low flame	40% from low flame	60% from low flame	80% from low flame	High flame
Combustion Efficiency	86.4	83.1	83.0	80.0	79.5	75.0
O_2 Percentage	3.0	5.0	5.1	6.8	7.3	10.1
CO_2 Percentage	13.5	11.3	11.2	10.6	10.3	8.1
CO ppm	60	60	50	40	40	80
NO ppm	0	0	0	0	0	0
NO_2 ppm	210	208	205	205	195	170
SO_2 ppm	1057	910	896	814	766	661
Flue Gas Temperature ^0C	221	254	255	286	306	316
Excess Air Percentage	17	37	38	48	54	96
Smoke Number	0	0	0	0	0	0

Table 27
BLB-1 Measured on 23rd April 2001 (After tuning)

Parameters	Burner Positions					
	Low flame	20% from low flame	40% from low flame	60% from low flame	80% from low flame	High flame
Combustion Efficiency	85.8	85.4	84.4	83.4	83.0	82.1
O_2 Percentage	4.8	4.3	4.1	4.3	4.0	4.6
CO_2 Percentage	12.1	12.0	12.3	12.5	12.8	12.3
CO ppm	80	70	70	90	80	70
NO ppm	0	0	0	0	0	0
NO_2 ppm	198	200	205	200	210	208
SO_2 ppm	1029	968	1080	1080	1095	972
Flue Gas Temperature ^0C	222	230	249	273	289	299
Excess Air Percentage	30	23	22	23	22	28
Smoke Number	0	0	0	0	0	0

Table 28
Boiler Dimensions

Parameter	BLB 1
Length (feet)	20
Diameter (feet)	12

Table 29
Boiler Surface Temperature – ^0C

Parameter	BLB 1
Cylinder Side	51
Back Side	188
Burner Side	78

Table 30
TDS of Water - ppm

Parameter	BLB 1
Feed Water	10
Boiler Water	3100

Feed water temperature: 98 ^0C

Organization : FN.

Table 31
Details of Boiler

Parameter	FNB 1
Type	Horizontal, 2-pass fire tube
Capacity	2000 kg/hr
Fuel Consumption	105 ltr/hr

Table 32
Details of Burner

Parameter	FNB 1
Type	Pressure jet atomizing
Blow Motor	5.5 kW
Heater	6 kW
Fuel preheating temperature	105 ^0C
Water Pump	4 kW

Table 33
FNB – 1 Measured on 08th November 2000 (Before Tuning)

Parameter	Low flame	20% from low flame	40% from low flame	60% from low flame	High flame
Combustion Efficiency	84.0	86.3	86.7	87	87.3
O_2 Percentage	11.5	8.7	5.7	4.5	4.1
CO_2 Percentage	7.0	9.1	11.5	12.3	12.6
CO ppm	80	70	85	65	95
NO ppm	198	203	222	227	225
NO_2 ppm	0	0	0	0	0
SO_2 ppm	380	554	725	861	847
Flue Gas Temperature ^0C	162.6	164.8	187.2	193.2	194.3
Excess Air Percentage		72	37	28	24
Smoke No.	0	0	0	0	0

Table 34
FNB – 1 Measured on 08th November 2000 (After Tuning)

Parameter	Low flame	20% from low flame	40% from low flame	60% from low flame	High flame
Combustion Efficiency	88.0	88.2	87.5	87	87.3
O_2 Percentage	6.5	5.4	5.0	4.5	4.1
CO_2 Percentage	11.0	11.8	12.0	12.3	12.6
CO ppm	85	97	70	55	75
NO ppm	200	207	215	227	225
NO_2 ppm	0	0	0	0	0
SO_2 ppm	384	560	766	861	847
Flue Gas Temperature ^0C	160.6	165.0	188.3	193.2	194.3
Excess Air Percentage	42	34	30	28	24
Smoke No.	0	0	0	0	0

Table 35
Boiler Dimensions

Parameter	FNB 1
Length (feet)	16
Diameter (feet)	8

Table 36
Boiler Surface Temperature – ^0C

Parameter	FNB 1
Cylinder Side	48
Back Side	128
Burner Side	78

Table 37
TDS of Water - ppm

Parameter	FNB 1
Feed Water	62
Boiler Water	3300

Feed water temperature: 80 ^0C

Organization : TB.

Table 38
Details of Boiler

Parameter	TBB 1
Type	Horizontal,3-pass fire tube
Capacity	13000 lb/hr
Fuel Consumption	230 ltr/hr

Table 39
Details of Burner

Parameter	TBB 1
Type	Pressure Jet Atomizing Automatic On/Off Controlling
Blow motor	7.5 kW
Heater	6 kW
Fuel preheating temperature	110 ^0C
Water pump	5 kW

Table 40
TBB – 1 Measured on 14th Sep 2000

Parameter	Trial 1		Trial 2	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	86.0	84.5	85.9	86.2
O_2 Percentage	4.2	3.8	4.6	3.6
CO_2 Percentage	12.5	12.9	12.3	12.8
CO ppm	70	55	80	85
NO ppm	212	232	203	240
NO_2 ppm	0	0	0	0
SO_2 ppm	962	951	829	940
Flue Gas Temperature ^0C	213	242	210.0	248
Excess Air Percentage	25	23	27	20
Smoke No.	0	0	0	0

Table 41
Boiler Dimensions

Parameter	TBB 1
Length (feet)	15
Diameter (feet)	8

Table 42
Boiler Surface Temperature – ^0C

Parameter	TBB 1
Cylinder Side	61
Back Side	138
Burner Side	90

Table 43
TDS of Water - ppm

Parameter	TBB 1
Feed Water	63
Boiler Water	3750

Feed water temperature: 74 ^0C

Organization : BC.

Table 44
Details of Boiler

Parameter	BCB 2	BCB 3
Type	Horizontal, 3-pass fire tube	Horizontal, 3-pass fire tube
Capacity	2000 kg/hr	3200 kg/hr
Fuel Consumption	92 ltr/hr	115 ltr/hr

Table 45
Details of Burner

Parameter	BCB 2	BCB 3
Type	Pressure Jet Atomizing Automatic ON/Off Controlling 3 Nozzles are available for 3 steps	Pressure Jet Atomizing Automatic ON/Off Controlling 2 steps
Blow Motor	3 kW	3 kW
Heater	3.5 kW	5 kW
Fuel preheating temp: ^0C	110 ^0C	110 ^0C
Water pump	5 kW	5 kW

Table 46
BCB 2,3 Measured on 07th September 2000 (Before Tuning)

Parameter	BCB – 2			BCB - 3	
	Step 1	Step 2	Step 3	Low Fire	High Fire
Combustion Efficiency	84.5	86.1	82.2	85.0	84.8
O_2 Percentage	7.8	0.9	3.4	9.6	5.8
CO_2 Percentage	9.8	15.1	12.9	8.7	11.4
CO ppm	55	9400	60	70	75
NO ppm	62	89	110	156	197
NO_2 ppm	0	0	0	0	0
SO_2 ppm	167	261	200	584	824
Flue Gas Temperature ^0C	207	240	280.0	179	222
Excess Air Percentage	60	5	20	80	36
Smoke No.	0	2	0	0	0

Table 47
BCB 2,3 Measured on 07th September 2000 (After Tuning)

Parameter	BCB – 2			BCB - 3	
	Step 1	Step 2	Step 3	Low Fire	High Fire
Combustion Efficiency	85.0	84.5	82.2	85.8	87.6
O_2 Percentage	6.0	3.1	3.4	7.0	3.6
CO_2 Percentage	11.2	13.3	12.9	10.0	12.8
CO ppm	75	60	60	65	55
NO ppm	200	96	110	162	173
NO_2 ppm	0	0	0	0	0
SO_2 ppm	170	254	200	69	883
Flue Gas Temperature ^0C	214	256	280	185.0	230
Excess Air Percentage	38	17	20	52	20
Smoke No.	0	0	0	0	0

Table 48
Boiler Dimensions

Parameter	BCB 2	BCB 3
Length (feet)	12	12
Diameter (feet)	7.5	7.5

Table 49
Boiler Surface Temperature – ^0C

Parameter	BCB 2	BCB 3
Cylinder Side	55	58
Back Side	170	162
Burner Side	75	82

Table 50
TDS of Water - ppm

Parameter	BCB 2	BCB 3
Feed Water	48	48
Boiler Water	3400	3250

Feed water temperature: 80 ^0C

Organization : LG.

Table 51
Details of Boiler

Parameter	LGB – 1	LGB - 2
Type	Oil fired, fire type, automatic controlled	Oil fired, fire type, automatic controlled
Capacity	6038 lbs/hr	750 lbs/hr
Fuel Consumption	135 ltr/hr	41 ltr/hr

Table 52
Details of Burner

Parameter	LGB – 1	LGB - 2
Type	Modulate Control	Pressure jet atomizing
Blow Motor	3 kW	2 kW
Heater	5 kW	2 kW
Fuel preheating temperature	110 ^0C	110 ^0C
Water pump	5 kW	3 kW

Table 53
LGB 1&2 Measured on 07th September 2000 (Before Tuning)

Parameter	LGB – 1			LGB - 2	
	25%	50%	90%	Low Fire	High Fire
Combustion Efficiency	85.8	84.2	85.7	86.0	78.0
O_2 Percentage	1.1	5.5	1.6	5.1	13.1
CO_2 Percentage	15.0	11.7	14.7	12.0	4.7
CO ppm	1600	70	1450	85	120
NO ppm	133	170	210	165	195
NO_2 ppm	0	0	0	0	0
SO_2 ppm	1118	833	1108	731	849
Flue Gas Temperature ^0C	205	191	200.0	159	200
Excess Air Percentage					
Smoke No.	2	2	2	0	0

Table 54
LGB 1&2 Measured on 07th September 2000 (After Tuning)

Parameter	LGB – 1			LGB - 2	
	25%	50%	90%	Low Fire	High Fire
Combustion Efficiency	82.5	84.4	85	80.2	85.0
O_2 Percentage	8.5	5.4	3.9	3.9	3.0
CO_2 Percentage	9.2	11.7	13.0	10.7	13.8
CO ppm	65	90	110	110	125
NO ppm	170	175	183	220	240
NO_2 ppm	0	0	0	0	0
SO_2 ppm	882	875	990	933	965
Flue Gas Temperature ^0C	177	188	195	202	205
Excess Air Percentage					
Smoke No.	0	0	0	0	0

Table 55
Boiler Dimensions

Parameter	LGB 1	LGB 2
Length (feet)	12	8
Width / Diam (feet)	6	5
Length (feet)	-	5

Table 56
Boiler Surface Temperature – ^0C

Parameter	LGB 1	LGB 2
Cylinder Side	57	51
Back Side	168	182
Burner Side	75	82

Table 57
TDS of Water - ppm

Parameter	LGB 1	LGB 2
Feed Water	48	48
Boiler Water	3300	3400

Feed water temperature: 72 ^0C

Organization : LD.

Table 58
Details of Boiler

Parameter	LDB 1
Type	3-pass, fire tubes, horizontal
Capacity	2800 kg/hr
Fuel Consumption	167 Ltr/hr

Table 59
Details of Burner

Parameter	LDB 1
Type	Compressed air atomizing
Blowe Motor	7.5 kW
Heater	7.5 kW
Fuel preheating temperature	110 ^{0}C
Water pump	3 kW

Table 60
LDB 1 Measured on 17th July 2000 (Before Tuning)

Parameter	Low Fire	High Fire	Middle Fire
Combustion Efficiency	87.0	84.8	-
O_2 Percentage	3.3	2.2	-
CO_2 Percentage	13.4	14.4	-
CO ppm	120	560	
NO ppm	210	240	
NO_2 ppm	0	0	
SO_2 ppm	880	970	
Flue Gas Temperature ^{0}C	157	236	-
Excess Air Percentage	19	11	-
Smoke No.	1	1	-

Table 61
LDB 1 Measured on 17th July 2000 (After Tuning)

Parameter	Trial 1			Trial 2		
	Low Fire	High Fire	Middle Fire	Low Fire	High Fire	Middle Fire
Combustion Efficiency	84.3	83.4	83.0	82.2	83.8	83.2
O_2 Percentage	4.2	3.5	4.0	6.6	3.3	4.3
CO_2 Percentage	12.6	12.3	12.8	10.7	13.3	12.6
CO ppm	90	70	65	60	110	95
NO ppm	210	224	251	214	238	243
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	930	989	881	675	1088	995
Flue Gas Temperature ^{0}C	200	233	229.0	210	226	227
Excess Air Percentage	24	20	22	42	19	25
Smoke No.	0	0	0	0	0	0

Table 62
Boiler Dimensions

Parameter	LDB 1
Length (feet)	15
Diameter (feet)	8

Table 63
Boiler Surface Temperature ^{0}C

Parameter	LDB 1
Cylinder Side	54
Back Side	109
Burner Side	182

Table 64
TDS of Water (ppm)

Parameter	LDB 1
Feed Water	58
Boiler Water	3550

Feed water temperature: 68 ^{0}C

Organization : BN.

Table 65
Details of Boilers

Parameter	BNB 1	BNB 2
Type	Water tube	Water tube
Capacity	10 Ton	10 Ton
Fuel Consumption	396 ltr./ hrs	396 ltr./ hrs

Table 66
Details of Burners

Parameter	BNB 1	BNB 2
Type	Compressed air atomizing	Compressed air atomizing
Blow Motor	11 kW	11 kW
Heater	24 kW	24 kW
Fuel preheating temperature	100 ^{0}C	100 ^{0}C
Water pump	15 kW	15 kW

Table 67
BNB 1 Measured on 28th June 2000

Parameter	Burner positions of full scale				
	0	25%	50%	75%	100%
Combustion Efficiency	84.0	83.2	85.3	85.7	85.8
O_2 Percentage	8.7	9.0	44.7	2.9	3.1
CO_2 Percentage	9.2	9.0	12.2	13.6	13.4
CO ppm	192	185	238	213	221
NO ppm	0	0	0	0	0
NO_2 ppm	192	185	238	213	221
SO_2 ppm	740	704	974	1185	1119
Flue Gas Temperature ^{0}C	208.2	216.8	231.4	239.2	234.8
Excess Air Percentage	72	76	29	16	17
Smoke No.	0	0	0	0	0

Table 68
BNB 2 Measured on 28th June 2000

Parameter	Burner position of full scale				
	0	25%	50%	75%	100%
Combustion Efficiency	80.2	81.3	83.4	83.1	83.0
O_2 Percentage	11.0	9.7	6.3	6.3	6.5
CO_2 Percentage	7.4	8.4	11.0	1.0	10.8
CO ppm	1448	172	198	194	158
NO ppm	0	0	0	0	0
NO_2 ppm	148	172	198	194	158
SO_2 ppm	590	601	704	838	906
Flue Gas Temperature ^0C	227.4	235.5	249.6	253.4	250.8
Excess Air Percentage	113	87	43	43	45
Smoke No.	0	0	0	0	0

Table 69
Boiler Dimensions

Parameter	BNB 1	BNB 2
Length (feet)	20	20
Width (feet)	12	12
Height (feet)	15	15

Table 70
Boiler Surface Temperature ^0C

Parameter	BNB 1	BNB 2
Cylinder Side	65	60
Back Side	88	86
Burner Side	105	108

Table 71
TDS of Water (ppm)

Parameter	BNB 1	BNB 2
Feed Water	25	25
Boiler Water	2800	2750

Feed water temperature: 72 ^0C

Organization : RR.

Table 72
Details of Boiler

Parameter	RRB 1	RRB 2	RRB3
Type	Reverse flame fire tube	3-pass fire tube	3-pass fire tube
Capacity	6000 kg/hr	3000 lb/hr	2000 kg / hr
Fuel Consumption	230 ltr/ hrs	63 ltr / hrs	63 ltr/ hrs

Table 73
Details of Burner

Parameter	RRB 1	RRB 2	RRB3
Type	Modulate automatic control	Pressure jet atomizing	Pressure jet atomizing
Blowe Motor	7.5 kW	3.5 kW	3.5 kW
Heater	10 kW	3.5 kW	3.5 kW
Fuel preheating temperature	110 ^{0}C	110 ^{0}C	110 ^{0}C
Water pump	7.5 kW	3 kW	3 kW

Table 74
RRB 1 Measured on 22nd June 2000 (Before Tuning)

Parameter	Burner Position			
	Low fire	30% from low fire	60% from low fire	High fire
Combustion Efficiency	87.5	81.1	78.5	83.5
O_2 Percentage	5.3	10.3	1.4	4.8
CO_2 Percentage	11.9	8.0	7.2	12.2
CO ppm	90	110	2100	120
NO ppm	181	188	221	263
NO_2 ppm	0	0	0	0
SO_2 ppm	633	618	1125	703
Flue Gas Temperature ^{0}C	135	175	183.0	226
Excess Air Percentage				
Smoke No.	0	0	0	0

Table 75
RRB 1 Measured on 22nd June 2000 (After Tuning)

Parameter	Burner Positions			
	Low fire	30% from low fire	60% from low fire	High fire
Combustion Efficiency	87.4	87.3	86.3	84.5
O_2 Percentage	4.1	2.4	3.1	3.8
CO_2 Percentage	12.9	14.0	13.5	12.9
CO ppm	100	660	250	180
NO ppm	187	164	210	243
NO_2 ppm	0	0	0	0
SO_2 ppm	813	979	893	831
Flue Gas Temperature ^{0}C	137	154	170.0	212
Excess Air Percentage				
Smoke No.	0	0	0	0

Table 76
RRB 2 Measured on 22nd June 2000

Parameter	Before Tuning		After Tuning	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	88.0	86.6	87.6	85.5
O_2 Percentage	1.2	1.5	3.2	2.0
CO_2 Percentage	14.8	14.7	13.4	14.3
CO ppm	2800	2600	280	990
NO ppm	181	208	193	241
NO_2 ppm	0	0	0	0
SO_2 ppm	1210	1180	892	1019
Flue Gas Temperature ^{0}C	160	179	140	200
Excess Air Percentage				
Smoke No.	2	2	0	0

Table 77
RRB 3 Measured on 22nd June 2000

Parameter	Low Fire	High Fire
Combustion Efficiency	79.5	80.7
O_2 Percentage	12.0	11.0
CO_2 Percentage	6.7	7.1
CO ppm	120	135
NO ppm	133	188
NO_2 ppm	0	0
SO_2 ppm	651	582
Flue Gas Temperature ^{0}C	175	180
Excess Air Percentage		
Smoke No.	0	0

Table 78
Boiler Dimensions

Parameter	RRB 1	RRB 2	RRB3
Length (feet)	20	7.5	7.5
Diameter (feet)	12	12	12

Table 79
Boiler Surface Temperature ^{0}C

Parameter	RRB 1	RRB 2	RRB3
Cylinder Side	48	51	53
Back Side	133	143	151
Burner Side	98	88	110

Table 80
TDS of Water (ppm)

Parameter	RRB 1	RRB 2	RRB3
Feed Water	55	55	55
Boiler Water	3350	3400	3510

Feed water temperature: 73 ^{0}C

Organization : RD.

Table 81
Details of Boiler

Parameter	RDB 1	RDB 2	RDB 3
Type	Fire tube	Fire tube	Fire tube
Capacity	5000 lb/hr	6000 lb/hr	2000 kg/hr
Fuel Consumption	117 ltr/hrs	125 ltr/ hrs	113 ltr/ hrs

Table 82
Details of Burner

Parameter	RDB 1	RDB 2	RDB 3
Type	Pressure jet atomizing	Pressure jet atomizing	Pressure jet atomizing
Blowe Motor	3 kW	3 kW	3 kW
Heater	4.5 kW	4.5 kW	4.5 kW
Fuel preheating temperature	110 ^{0}C	110 ^{0}C	110 ^{0}C
Water pump	3 kW	3 kW	3 kW

Table 83
RdB 1,2&3 Measured on 27th April 2000 (Before Tuning)

Parameter	RDB 1		RDB 2	RDB 3	
	Low Fire	High Fire		Low Fire	High Fire
Combustion Efficiency	86.6	87.4	81.4	83.8	86.5
O_2 Percentage	6.6	3.1	8.5	7.2	3.8
CO_2 Percentage	10.7	13.6	9.5	10.3	12.9
CO ppm	110	80	95	120	140
NO ppm	167	182	249	193	211
NO_2 ppm	0	0	0	0	0
SO_2 ppm	665	890	538	568	792
Flue Gas Temperature ^{0}C	154	174	215	170	180
Excess Air Percentage					
Smoke No.	-	-	0	-	-

Table 84
RdB 1,2&3 Measured on 27th April 2000 (After Tuning)

Parameter	RDB 1		RDB 2	RDB 3	
	Low Fire	High Fire		Low Fire	High Fire
Combustion Efficiency	87.8	87.5	88.7	86.8	86.5
O_2 Percentage	4.4	3.0	3.8	5.2	3.8
CO_2 Percentage	12.6	13.6	12.9	11.9	12.9
CO ppm	160	90	120	110	70
NO ppm	188	193	221	193	231
NO_2 ppm	0	0	0	0	0
SO_2 ppm	814	935	883	671	729
Flue Gas Temperature ^{0}C	156	170	199	160	180
Excess Air Percentage					
Smoke No.	0	0	0	0	0

Table 85
Boiler Dimensions

Parameter	RDB 1	RDB 2	RDB 3
Length (feet)	14	7.5	6.5
Diameter (feet)	6	15	14

Table 86
Boiler Surface Temperature ^0C

Parameter	RDB 1	RDB 2	RDB 3
Cylinder Side	48	48	53
Back Side	134	142	138
Burner Side	70	82	84

Table 87
TDS of Water (ppm)

Parameter	RDB 1	RDB 2	RDB 3
Feed Water	44	44	60
Boiler Water	3450	3000	3300

Feed water temperature: 76 ^0C

Organization : TA.

Table 88
Details of Boiler

Parameter	TAB 1
Type	Fire tube reverse flame
Capacity	1600 lb/hr
Fuel Consumption	46 ltr/ hrs

Table 89
Details of Burner

Parameter	TAB 1
Type	Pressure jet atomizing
Blow Motor	2.8 kW
Heater	3.0 kW
Fuel preheating temperature	110 0C
Water pump	3 kW

Table 90
TAB 01 Measured on 3rd April 2000 (Before Tuning)

Parameter	TAB 1	
	Low Fire	High Fire
Combustion Efficiency	80.9	78.3
O_2 Percentage	10.4	9.3
CO_2 Percentage	7.9	8.7
CO ppm	160	130
NO ppm	190	231
NO_2 ppm	0	0
SO_2 ppm	503	571
Flue Gas Temperature ^0C	176	218
Excess Air Percentage		
Smoke No.	0	0

Table 91
TAB 01 Measured on 3rd April 2000 (After Tuning)

Parameter	TAB 1	
	Low Fire	High Fire
Combustion Efficiency	84.2	84.3
O_2 Percentage	6.4	5.4
CO_2 Percentage	10.4	11.7
CO ppm	80	90
NO ppm	179	218
NO_2 ppm	0	0
SO_2 ppm	673	708
Flue Gas Temperature ^0C	148	187
Excess Air Percentage		
Smoke No.	0	0

Table 92
Boiler Dimensions

Parameter	Dimension
Length (feet)	8
Width (feet)	5
Height (feet)	5

Table 93
Boiler Surface Temperature ^0C

Parameter	Measurements
Cylinder Side	63
Back Side	145
Burner Side	98

Table 94
TDS of Water (ppm)

Parameter	Mech Mar Boiler
Feed Water	66
Boiler Water	3370

Feed water temperature: 72 ^0C

Organization : FW.

Table 95
Details of Boilers

Parameter	FWB 1
Type	Horizontal fire tube
Capacity	3000 kg/H @15.75 kg/cm^2
Fuel Consumption	184 ltr / hrs

Table 96
Details of Burner

Parameter	FWB 1
Type	Pressure jet atomizing
Blow Motor	5.5 kW
Heater	7.5 kW
Fuel preheating temperature	100 ^0C
Water pump	4.5 kW

Table 97
FWB 1 Measured on 10th February 2000

Parameter	Trial 1	Trial 2	Trial 3
Combustion Efficiency	89.7	89.7	89.6
O_2 Percentage	10.2	10.0	9.9
CO_2 Percentage	8.1	8.2	8.3
CO ppm	0.004	0.001	0.002
NO ppm	143	145	145
NO_2 ppm	0	0	0
SO_2 ppm	591	657	6644
Flue Gas Temperature ^0C	190.5	192.8	194.8
Excess Air Percentage			
Smoke No.	0	0	0

Table 98
Boiler Dimensions

Parameter	Dimension
Length (feet)	14
Diameter (feet)	7.5

Table 99
Boiler Surface Temperature ^0C

Parameter	Temperature
Cylinder Side	63
Back Side	138
Burner Side	89

Table 100
TDS of Water (ppm)

Parameter	TDS
Feed Water	64
Boiler Water	2900

Feed water temperature: 68 ^0C

Organization : RL.

Table 101
Details of Boilers

Parameter	RLB 1	RLB 2
Type	Fire tube, 3-pass	Fire tube, two pass
Capacity	20000 lbs/hr	8000 lbs/hr
Fuel Consumption	300 ltr/hrs	129 ltr/hrs

Table 102
Details of Burner

Parameter	RLB 1	RLB 2
Type	Pressure jet atomizing	Pressure jet atomizing
Blowe Motor	7.5 kW	4 kW
Heater	12 kW	6 kW
Fuel preheating temperature	110 ^0C	110 ^0C
Water pump	11 kW	4.5 kW

Table 103
RLB 1&2 Measured on 12th February 2000

Parameter	RLB 1		RLB 2	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	<50	84.1	<50	68.0
O_2 Percentage	19.4	4.1	19.0	14.0
CO_2 Percentage	0.2	12.9	0.2	6.1
CO ppm	-	160	-	360
NO ppm	-	276	-	283
NO_2 ppm	-	0	-	0
SO_2 ppm	-	916	-	416
Flue Gas Temperature ^0C	165	213	160	243
Excess Air Percentage			-	
Smoke No.	0	0	0	0

Table 104
Boiler Dimensions

Parameter	RLB 1	RLB 2
Length (feet)	20	10
Diameter (feet)	10	6.5

Table 105
Boiler Surface Temperature ^0C

Parameter	RLB 1	RLB 2
Cylinder Side	62	58
Back Side	152	138
Burner Side	92	98

Table 106
TDS of Water (ppm)

Parameter	RLB 1	RLB 2
Feed Water	52	52
Boiler Water	3360	3400

Feed water temperature: 75 ^0C

Organization : **FC.**

Table 107
Details of Boilers

Parameter	FCB 1	FCB 2
Type	3-pass reverse flame, wet back	3-pass reverse flame, wet back
Capacity	5802 kg/hr	5448 kg/hr
Fuel Consumption	312 Ltr/hr	237 Ltr/hr

Table 108
Details of Burner

Parameter	FCB 1	FCB 2
Type	Rotary cup automatic	Pressure jet atomizing
Blow Motor	7.5 kW	7.5 kW
Heater	12 kW	12 kW
Fuel preheating temperature	80 ^0C	80 ^0C
Water Pump	8.5 kW	8.5 kW

Table 109
FCB 1 Measured on November 1999

Parameter	Low flame	25% from low flame	50% from low flame	75% from low flame	High flame
Combustion Efficiency	87.2	87.2	84.2	83.5	83.5
O_2 Percentage	2.1	2.4	6.7	6.0	5.8
CO_2 Percentage	14.2	13.9	10.7	11.2	11..5
CO ppm	100	100	75	80	90
NO ppm	227	231	214	220	220
NO_2 ppm	0	0	0	0	0
SO_2 ppm	870	868	675	700	721
Flue Gas Temperature ^0C	239	238	256	270	282
Excess Air Percentage	10	13	44	38	36
Smoke No.	0	0	0	0	0

Table 110
FCB 2 Measured on November 1999 (Before Tuning)

Parameter	Low flame	20% from low flame	40% from low flame	60% from low flame	High flame
Combustion Efficiency	79..5	80.0	81.0	82.8	85.2
O_2 Percentage	12.8	12.4	11.5	9.1	5.8
CO_2 Percentage	6.2	6.3	7.1	8.8	11.4
CO ppm	2100	1800	200	100	100
NO ppm	111	114	138	193	254
NO_2 ppm	0	0	0	0	0
SO_2 ppm	400	413	470	585	767
Flue Gas Temperature ^0C	233	234	237	246	248
Excess Air Percentage	156	142	116	72	36
Smoke No.	0	0	0	0	0

Table 111
FCB 2 Measured on November 1999 (After Tuning)

Parameter	Low flame	20% from low flame	40% from low flame	60% from low flame	High flame
Combustion Efficiency	83.7	83.5	83.4	82.8	85.2
O_2 Percentage	6.0	6.4	6.6	6.8	5.8
CO_2 Percentage	11.3	10.9	10.6	10.4	11.4
CO ppm	90	85	90	75	90
NO ppm	224	228	232	240	254
NO_2 ppm	0	0	0	0	0
SO_2 ppm	660	689	680	585	767
Flue Gas Temperature ^0C	235	238	240	246	248
Excess Air Percentage	38	41	44	46	36
Smoke No.	0	0	0	0	0

Table 112
Boiler Dimensions

Parameter	FCB 1	FCB 2
Length (feet)	18	18
Diameter (feet)	8	8

Table 113
Boiler Surface Temperature ^{0}C

Parameter	FCB 1	FCB 2
Cylinder Side	52	57
Back Side	144	153
Burner Side	98	88

Table 114
TDS of Water (ppm)

Parameter	FCB 1	FCB 2
Feed Water	53	53
Boiler Water	3300	3500

Feed water temperature: 72 ^{0}C

Organization : TL.

Table 115
Details of Boilers

Parameter	Description
Type	3-pass, fire tube
Capacity	2000 kg/hr
Fuel Consumption	110 ltr/ hrs

Table 116
Details of Burner

Parameter	Description
Type	Pressure jet atomizing
Blow Motor	3.5 kW
Heater	4.0 kW
Fuel preheating temperature	110 ^{0}C
Water pump	3 kW

Table 117
TLB 1 Measured on 21st April 1999

Parameter	Trial 1		Trial 2		Trial 3	
	High Fire	Low Fire	High Fire	Low Fire	High Fire	Low Fire
Combustion Efficiency	86.6	85.5	86.4	85.7	86.2	85.1
O_2 Percentage	3.4	7.8	3.2	7.5	3.3	8.5
CO_2 Percentage	13.2	9.7	13.2	9.9	13.2	9.1
CO ppm	280.0	153.0	599.0	690.0	657.0	635.0
NO ppm	214	193	221	182	231	201
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	1120	578	1073	634	982	524
Flue Gas Temperature ^{0}C	204	178	208	178	210	177
Excess Air Percentage						
Smoke No.	0	0	0	0	0	0

Table 118
Boiler Dimensions

Parameter	Measurement
Length (feet)	10
Width (feet)	6
Height (feet)	6

Table 119
Boiler Surface Temperature

Parameter	Measurement
Body Side	70
Back Side	163
Burner Side	118

Table 120
TDS of Water (ppm)

Parameter	Measurement
Feed Water	60
Boiler Water	2900

Feed water temperature: 75 ^{0}C

Organization : TK.

Table 121
Details of Boilers

Parameter	TKB 1	TKB 2
Type	Reverse flame single pass	Reverse flame single pass
Capacity	10 tons/hr	10 tons/hr
Fuel Consumption	275 ltr/ hrs	275 ltr/ hrs

Table 122
Details of Burner

Parameter	TKB 1	TKB 2
Type	Pressure jet atomizing	Pressure jet atomizing
Blowe Motor	11 kW	11 kW
Heater	12 kW	12 kW
Fuel preheating temperature	100 ^{0}C	100 ^{0}C
Water pump	7.5 kW	7.5 kW

Table 123
TKB 1&2 Measured on 23rd May 2000

Parameter	TKB 1		TKB 2	
	High	Low	High	Low
Combustion Efficiency	81.5	83.5	86.3	85.8
O_2 Percentage	3.5	3.6	2.4	4.3
CO_2 Percentage	13.1	13.1	14.1	12.6
CO ppm	120	135	960	70
NO ppm	283	278	211	193
NO_2 ppm	0	0	0	0
SO_2 ppm	968	983	1018	892
Flue Gas Temperature ^{0}C	275	227	182	174
Excess Air Percentage				
Smoke No.	2	2	0	0

Table 124
Boiler Dimensions

Parameter	TKB 1	TKB 2
Length (feet)	18	18
Diameter (feet)	10	10

Table 125
Boiler Surface Temperature ^0C

Parameter	TKB 1	TKB 2
Cylinder Side	75	68
Back Side	183	210
Burner Side	115	123

Table 126
TDS of Water (ppm)

Parameter	TKB 1	TKB 2
Feed Water	56	56
Boiler Water	3500	3400

Feed water temperature: 80 ^0C

Organization : TN.

Table 127
Details of Boiler

Parameter	TNB 1	TNB 2
Type	3 Pass fire tube	3 Pass fire tube
Capacity	1250 kg/hr	1600 kg/hr
Fuel Consumption	75 Ltr/hr	100 Ltr/hr

Table 128
Details of Burner

Parameter	TNB 1	TNB 2
Type	Pressure jet atomizing	Pressure jet atomizing
Blow Motor	3.5 kW	4.0 kW
Heater	4.5 kW	4.5 kW
Fuel preheating temperature	100 ^0C	100 ^0C
Pump motor	4.5 kW	4.5 kW

Table 129
TNB 1&2 Measured on 24th May 2000 (Before tuning)

Parameter	TNB 1		TNB 2	
	High	Low	High	Low
Combustion Efficiency	78.1	82.6	78.4	78.6
O_2 Percentage	7.6	5.1	7.5	10.9
CO_2 Percentage	10.0	12.2	10.1	7.6
CO ppm	140	230	400	300
NO ppm	381	298	361	283
NO_2 ppm	0	0	0	0
SO_2 ppm	831	743	635	583
Flue Gas Temperature ^0C	340	248	323	250
Excess Air Percentage				
Smoke No.	0	0	0	0

Table 130
TNB 1&2 Measured on 24th May 2000 (After tuning)

Parameter	TNB 1		TNB 2	
	High	Low	High	Low
Combustion Efficiency	80.2	85.2	80.1	82.4
O_2 Percentage	4.4	3.0	6.5	7.0
CO_2 Percentage	12.5	13.4	11.4	10.8
CO ppm	180	130	360	500
NO ppm	310	280	420	198
NO_2 ppm	0	0	0	0
SO_2 ppm	820	930	570	592
Flue Gas Temperature ^{0}C	344	248	318	230
Excess Air Percentage				
Smoke No.	0	0	0	0

Table 131
Boiler Dimensions

Parameter	TNB 1	TNB 2
Length (Feet)	15	17
Diameter (Feet)	6	6

Table 132
Boiler Surface Temperature

Parameter	TNB 1	TNB 2
Cylinder Side	98	110
Back Side	183	195
Burner Side	68	63

Table 133
TDS of Water (ppm)

Parameter	TNB 1	TNB 2
Feed Water	63	63
Boiler Water	2800	3000

Feed water temperature: 78 ^{0}C

Organization : CS.

Table 134
Details of Boilers

Parameter	CSB 1	CSB 2	CSB 3
Type	Horizontal, fire tube	Horizontal fire tube	Horizontal fire tube
Capacity	6000 kg/hr	5000 pph	2000 kg/hr
Fuel Consumption	165 Ltr/hr	115 Ltr/hr	115 Ltr/hr

Table 135
Details of Burner

Parameter	CSB 1	CSB 2	CSB 3
Type	Pressure jet atomize Modulating control	Pressure jet atomizing high low	Pressure jet atomizing high low
Blowe Motor	15 kW	4 kW	4.5 kW
Heater	12 kW	8 kW	13.2 kW
Fuel preheating temperature	110 ^{0}C	110 ^{0}C	110 ^{0}C
Water pump	5 kW	3 kW	3 kW

Table 136
CSB 1&2 Measured on 9th August 2000

Parameter	CSB 1			CSB 2	
	Low Fire	Middle Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	79.7	79.6	83.4	81.1	81.0
O_2 Percentage	10.1	10.0	6.9	6.2	4.1
CO_2 Percentage	8.2	8.1	10.6	11.1	12.8
CO ppm	170	160	210	180	90
NO ppm	218	231	223	272	310
NO_2 ppm	0	0	0	0	0
SO_2 ppm	568	633	594	631	879
Flue Gas Temperature ^0C	203	206	198.0	250	298
Excess Air Percentage	87	87	47	40	22
Smoke No.	0	1	2	0	1

Table 137
CSB 1 Measured on 20th February 2000

Parameter	Low flame	25% from low flame	50% from low flame	75% from low flame	High flame
Combustion Efficiency	83.0	82.0	83.0	82.0	82.9
O_2 Percentage	8.2	10	6.1	6.5	4.3
CO_2 Percentage	9.6	8.2	11.0	10.8	12.7
CO ppm	360	280	119	230	189
NO ppm	386	287	420	368	398
NO_2 ppm	0	0	0	0	0
SO_2 ppm	710	624	738	922	1072
Flue Gas Temperature ^0C	215	216	236	250	268
Excess Air Percentage					
Smoke No.	0	0	0	0	0

Table 138
CSB 2&3 Measured on 20th February 2000

Parameter	CSB 3		CSB 2	
	Low Fire	High Fire	Low Fire	High Fire
Combustion Efficiency	84.5	77.2	70.3	75.8
O_2 Percentage	4.3	11.3	11.7	5.7
CO_2 Percentage	12.6	7.2	6.8	11.5
CO ppm	270	560	420	258
NO ppm	178	218	288	335
NO_2 ppm	0	0	0	0
SO_2 ppm	978	635	583	729
Flue Gas Temperature ^0C	219	230	308	376
Excess Air Percentage				
Smoke No.	0	0	0	0

Table 139
Boiler Dimensions

Parameter	CSB 1	CSB 2	CSB 3
Length (feet)	12	8.5	5.8
Diameter or Width (feet)	9	5.5	10.5
Height (feet)	-	5	-

Table 140
Boiler Surface Temperature

Parameter	CSB 1	CSB 2	CSB 3
Cylinder Side	60	55	55
Back Side	180	108	140
Burner Side	75	180	125

Table 141
TDS of Water (ppm)

Parameter	CSB 1	CSB 2	CSB 3
Feed Water	610	610	610
Boiler Water	6300	5800	7680

Feed water temperature: 60 ^{0}C

Organization : TH.

Table 142
Details of Boilers

Parameter	THB 1	THB 2	THB 3
Type	Horizontal, 3-pass fire tube	Horizontal fire tube	Horizontal fire tube
Capacity	12000 lb/hr	12000 lb/hr	12000 lb/hr
Fuel Consumption	285 Ltr/hr	275 Ltr.hr	295 Ltr/hr

Table 143
Details of Burner

Parameter	THB 1	THB 2	THB 3
Type	Pressure jet atomize Modulating control	Pressure jet atomize Modulating control	Pressure jet atomize Modulating control
Blowe Motor	5.5 kW	5.5 kW	5.5 kW
Heater	10 kW	10 kW	10 kW
Fuel preheating temperature	110 ^{0}C	110 ^{0}C	110 ^{0}C
Water pump	7.5 kW	7.5 kW	7.5 kW

Table 144
TNB 1 Measured on 16th February 2001 (Before tuning)

Parameter	Burner Position of full scale				
	Low	25%	50%	75%	High
O_2%	8.4	9.3	8.8	8.1	7.2
CO_2 %	9.4	8.8	9.1	9.6	10.3
CO PPm	40	20	20	20	20
NO PPm	161	166	196	211	226
NO_2 PPm	0	0	0	0	0
SO_2 PPm	974	901	942	1010	1066
Flue Temp ^{0}C	213	223	238	248	252
Excess Air %	67	80	74	64	53
Smoke No.	0	0	0	0	0
Efficiency %	84.2	82.7	82.2	82.2	82.6

Table 145
TNB 1 Measured on 16th February 2001 (After tuning)

Parameter	Burner Position of full scale				
	Low	25%	50%	75%	High
O_2 Percentage	5.1	4.5	4.6	4.5	4.6
CO_2 Percentage	11.9	12.4	12.3	12.3	12.3
CO PPm	80	170	120	50	60
NO PPm	141	216	214	163	225
NO_2 PPm	0	0	0	0	0
SO_2 PPm	921	849	859	957	975
Flue Temp. ^oC	197	207	211	210	212
Excess Air %	32	27	28	27	28
Smoke No.	0	0	0	0	0
Efficiency %	87.0	86.5	86.3	86.5	86.2

Table 146
TNB 2 Measured on 16th February 2001 (Before tuning)

Parameter	Burner Position of full scale				
	Low	25%	50%	75%	High
O_2 Percentage	7.4	8.2	8.0	8.5	8.0
CO_2 Percentage	10.1	9.6	9.7	9.4	9.7
CO PPm	40	30	40	40	40
NO PPm	175	174	177	182	187
NO_2 PPm	0	0	0	0	0
SO_2 PPm	1042	957	968	931	948
Flue Temp. ^oC	213	214	216	224	225
Excess Air %	55	64	63	68	63
Smoke No.	0	0	0	0	0
Efficiency %	84.5	83.9	83.9	83.1	83.4

Table 147
TNB 2 Measured on 16th February 2001 (After tuning)

Parameter	Burner Position of full scale				
	Low	25%	50%	75%	High
O_2 Percentage	9.0	9.3	7.2	1.0	2.2
CO_2 Percentage	9.0	8.7	10.3	15.0	14.1
CO PPm	150	200	100	9300	150
NO PPm	148	158	213	202	235
NO_2 PPm	0	0	0	0	0
SO_2 PPm	235	518	784	855	861
Flue Temp. ^oC	199.5	211.6	232.3	236.1	243.1
Excess Air %	75	81	53	5	11
Smoke No.	0	0	0	01	0
Efficiency %	84.2	83.2	83.6	86.5	85.8

Table 148
TNB 3 Measured on 16th February 2001

Parameter	Burner Position of full scale				
	Low	25%	50%	75%	High
O_2 Percentage	5.2	5.3	4.3	2.1	2.3
CO_2 Percentage	11.8	11.8	12.5	14.2	14.0
CO PPm	40	20	20	30	50
NO PPm	174	200	235	248	253
NO_2 PPm	0	0	0	0	0
SO_2 PPm	776	823	907	1037	902
Flue Temp. ^0C	216.5	226.9	245.8	259.4	256.0
Excess Air %	33	33	26	11	12
Smoke No.	0	0	0	0	0
Efficiency %	85.7	85.2	84.8	85.2	85.2

Table 149
Boiler Dimensions

Parameter	THB 1	THB 2	THB 3
Length (feet)	14	14	14
Diameter (feet)	7	7	7

Table 150
Boiler Surface Temperature ^0C

Parameter	THB 1	THB 2	THB 3
Cylinder Side	48	45	46
Back Side	108	110	106
Burner Side	104	112	109

Table 151
TDS of Water (ppm)

Parameter	THB 1	THB 2	THB 3
Feed Water	65	65	65
Boiler Water	4200	3750	3800

Feed water temperature: 72 ^0C

Organization : TS.

Table 152
Details of Boiler

Parameter	TSB 1	TSB 2	TSB 3
Type	Fire Tube	Fire Tube	Fire Tube
Capacity	1120 kg/hr	1120 kg/hr	2000 kg/hr
Fuel Consumption	68 Ltr/hr	68 Ltr/hr	105 Ltr/hr

Table 153
Details of Burner

Parameter	TSB 1	TSB 2	TSB 3
Type	Pressure Jet Atomizing	Pressure Jet Atomizing	Pressure Jet Atomizing
Blow Motor	3 kW	3 kW	5 kW
Heater	4.5 kW	4.5 kW	6 kW
Fuel preheating temperature	100 ^0C	100 ^0C	100 ^0C
Water Pump	3 kW	3 kW	4 kW

Table 154
TSB 1,2&3 Measured on 25th July 2000

Parameter	TSB 1		TSB 2		TSB 3	
	High Fire	Low Fire	High Fire	Low Fire	High Fire	Low Fire
Combustion Efficiency	79.2	80.9	84.8	87.1	82.4	84.1
O_2 Percentage	11.2	11.7	7.2	10.3	4.2	8.3
CO_2 Percentage	7.2	6.8	10.1	7.8	12.3	9.3
CO ppm	140	120	182	119	262	169
NO ppm	140	120	182	119	262	169
NO_2 ppm	0	0	0	0	0	0
SO_2 ppm	529	495	906	666	1032	734
Flue Gas Temperature ^{0}C	237.1	206.2	211.5	139.4	298.7	210.7
Excess Air Percentage	116	128	53	98	25	66
Smoke No.	0	0	0	0	0	0

Table 155
Boiler Dimensions

Parameter	TSB 1	TSB 2	TSB 3
Length (Feet)	14	14	18
Diameter (Feet)	7.5	7.5	8.0

Table 156
Boiler Surface Temperature ^{0}C

Parameter	TSB 1	TSB 2	TSB 3
Cylinder Side	58	55	54
Back Side	138	151	163
Burner Side	122	109	118

Table 157
TDS of Water (ppm)

Parameter	TSB 1	TSB 2	TSB 3
Feed Water	56	56	56
Boiler Water	3300	3000	3600

Feed water temperature: 73 ^{0}C

Organization : PN.

Table 158
Details of Boiler

Parameter	Description
Type	4-pass, fire tube
Capacity	4000 kg/hr
Fuel Consumption	240 Ltr/hr

Table 159
Details of Burner

Parameter	Description
Type	Pressure Jet Atomizing
Blow Motor	3 kW
Heater	5 kW
Fuel preheating temperature	100 ^{0}C
Water pump	5 kW

Table 160
PNB 1 Measured on 11th July 2000

Parameter	High Fire	Low Fire
Combustion Efficiency	83.0	80.9
O_2 Percentage	7.5	10.8
CO_2 Percentage	10.1	7.9
CO ppm	160	120
NO ppm	220	192
NO_2 ppm	0	0
SO_2 ppm	682	634
Flue Gas Temperature ^0C	214	189
Excess Air Percentage	52	100
Smoke No.	1	1

Table 161
Boiler Dimensions

Parameter	Boiler
Length (feet)	15
Diameter (feet)	8

Table 162
Boiler Surface Temperature – ^0C

Parameter	Boiler
Cylinder Side	48
Back Side	140
Burner Side	105

Table 163
TDS of Water - ppm

Parameter	Boiler
Feed Water	65
Boiler Water	3400

Feed water temperature: 80 ^0C

Description of boiler identification number

Symbol	Identification
First two character	Organization
Third character and first digit	Organizational serial number of the boiler

APPENDIX B
RESULTS

Table 01

No.	Boiler Identification Number	Exergytic Efficiency (%)	Flue gas Temperature (^{0}C)	Steam Output (kg / hr)	Excess air (%)	CO_2 Emission (kg/ kg of steam)	Energy Efficiency (%)
1	CUB10797	26.77	278	3792	24.40	0.215	82.15
2	CUB20797	27.14	254	3845	23.60	0.212	83.30
3	CUB30797	26.84	253	3803	34.80	0.215	82.40
4	CUB10698	27.34	232	3874	27.60	0.211	83.95
5	CUB20698	25.61	251	3628	78.00	0.225	78.60
6	CUB30698	26.39	289	3738	29.20	0.219	81.00
7	CUB40698	26.55	277	3761	17.50	0.217	81.49
8	CUB30799	27.13	242	3844	29.20	0.212	83.30
9	CUB40799	26.45	238	3747	34.00	0.218	81.19
10	CUB2B/T0799	25.42	184	3600	156.00	0.226	78.00
11	CUB2A/T0799	27.23	188	3858	47.00	0.212	83.60
12	CUB1B/T1099	22.58	193	3196	194.00	0.253	69.25
13	CUB3B/T1099	28.37	199	4020	4.50	0.201	87.10
14	CUB4B/T1099	26.08	220	3678	87.00	0.222	79.69
15	CUB1A/T1099	27.19	223	3851	33.20	0.212	83.45
16	CUB3A/T1099	27.43	210	3886	7.00	0.210	84.20
17	CUB4A/T1099	27.79	225	3921	33.20	0.208	84.95
18	CUB1B/T10299	25.68	290	3639	34.80	0.225	78.85
19	CUB2B/T10299	26.88	254	3808	34.80	0.215	82.50
20	CUB4B/T10299	25.74	274	3632	59.40	0.225	78.69
21	CUB1A/T10299	26.50	280	3754	26.80	0.218	81.35
22	CUB2A/T10299	27.20	246	3854	23.60	0.212	83.50
23	CUB4A/T10299	27.02	266	3812	30.80	0.214	82.59
24	CUB1B/T0800	25.66	269	3634	56.90	0.225	78.75
25	CUB2B/T0800	25.66	247	3840	24.40	0.225	83.20
26	CUB4B/T0800	25.42	226	3600	156.00	0.221	77.99
27	CUB1A/T0800	26.79	268	3796	28.40	0.215	82.25
28	CUB4A/T0800	27.64	210	3900	26.00	0.209	84.49
29	CUB1B/T0101	24.56	292	3477	97.80	0.234	75.35
30	CUB3B/T0101	27.59	229	3909	13.00	0.209	84.70
31	CUB4B/T0101	25.85	223	3646	118.80	0.223	78.99
32	CUB1A/T0101	26.31	310	3727	22.80	0.219	80.75
33	CUB4A/T0101	26.37	228	3720	27.60	0.220	80.59
34	CUB1B/T0501	26.18	261	3708	55.80	0.220	80.35
35	CUB3B/T0501	26.62	289	3771	20.00	0.217	81.70
36	CUB4B/T0501	26.73	301	3816	9.00	0.212	82.69
37	CUB1A/T0501	26.63	265	3773	17.50	0.216	81.75
38	CUB4A/T0501	26.34	349	3715	27.60	0.219	80.49
39	BLB1B/T1100	28.85	208	3787	23.60	0.199	85.00
40	BLB1A/T1100	28.89	213	3792	25.20	0.199	85.10
41	BLB1B/T0401	27.85	255	3654	30.80	0.206	82.00
42	BLB1A/T0401	28.32	249	3716	22.80	0.203	83.40
43	FNB1B/T1100	28.21	187	1535	35.50	0.205	85.48
44	FNB1A/T1100	28.46	188	1549	30.00	0.203	86.28
45	TBB10900	27.24	248	3243	21.00	0.213	83.43
46	BCB1B/T0900	28.22	240	1350	4.50	0.193	84.98
47	BCB2B/T0900	27.91	180	1668	81.00	0.207	83.98
48	BCB1A/T0900	27.68	256	1324	10.70	0.209	83.38
49	BCB2A/T0900	28.16	185	1683	47.00	0.205	84.78
50	LGB1B/T0900	27.83	200	1960	8.00	0.206	84.84
51	LGB2B/T0900	25.14	200	536	159.80	0.229	76.87
52	LGB1A/T0900	27.57	195	1942	16.30	0.210	84.14
53	LGB2A/T0900	27.78	205	585	17.00	0.208	83.87

Table 01 (Contd.)

No.	Boiler Identification Number	Exergytic Efficiency (%)	Flue gas Temperature (^0C)	Steam Output (kg / hr)	Excess air (%)	CO_2 Emission (kg/ kg of steam)	Energy Efficiency (%)
54	LDB1B/T0700	27.28	236	2371	11.40	0.211	83.52
55	LBD1A/T0700	26.82	233	2331	19.50	0.216	82.12
56	BNB10600	27.86	231	5759	27.60	0.207	84.25
57	BNB20600	27.24	250	5629	49.70	0.212	82.35
58	RRB1B/T0600	25.22	183	3013	114.20	0.229	77.13
59	RRB1A/T0600	27.78	170	3318	17.50	0.208	84.93
60	RRB2B/T0600	27.75	180	906	7.50	0.205	85.02
61	RRB2A/T0600	27.42	200	895	10.00	0.197	83.92
62	RRB3A/T0600	25.80	180	842	105.00	0.224	78.97
63	RDB1B/T0400	28.26	154	1717	43.40	0.205	85.83
64	RDB1A/T0400	28.65	156	1741	25.20	0.202	87.03
65	RDB2B/T0400	26.50	215	1726	65.00	0.218	80.53
66	RDB2A/T0400	28.90	200	1883	21.00	0.200	87.83
67	RDB3B/T0400	27.25	170	1598	49.20	0.212	82.84
68	RDB3A/T0400	28.23	160	1656	31.60	0.205	85.84
69	TAB1B/T0400	25.02	218	600	76.50	0.230	76.88
70	TAB1A/T0400	26.93	187	646	33.20	0.214	82.88
71	FWB1B/T0200	26.01	193	2482	87.00	0.223	80.03
72	RLB10200	28.75	213	4258	22.80	0.212	82.90
73	RLB20200	21.95	243	1477	194.00	0.262	66.88
74	FCB11199	27.01	270	4391	38.00	0.215	82.49
75	FCB2B/T1199	26.17	237	3949	116.50	0.221	79.94
76	FCB2A/T1199	26.95	240	4068	43.40	0.215	82.34
77	TLB10499	28.89	204	1611	19.00	0.200	85.25
78	TKB10500	26.55	275	3808	19.50	0.218	80.08
79	TKB20500	28.10	182	4031	12.80	0.205	84.87
80	TNB1B/T0500	25.02	340	978	44.60	0.231	75.80
81	TNB1A/T0500	25.71	344	1005	25.40	0.224	77.90
82	TNB2B/T0500	25.25	323	1287	52.50	0.229	76.34
83	TNB2A/T0500	25.81	318	1316	42.50	0.224	78.04
84	CSB10800	17.12	236	2159	87.00	0.337	78.37
85	CSB20800	25.73	298	1540	22.80	0.225	80.18
86	CSB10201	26.36	236	2253	38.90	0.221	81.77
87	CSB20201	23.78	376	1437	35.60	0.241	74.88
88	CSB30201	24.39	230	1463	49.20	0.235	76.24
89	THB1B/T0201	26.15	238	3876	24.40	0.222	81.47
90	THB1A/T0201	27.46	211	4071	109.60	0.211	85.57
91	THB20201	26.69	216	3818	49.20	0.217	83.17
92	THB3B/T0201	26.61	232	4082	111.90	0.218	82.88
93	THB3A/T0201	27.00	246	4141	69.20	0.215	84.08
94	TSB10500	25.31	237	897	26.80	0.228	77.44
95	TSB20500	27.14	212	962	58.00	0.213	83.09
96	TSB30500	26.32	299	1431	23.60	0.219	80.82
97	PNB10500	24.58	189	3072	101.40	0.235	80.63

Table 02

No.	Boiler Identification Number	Cost of Steam at Different Fuel Prices - Exergy Based (Rs./MJ)				Cost of Steam at Different Fuel Prices - Energy Based (Rs./MJ)			
		Rs.16.50	Rs.18.00	Rs.20.00	Rs.25.00	Rs.16.50	Rs.18.00	Rs.20.00	Rs.25.00
1	CUB10797	1.49	1.61	1.78	2.19	0.51	0.56	0.62	0.77
2	CUB20797	1.47	1.59	1.75	2.16	0.50	0.55	0.61	0.76
3	CUB30797	1.49	1.61	1.75	2.19	0.51	0.56	0.62	0.77
4	CUB10698	1.46	1.58	1.75	2.15	0.50	0.55	0.61	0.76
5	CUB20698	1.55	1.68	1.85	2.28	0.53	0.58	0.64	0.80
6	CUB30698	1.51	1.63	1.79	2.21	0.52	0.57	0.63	0.79
7	CUB40698	1.50	1.63	1.80	2.22	0.51	0.56	0.62	0.77
8	CUB30799	1.47	1.60	1.77	2.19	0.50	0.55	0.61	0.76
9	CUB40799	1.51	1.63	1.79	2.21	0.51	0.56	0.62	0.77
10	CUB2B/T0799	1.56	1.69	1.87	2.30	0.53	0.58	0.64	0.80
11	CUB2A/T0799	1.46	1.58	1.75	2.15	0.50	0.55	0.61	0.76
12	CUB1B/T1099	1.76	1.90	2.10	2.58	0.60	0.65	0.73	0.91
13	CUB3B/T1099	1.41	1.52	1.68	2.07	0.48	0.52	0.58	0.73
14	CUB4B/T1099	1.50	1.63	1.80	2.22	0.52	0.57	0.63	0.79
15	CUB1A/T1099	1.47	1.59	1.75	2.16	0.50	0.55	0.61	0.76
16	CUB3A/T1099	1.45	1.57	1.74	2.14	0.50	0.55	0.61	0.76
17	CUB4A/T1099	1.41	1.53	1.69	2.09	0.49	0.53	0.59	0.74
18	CUB1B/T10299	1.55	1.68	1.85	2.28	0.53	0.58	0.64	0.80
19	CUB2B/T10299	1.48	1.60	1.77	2.18	0.51	0.56	0.62	0.77
20	CUB4B/T10299	1.52	1.65	1.82	2.25	0.52	0.57	0.63	0.79
21	CUB1A/T10299	1.50	1.63	1.80	2.21	0.51	0.56	0.62	0.77
22	CUB2A/T10299	1.46	1.59	1.75	2.15	0.50	0.55	0.61	0.76
23	CUB4A/T10299	1.45	1.57	1.74	2.14	0.50	0.55	0.61	0.76
24	CUB1B/T0800	1.55	1.68	1.85	2.28	0.53	0.58	0.64	0.80
25	CUB2B/T0800	1.55	1.68	1.85	2.28	0.50	0.55	0.61	0.76
26	CUB4B/T0800	1.56	1.69	1.87	2.30	0.53	0.58	0.64	0.80
27	CUB1A/T0800	1.49	1.61	1.78	2.19	0.51	0.56	0.62	0.77
28	CUB4A/T0800	1.42	1.54	1.70	2.10	0.49	0.53	0.59	0.74
29	CUB1B/T0101	1.62	1.75	1.93	2.38	0.56	0.61	0.68	0.85
30	CUB3B/T0101	1.45	1.57	1.73	2.12	0.49	0.53	0.59	0.74
31	CUB4B/T0101	1.51	1.64	1.81	2.24	0.52	0.57	0.63	0.79
32	CUB1A/T0101	1.52	1.64	1.81	2.23	0.52	0.57	0.63	0.79
33	CUB4A/T0101	1.48	1.61	1.78	2.20	0.51	0.56	0.62	0.77
34	CUB1B/T0501	1.52	1.65	1.82	2.24	0.52	0.57	0.63	0.79
35	CUB3B/T0501	1.50	1.62	1.79	2.20	0.51	0.56	0.62	0.77
36	CUB4B/T0501	1.46	1.59	1.75	2.17	0.50	0.55	0.61	0.76
37	CUB1A/T0501	1.50	1.62	1.79	2.20	0.51	0.56	0.62	0.77
38	CUB4A/T0501	1.49	1.61	1.78	2.20	0.51	0.56	0.62	0.77
39	BLB1B/T1100	1.34	1.45	1.61	1.98	0.49	0.53	0.59	0.74
40	BLB1A/T1100	1.34	1.45	1.60	1.98	0.49	0.53	0.59	0.74
41	BLB1B/T0401	1.39	1.51	1.66	2.06	0.52	0.57	0.63	0.79
42	BLB1A/T0401	1.36	1.48	1.64	2.02	0.50	0.55	0.61	0.76
43	FNB1B/T1100	1.41	1.53	1.68	2.07	0.50	0.55	0.61	0.76
44	FNB1A/T1100	1.40	1.51	1.67	2.05	0.50	0.55	0.61	0.76
45	TBB10900	1.44	1.56	1.72	2.13	0.50	0.55	0.61	0.76
46	BCB1B/T0900	1.39	1.51	1.66	2.05	0.50	0.55	0.61	0.76
47	BCB2B/T0900	1.40	1.52	1.68	2.07	0.50	0.55	0.61	0.76
48	BCB1A/T0900	1.42	1.54	1.70	2.09	0.51	0.56	0.62	0.77
49	BCB2A/T0900	1.39	1.51	1.67	2.06	0.50	0.55	0.61	0.76
50	LGB1B/T0900	1.40	1.52	1.68	2.08	0.49	0.53	0.59	0.74
51	LGB2B/T0900	1.58	1.71	1.88	2.32	0.61	0.66	0.74	0.92
52	LGB1A/T0900	1.42	1.54	1.70	2.10	0.50	0.55	0.61	0.76
53	LGB2A/T0900	1.43	1.55	1.71	2.10	0.56	0.61	0.68	0.85

Table 02 (Contd.)

No.	Boiler Identification Number	Cost of Steam at Different Fuel Prices - Exergy Based (Rs./MJ)				Cost of Steam at Different Fuel Prices - Energy Based (Rs./MJ)			
		Rs.16.50	Rs.18.00	Rs.20.00	Rs.25.00	Rs.16.50	Rs.18.00	Rs.20.00	Rs.25.00
54	LDB1B/T0700	1.44	1.56	1.73	2.13	0.50	0.55	0.61	0.76
55	LBD1A/T0700	1.47	1.59	1.75	2.17	0.51	0.56	0.62	0.77
56	BNB10600	1.40	1.52	1.68	2.07	0.49	0.53	0.59	0.74
57	BNB20600	1.43	1.55	1.72	2.12	0.49	0.53	0.59	0.74
58	RRB1B/T0600	1.56	1.70	1.87	2.31	0.54	0.59	0.65	0.82
59	RRB1A/T0600	1.43	1.55	1.70	2.10	0.49	0.53	0.59	0.74
60	RRB2B/T0600	1.44	1.55	1.71	2.11	0.52	0.57	0.63	0.79
61	RRB2A/T0600	1.45	1.57	1.73	2.13	0.50	0.55	0.61	0.76
62	RRB3A/T0600	1.54	1.67	1.84	2.26	0.53	0.58	0.64	0.80
63	RDB1B/T0400	1.38	1.50	1.65	2.04	0.48	0.52	0.58	0.73
64	RDB1A/T0400	1.36	1.48	1.63	2.02	0.47	0.51	0.57	0.71
65	RDB2B/T0400	1.48	1.60	1.77	2.18	0.51	0.56	0.62	0.77
66	RDB2A/T0400	1.36	1.47	1.63	2.01	0.47	0.51	0.57	0.71
67	RDB3B/T0400	1.45	1.57	1.73	2.14	0.50	0.55	0.61	0.76
68	RDB3A/T0400	1.40	1.52	1.67	2.06	0.49	0.53	0.59	0.74
69	TAB1B/T0400	1.61	1.74	1.92	2.35	0.57	0.62	0.69	0.86
70	TAB1A/T0400	1.50	1.62	1.78	2.19	0.53	0.58	0.64	0.80
71	FWB1B/T0200	1.52	1.65	1.82	2.24	0.52	0.57	0.63	0.79
72	RLB10200	1.44	1.56	1.72	2.13	0.50	0.55	0.61	0.76
73	RLB20200	1.78	1.93	2.13	2.63	0.63	0.69	0.76	0.95
74	FCB11199	1.45	1.57	1.74	2.15	0.50	0.55	0.61	0.76
75	FCB2B/T1199	1.50	1.62	1.79	2.21	0.52	0.57	0.63	0.79
76	FCB2A/T1199	1.45	1.58	1.74	2.15	0.50	0.55	0.61	0.76
77	TLB10499	1.37	1.48	1.64	2.02	0.48	0.52	0.58	0.73
78	TKB10500	1.48	1.61	1.77	2.19	0.51	0.56	0.62	0.77
79	TKB20500	1.40	1.52	1.68	2.07	0.48	0.52	0.58	0.73
80	TNB1B/T0500	1.58	1.72	1.89	2.33	0.57	0.62	0.69	0.86
81	TNB1A/T0500	1.54	1.67	1.84	2.27	0.55	0.60	0.67	0.83
82	TNB2B/T0500	1.56	1.69	1.87	2.30	0.55	0.60	0.67	0.83
83	TNB2A/T0500	1.53	1.65	1.83	2.25	0.54	0.59	0.65	0.82
84	CSB10800	2.37	2.56	2.82	3.46	0.56	0.61	0.68	0.85
85	CSB20800	1.57	1.69	1.87	2.30	0.51	0.56	0.62	0.77
86	CSB10201	1.52	1.65	1.82	2.24	0.57	0.62	0.69	0.86
87	CSB20201	1.75	1.89	2.07	2.53	0.57	0.62	0.69	0.86
88	CSB30201	1.47	1.60	1.76	2.18	0.57	0.62	0.69	0.86
89	THB1B/T0201	1.45	1.57	1.74	2.15	0.51	0.56	0.62	0.77
90	THB1A/T0201	1.57	1.70	1.87	2.31	0.49	0.53	0.59	0.74
91	THB20201	1.47	1.59	1.75	2.16	0.50	0.55	0.61	0.76
92	THB3B/T0201	1.67	1.81	1.99	2.44	0.50	0.55	0.61	0.76
93	THB3A/T0201	1.49	1.62	1.79	2.21	0.49	0.53	0.59	0.74
94	TSB10500	1.42	1.54	1.71	2.11	0.57	0.62	0.69	0.86
95	TSB20500	1.47	1.59	1.76	2.17	0.57	0.62	0.69	0.86
96	TSB30500	1.51	1.63	1.80	2.22	0.57	0.62	0.69	0.86
97	PNB10500	1.60	1.73	1.91	2.36	0.57	0.62	0.69	0.86

Table 03

No.	Boiler Identification Number	Percentage Exergy Loses				Percentage Energy Loss			Flue gas loss
		Flue Gas	Blow Down	Surface Losses	Exergy Destruction	Flue gas	Blow down	Surface Losses	(MJ/kg of Steam)
1	CUB10797	5.69	0.09	0.34	67.11	16.6	0.6	0.65	0.185
2	CUB20797	6.45	0.09	0.37	65.95	15.4	0.6	0.70	0.207
3	CUB30797	6.69	0.09	0.38	66.00	16.3	0.6	0.70	0.217
4	CUB10698	5.01	0.10	0.34	67.20	14.8	0.6	0.65	0.160
5	CUB20698	5.98	0.08	0.37	67.94	20.1	0.6	0.70	0.203
6	CUB30698	6.06	0.09	0.38	67.08	17.7	0.6	0.70	0.200
7	CUB40698	5.63	0.09	0.21	67.83	17.5	0.6	0.40	0.184
8	CUB30799	5.08	0.09	0.38	67.32	15.4	0.6	0.70	0.163
9	CUB40799	5.05	0.09	0.21	68.09	17.8	0.6	0.40	0.165
10	CUB2B/T0799	5.12	0.08	0.37	69.00	20.7	0.6	0.70	0.175
11	CUB2A/T0799	4.23	0.09	0.37	68.07	15.1	0.6	0.70	0.135
12	CUB1B/T1099	5.97	0.08	0.34	66.84	29.5	0.6	0.65	0.230
13	CUB3B/T1099	4.26	0.10	0.38	66.89	11.6	0.6	0.70	0.131
14	CUB4B/T1099	5.22	0.09	0.21	68.40	19.3	0.6	0.40	0.174
15	CUB1A/T1099	4.73	0.10	0.34	67.63	15.3	0.6	0.65	0.151
16	CUB3A/T1099	4.43	0.09	0.37	67.68	14.5	0.6	0.70	0.140
17	CUB4A/T1099	4.80	0.09	0.21	67.10	14.0	0.6	0.40	0.150
18	CUB1B/T1029	5.75	0.09	0.34	68.16	19.9	0.6	0.65	0.195
19	CUB2B/T1029	6.54	0.09	0.37	66.11	16.2	0.6	0.70	0.212
20	CUB4B/T1029	6.52	0.09	0.21	67.46	20.3	0.6	0.40	0.220
21	CUB1A/T1029	5.84	0.09	0.34	67.22	17.4	0.6	0.65	0.192
22	CUB2A/T1029	5.18	0.09	0.37	67.15	15.2	0.6	0.70	0.166
23	CUB4A/T1029	5.62	0.09	0.21	67.05	16.4	0.6	0.40	0.181
24	CUB1B/T0800	6.05	0.09	0.34	67.86	20.0	0.6	0.65	0.205
25	CUB2B/T0800	5.14	0.08	0.37	68.72	15.5	0.6	0.70	0.165
26	CUB4B/T0800	6.26	0.08	0.21	68.34	21.0	0.6	0.40	0.213
27	CUB1A/T0800	5.58	0.09	0.34	67.18	16.5	0.6	0.65	0.181
28	CUB4A/T0800	4.58	0.08	0.21	67.47	14.5	0.6	0.40	0.144
29	CUB1B/T0101	7.47	0.09	0.34	67.55	23.4	0.6	0.65	0.265
30	CUB3B/T0101	4.72	0.09	0.38	67.22	14.0	0.6	0.70	0.149
31	CUB4B/T0101	5.70	0.08	0.21	68.14	20.0	0.6	0.40	0.192
32	CUB1A/T0101	6.36	0.09	0.34	66.89	18.0	0.6	0.65	0.210
33	CUB4A/T0101	4.76	0.09	0.21	68.56	18.4	0.6	0.40	0.157
34	CUB1B/T0501	5.82	0.09	0.34	67.57	18.4	0.6	0.65	0.193
35	CUB3B/T0501	5.85	0.09	0.38	67.06	17.0	0.6	0.70	0.191
36	CUB4B/T0501	5.88	0.09	0.21	67.08	16.3	0.6	0.40	0.189
37	CUB1A/T0501	5.44	0.09	0.34	67.48	17.0	0.6	0.65	0.178
38	CUB4A/T0501	7.54	0.09	0.21	65.83	18.5	0.6	0.40	0.249
39	BLB1B/T1100	4.39	0.02	0.36	66.37	14.0	0.3	0.70	0.133
40	BLB1A/T1100	4.47	0.02	0.36	66.26	13.9	0.3	0.70	0.135
41	BLB1B/T0401	6.84	0.02	0.36	64.93	17.0	0.3	0.70	0.214
42	BLB1A/T0401	5.09	0.02	0.36	66.20	15.6	0.3	0.70	0.157
43	FNB1B/T1100	4.12	0.11	0.12	67.36	13.3	0.8	0.50	0.127
44	FNB1A/T1100	4.09	0.11	0.20	67.12	12.5	0.8	0.47	0.125
45	TBB10900	5.12	0.10	0.17	67.37	15.5	0.8	0.32	0.163
46	BCB1B/T0900	4.68	0.08	0.32	66.70	13.9	0.5	0.60	0.144
47	BCB2B/T0900	4.24	0.09	0.27	67.49	15.0	0.5	0.52	0.132
48	BCB1A/T0900	6.38	0.08	0.32	65.54	15.5	0.5	0.60	0.201
49	BCB2A/T0900	4.30	0.09	0.27	67.18	14.2	0.5	0.60	0.133
50	LGB1B/T0900	4.28	0.09	0.18	67.62	14.2	0.5	0.40	0.134
51	LGB2B/T0900	7.05	0.08	0.33	67.41	22.0	0.5	0.60	0.244
52	LGB1A/T0900	4.15	0.08	0.18	68.13	15.0	0.5	0.40	0.131
53	LGB2A/T0900	4.24	0.08	0.33	67.57	15.0	0.5	0.60	0.133

Table 03 (Contd.)

No.	Boiler Identification Number	Percentage Exergy Loses				Percentage Energy Loss			Flue gas loss (MJ/kg of Steam)
		Flue Gas	Blow Down	Surface Losses	Exergy Destruction	Flue gas	Blow down	Surface Losses	
54	LDB1B/T0700	4.75	0.09	0.25	67.62	15.2	0.8	0.48	0.151
55	LBD1A/T0700	5.13	0.09	0.25	67.69	16.6	0.8	0.48	0.166
56	BNB10600	5.03	0.05	0.28	66.78	14.7	0.5	0.55	0.157
57	BNB20600	5.44	0.05	0.26	67.01	16.6	0.5	0.55	0.174
58	RRB1B/T0600	4.72	0.09	0.27	69.70	21.5	0.8	0.57	0.163
59	RRB1A/T0600	3.90	0.10	0.27	67.92	13.7	0.8	0.57	0.123
60	RRB2B/T0600	4.03	0.09	0.38	67.74	13.4	0.8	0.78	0.127
61	RRB2A/T0600	4.14	0.09	0.38	67.96	14.5	0.8	0.78	0.131
62	RRB3A/T0600	4.65	0.09	0.41	69.05	19.3	0.8	0.93	0.157
63	RDB1B/T0400	3.65	0.08	0.12	67.89	13.4	0.5	0.27	0.112
64	RDB1A/T0400	3.74	0.08	0.12	67.42	12.2	0.5	0.27	0.114
65	RDB2B/T0400	4.43	0.08	0.17	68.82	18.6	0.5	0.37	0.146
66	RDB2A/T0400	4.34	0.09	0.17	66.05	11.3	0.5	0.37	0.131
67	RDB3B/T0400	4.01	0.10	0.22	68.41	16.2	0.5	0.46	0.128
68	RDB3A/T0400	3.68	0.11	0.22	67.76	13.2	0.5	0.46	0.113
69	TAB1B/T0400	5.01	0.10	0.33	69.52	21.7	0.8	0.62	0.175
70	TAB1A/T0400	4.10	0.11	0.33	68.52	15.7	0.8	0.62	0.133
71	FWB1B/T0200	4.46	0.12	0.18	69.21	18.8	0.8	0.35	0.149
72	RLB10200	4.46	0.09	0.21	68.00	15.9	0.8	0.40	0.143
73	RLB20200	6.79	0.07	0.16	71.00	32.0	0.8	0.32	0.269
74	FCB11199	5.79	0.09	0.11	67.00	16.5	0.8	0.21	0.187
75	FCB2B/T1199	6.28	0.08	0.13	67.34	19.0	0.8	0.26	0.209
76	FCB2A/T1199	5.24	0.09	0.13	67.59	16.6	0.8	0.26	0.169
77	TLB10499	4.28	0.13	0.33	66.37	13.4	0.8	0.55	0.133
78	TKB10500	5.62	0.09	0.38	67.36	18.5	0.8	0.62	0.184
79	TKB20500	3.97	0.10	0.37	67.46	13.7	0.8	0.61	0.123
80	TNB1B/T0500	7.82	0.12	0.94	66.10	21.9	0.8	1.50	0.272
81	TNB1A/T0500	7.15	0.12	0.94	66.05	19.8	0.8	1.50	0.242
82	TNB2B/T0500	7.19	0.11	0.83	66.62	21.6	0.8	1.26	0.248
83	TNB2A/T0500	6.78	0.11	0.83	66.46	19.9	0.8	1.26	0.228
84	CSB10800	5.87	0.13	0.34	76.53	20.4	0.6	0.63	0.204
85	CSB20800	6.12	0.15	0.17	67.83	18.9	0.6	0.32	0.207
86	CSB10201	5.04	0.20	0.34	67.38	17.0	0.6	0.63	0.168
87	CSB20201	8.27	0.14	0.17	67.41	24.2	0.6	0.32	0.300
88	CSB30201	5.82	0.17	0.19	69.42	24.2	0.6	0.36	0.208
89	THB1B/T0201	5.61	0.09	0.06	68.09	17.8	0.6	0.13	0.187
90	THB1A/T0201	4.53	0.09	0.06	68.02	13.7	0.6	0.13	0.143
91	THB20201	4.42	0.10	0.06	68.73	16.1	0.6	0.13	0.144
92	THB3B/T0201	5.31	0.10	0.05	67.92	16.4	0.6	0.12	0.174
93	THB3A/T0201	5.21	0.10	0.05	67.65	15.2	0.6	0.12	0.168
94	TSB10500	6.03	0.09	0.50	68.05	20.8	0.8	0.96	0.207
95	TSB20500	4.70	0.11	0.44	67.58	15.2	0.8	0.91	0.151
96	TSB30500	6.20	0.09	0.41	66.97	17.6	0.8	0.78	0.205
97	PNB10500	4.65	0.10	0.07	70.73	18.3	0.8	0.86	0.164

Description of boiler idntification number

Symbol	Identification
First two charactor	Organization
Third character and first digit	Organizational serial number of the boiler
A/T or B/T	After tuning or Before tuning
Next two digit	The month measurements taken
Final two digit	The year measurements taken

APPENDIX C

IDEAL GAS ENTHALPIES, ENTROPIES AND STANDARD MOLAR CHEMICAL EXERGIES OF COMBUSTION PRODUCTS

Table 01

Ideal gas sensible enthalpies $h_T - h_{298}$ (kJ / kg mol) of combustion products

Temperature, K	CO	CO_2	H	OH	H_2	N	NO	NO_2	N_2	N_2O	O	O_2	SO_2	H_2O
200	−2858	−3414	−2040	−2976	−2774	−2040	−2951	−3495	−2857	−3553	−2186	−2868	−3736	−3282
240	−1692	−2079	−1209	−1756	−1656	−1209	−1743	−2104	−1692	−2164	−1285	−1703	−2258	−1948
260	−1110	−1383	−793	−1150	−1091	−793	−1142	−1392	−1110	−1438	−840	−1118	−1496	−1279
280	−529	−665	−377	−546	−522	−378	−543	−672	−528	−692	−398	−533	−718	−609
298.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
300	54	69	38	55	53	38	55	68	54	72	41	54	74	62
320	638	823	454	654	630	454	652	816	636	854	478	643	881	735
340	1221	1594	870	1251	1209	870	1248	1571	1219	1654	913	1234	1702	1410
360	1805	2382	1285	1847	1791	1286	1845	2347	1802	2470	1346	1828	2538	2088
380	2389	3184	1701	2442	2373	1701	2442	3130	2386	3302	1777	2425	3387	2769
400	2975	4003	2117	3035	2959	2117	3040	3927	2971	4149	2207	3025	4250	3452
420	3563	4835	2532	3627	3544	2533	3638	4735	3557	5010	2635	3629	5126	4139
440	4153	5683	2948	4219	4131	2949	4240	5557	4143	5884	3063	4236	6015	4829
460	4643	6544	3364	4810	4715	3364	4844	6392	4731	6771	3490	4847	6917	5523
480	5335	7416	3779	5401	5298	3780	5450	7239	5320	7670	3918	5463	7831	6222
500	5931	8305	4196	5992	5882	4196	6059	8099	5911	8580	4343	6084	8758	6925
550	7428	10572	5235	7385	6760	5235	7592	10340	7395	10897	5402	7653	11123	8699
600	8942	12907	6274	8943	8811	6274	9144	12555	8894	13295	6462	9244	13544	10501
650	10477	15303	7314	10423	10278	7314	10716	14882	10407	15744	7515	10859	16022	12321
700	12023	17754	8353	11902	11749	8353	12307	17250	11937	18243	8570	12499	18548	14192
750	13592	20260	9392	13391	13223	9329	13919	19671	13481	20791	9620	14158	21117	16082
800	15177	22806	10431	14880	14702	10431	15548	22136	15046	23383	10671	15835	23721	18002
850	16781	25398	11471	16384	16186	11471	17195	24641	16624	26014	11718	17531	26369	19954
900	18401	28030	12510	17888	17676	12510	18858	27179	18223	28681	12767	19241	29023	21938
950	20031	30689	13550	19412	19175	13550	20537	29749	19834	31381	13812	20965	31714	23954
1000	21690	33397	14589	20935	20680	14589	22229	32344	21463	34110	14860	22703	34428	26000
1100	25035	38884	16667	24024	23719	16667	25653	37605	24760	39647	16950	26212	39914	30191
1200	28430	44473	18746	27160	26797	18746	29120	42946	28109	45274	19039	29761	45464	34506
1300	31868	50148	20824	30342	29918	20824	32626	48351	31503	50976	21126	33344	51069	38942
1400	35343	55896	22903	33569	33082	22903	36164	53808	34936	56740	23212	36957	56718	43493
1500	38850	61705	24982	36839	36290	24982	39729	59309	38405	62557	25296	40599	62404	48151
1600	42385	67569	27060	40151	39541	27060	43319	64846	41904	68420	27381	44266	68123	52908
1700	45945	73480	29139	43502	42835	29139	46929	70414	45429	74320	29464	47958	73870	57758
1800	49526	79431	31217	46889	46169	31218	50557	76007	48978	80254	31547	51673	79642	62693
1900	53126	85419	33296	50310	49541	33296	54201	81624	52548	86216	33630	55413	85436	67706
2000	56744	91439	35375	53762	52951	35375	57859	87259	56137	92203	35713	59175	91250	72790
2100	60376	97488	37453	57243	56397	37454	61530	92911	59742	98212	37796	62961	97081	77941
2200	64021	103562	39532	60752	59876	39534	65212	98577	63361	104240	39878	66769	102929	83153
2300	67683	109660	41610	64285	63387	41614	68904	104257	66995	110284	41962	70600	108792	88421
2400	71324	115779	43689	67841	66928	43695	72606	109947	70640	116344	44045	74453	114669	93741
2500	74985	121917	45768	71419	70498	45777	76316	115648	74296	122417	46130	78328	120559	99108
2600	78673	128073	47846	75017	74096	47860	80034	121357	77963	128501	48216	82224	126462	104520
2700	82369	134246	49925	78633	77720	49945	83759	127075	81639	134596	50303	86141	132376	109973
2800	86074	140433	52004	82267	81369	52033	87491	132799	85323	140701	52391	90079	138302	115464
2900	89786	146636	54082	85918	85043	54124	91229	138530	89015	146814	54481	94036	144238	120990
3000	93504	152852	56161	89584	88740	56218	94973	144267	92715	152935	56574	98013	150184	126549
3500	112185	184109	66554	108119	107555	66769	113768	173020	111306	183636	67079	118165	180057	154768
4000	130989	215622	75947	126939	126874	77532	132671	201859	130027	214453	77675	188705	210145	183552
4500	149895	247354	87340	145991	146660	88614	151662	230756	148850	245348	88386	159572	240427	212764
5000	168890	279283	97733	165246	166876	100111	170730	259692	167763	276299	99222	180749	270893	242313

Table 02

Ideal gas entropies s^0 (kJ / kg mol.K) of combustion products

Temperature, K	CO	CO_2	H	OH	H_2	N	NO	NO_2	N_2	N_2O	O	O_2	SO_2	H_2O
200	186.0	200.0	106.4	171.6	119.4	145.0	198.7	225.9	180.0	205.6	152.2	193.5	233.0	175.5
240	191.3	206.0	110.1	177.1	124.5	148.7	204.1	232.2	185.2	211.9	156.2	198.7	239.9	181.4
260	193.7	208.8	111.8	179.5	126.8	150.4	206.6	235.0	187.6	214.8	158.0	201.1	242.8	184.1
280	195.3	211.5	113.3	181.8	129.2	151.9	208.8	237.7	189.8	217.5	159.7	203.3	245.8	186.6
298.15	197.7	213.8	114.7	183.7	130.7	153.3	210.8	240.0	191.6	220.0	161.1	205.1	248.2	188.8
300	197.8	214.0	114.8	183.9	130.9	153.4	210.9	240.3	191.8	220.2	161.2	205.3	248.5	189.0
320	199.7	216.5	116.2	185.9	132.8	154.8	212.9	242.7	193.7	222.7	162.6	207.2	251.1	191.2
340	201.5	218.8	117.4	187.7	134.5	156.0	214.7	245.0	195.5	225.2	163.9	209.0	253.6	193.3
360	203.2	221.0	118.6	189.4	136.2	157.2	216.4	247.2	197.2	227.5	165.2	210.7	256.0	195.2
380	204.7	223.2	119.7	191.0	137.7	158.3	218.0	249.3	198.7	229.7	166.3	212.5	258.2	197.1
400	206.2	225.3	120.8	192.5	139.2	159.4	219.5	251.3	200.2	231.9	167.4	213.8	260.4	198.8
420	207.7	227.3	121.8	194.0	140.6	160.4	221.0	253.2	201.5	234.0	168.4	215.3	262.5	200.5
440	209.0	229.3	122.8	195.3	141.9	161.4	222.3	255.1	202.9	236.0	169.4	216.7	264.6	202.0
460	210.4	231.2	123.7	196.6	143.2	162.3	223.7	257.0	204.2	238.0	170.4	218.0	266.6	203.6
480	211.6	233.1	124.6	197.9	144.5	163.1	225.0	258.8	205.5	239.9	171.3	219.4	268.5	205.1
500	212.8	234.9	125.5	199.1	145.7	164.0	226.3	260.6	206.7	241.8	172.2	220.7	270.5	206.5
550	215.7	239.2	127.5	201.8	148.6	166.0	229.1	264.7	209.4	246.2	174.2	223.7	274.9	210.5
600	218.3	243.3	129.3	204.4	151.1	167.8	231.9	268.8	212.2	250.4	176.1	226.5	279.2	213.1
650	220.8	247.1	131.0	206.8	153.4	169.4	234.4	272.6	214.6	254.3	177.7	229.1	283.1	215.9
700	223.1	250.8	132.5	209.0	155.6	171.0	236.8	276.0	216.9	258.0	179.3	231.5	286.9	218.7
750	225.2	255.4	133.9	211.1	157.6	172.5	239.0	279.3	219.0	261.5	180.7	233.7	290.4	221.3
800	227.3	257.5	135.2	213.0	159.5	173.8	241.1	282.5	221.0	264.8	182.1	235.9	293.8	223.8
850	229.2	260.6	136.4	214.8	161.4	175.1	243.0	285.5	223.0	268.0	183.4	237.9	297.0	226.2
900	231.1	263.6	137.7	216.5	163.1	176.3	245.0	288.4	224.8	271.1	184.6	239.9	300.1	228.5
950	232.8	266.5	138.8	218.1	164.7	177.4	246.8	291.3	226.5	274.0	185.7	241.8	303.0	230.6
1000	234.5	269.3	139.9	219.7	166.2	178.5	248.4	293.9	228.2	276.8	186.8	243.6	305.8	232.7
1100	237.7	274.5	141.9	222.7	169.1	180.4	251.8	298.9	231.3	282.1	188.8	246.9	311.0	236.7
1200	240.7	279.4	143.7	225.4	171.8	182.2	254.8	303.6	234.2	287.0	190.6	250.0	315.8	240.5
1300	243.4	283.9	145.3	228.0	174.3	183.9	257.6	307.9	236.9	291.5	192.3	252.9	320.3	244.0
1400	246.0	288.2	146.9	230.3	176.6	185.4	260.2	311.9	239.5	295.8	193.8	255.6	324.5	247.4
1500	248.4	292.2	148.3	232.6	178.8	186.9	262.7	315.7	241.9	299.8	195.3	258.1	328.4	250.6
1600	250.7	296.0	149.6	234.7	180.9	188.2	265.0	319.3	244.1	303.6	196.6	260.4	332.1	253.7
1700	252.9	299.6	150.9	236.8	182.9	189.5	267.2	322.7	246.3	307.2	197.9	262.7	335.6	256.6
1800	254.9	303.0	152.1	238.7	184.8	190.7	269.3	325.9	248.3	310.6	199.1	264.8	338.9	259.5
1900	256.8	306.2	153.2	240.6	186.7	191.8	271.3	328.9	250.2	313.8	200.2	266.8	342.0	262.2
2000	258.7	309.3	154.3	242.3	188.4	192.9	273.1	331.8	252.1	316.9	201.3	268.7	345.0	264.8
2100	260.5	312.2	155.3	244.0	190.1	193.9	274.9	334.5	253.8	319.8	202.3	270.6	347.9	267.3
2200	262.2	315.1	156.3	245.7	191.7	194.8	276.6	337.2	255.5	322.6	203.2	272.4	350.6	269.7
2300	263.8	317.8	157.2	247.2	193.3	195.8	278.3	339.7	257.1	325.3	204.2	274.1	353.2	272.0
2400	265.4	320.4	158.1	248.7	194.8	196.7	279.8	342.1	258.7	327.9	205.0	275.7	355.7	274.3
2500	266.9	322.9	158.9	250.2	196.2	197.5	281.4	344.5	260.2	330.4	205.9	277.3	358.1	276.5
2600	268.3	325.3	159.7	251.6	197.7	198.3	282.8	346.7	261.6	332.7	206.7	278.8	360.4	278.6
2700	269.7	327.6	160.5	253.0	199.0	199.1	284.2	348.9	263.0	335.0	207.5	280.3	362.6	380.7
2800	271.0	329.9	161.3	254.3	200.3	199.9	285.6	350.9	264.3	337.3	208.3	281.7	364.8	282.7
2900	272.3	332.1	162.0	255.6	201.6	200.6	286.9	352.9	265.6	339.4	209.0	283.1	366.9	284.6
3000	273.6	334.2	162.7	256.8	202.9	201.3	288.2	354.9	266.9	341.5	209.7	284.4	368.9	286.5
3500	279.4	343.8	165.9	262.5	208.7	204.6	294.0	363.8	272.6	350.9	212.9	290.7	378.1	295.2
4000	284.4	352.2	168.7	267.6	213.8	207.4	299.0	371.5	277.6	359.2	215.8	296.2	386.1	302.9
4500	288.8	359.7	171.1	272.1	218.5	210.1	303.5	378.3	282.1	366.5	218.3	301.1	393.3	309.8
5000	292.8	366.4	173.3	276.1	222.8	212.5	307.5	384.4	286.0	373.0	220.6	305.5	399.7	316.0

Table 03

Standard Molar Chemical Availability, $\bar{a}^{ch}$ (kJ/kmol), of Various 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
Methanol	$CH_3OH(g)$	715,070	722,300
Methanol	$CH_3OH(l)$	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

[a] J. Ahrendts, "Die Exergie Chemisch Reaktionsfähiger Systeme," *VDI-Forschungsheft*, VDI-Verlag, Dusseldorf, 579, 1977. Also see "Reference States," *Energy—The International Journal*, 5: 667–677, 1980. In Model I, p_0 = 1.019 atm. This model attempts to impose a criterion that the reference environment be in equilibrium. The reference substances are determined assuming restricted chemical equilibrium for nitric acid and nitrates and unrestricted thermodynamic equilibrium for all other chemical components of the atmosphere, the oceans, and a portion of the Earth's crust. The chemical composition of the gas phase of this model approximates the composition of the natural atmosphere.

[b] J. Szargut, D. R. Morris, and F. R. Steward, *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, Hemisphere, New York, 1983. In Model II, p_0 = 1.0 atm. In developing this model a reference substance is selected for each chemical element from among substances that contain the element being considered and that are abundantly present in the natural environment, even though the substances are not in completely mutual stable equilibrium. An underlying rationale for this approach is that substances found abundantly in nature have little economic value. On an overall basis, the chemical composition of the availability reference environment of Model II is closer than Model I to the composition of the natural environment, but the equilibrium criterion is not always satisfied.