THE APPLICATION OF EXERGY ANALYSIS ON AN EDUCATIONAL STEAM POWER PLANT

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Istimewa Buat Isteri Tercinta,
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" Terima kasih atas sokongan dan doronganmu"
Buat Anak-anakku,
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Serta Untuk
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ABSTRACT

The performance of an educational steam power plant with rated output of 20 kW was analyzed based on the first and second laws of thermodynamics. Experimental data was obtained from the educational steam power plant located at the Thermodynamics laboratory, Faculty of Engineering, Kolej Universiti Tun Hussein Onn (KUITTHO) which used diesel as a fuel. Experiments were carried out to evaluate the performance of the steam power plant. The energy and exergy balances were carried out on each of component of the power plant, excluding the feedwater pump. The energy interactions, the exergy losses and the efficiencies of each component based on the first and second law of thermodynamic were evaluated. The results of the analysis show that the performance of the plant is influenced by both the boiler pressure and the superheater temperature. It was found that, the thermal and exergy efficiencies of the plant are 8.9% and 5.2% respectively. The results also indicate that, the major source of exergy destruction occurred in the steam boiler followed by losses in the turbine and condenser. The exergy losses in boiler are mainly due to the heat loss during the combustion process. Conversion of chemical energy to heat energy and heat transfer between the combustion gases and water are the other causes of destructions.

ABSTRAK

Analisis prestasi loji kuasa stim dengan keluaran 20 Kw dilakukan berdasarkan hukum termodinamik pertama dan kedua. Keputusan ujikaji diperolehi dari ujikaji yang dijalankan keatas loji kuasa stim yang terdapat di Makmal Termodinamik, Fakulti Mekanikal, Kolej Universiti Tun Hussein Onn (KUITTHO) dimana minyak diesel digunakan sebagai tenaga pembakar. Tujuan ujikaji yang dijalankan keatas sistem ini adalah untuk menilai prestasi loji kuasa stim ini. Kaedah keseimbangan tenaga dan keseimbangan eksergi telah dijalankan keatas setiap komponen yang terdapat di loji kuasa stim ini kecuali komponen pam. Penilaian terhadap tindakbalas tenaga, kehilangan eksergi dan kecekapan setiap komponen adalah berdasarkan kepada kaedah hukum pertama dan hukum kedua termodinamik. Keputusan analisis menunjukkan bahawa prestasi loji ini dipengaruhi oleh tekanan dandang dan suhu pemanas lampau. Didapati bahawa, kecekapan hukum pertama termodinamik loji ini ialah 8.9 % manakala kecekapan hukum kedua termodinamik ialah 5.2%. Keputusan yang diperolehi juga menunjukan bahawa kehilangan eksergi yang terbesar adalah daripada dandang, diikuti oleh turbin dan pemeluwap. Kehilangan eksergi yang terdapat di dandang adalah terutamanya disebabkan oleh kehilangan tenaga semasa proses pembakaran. Sebab-sebab yang lain adalah kerana kehilangan tenaga semasa perpindahan tenaga kimia ke tenaga haba dan kehilangan disebabkan perpindahan haba diantara udara pembakaran dan air.

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SYMBOL	SUBJECT
A	Surface area
cv	Control volume
CV_F	Calorific value of fuel
e	Exit condition
E	Energy
h	Specific enthalpy, u+Pv, kJ/kg
h_o	Environment specific enthalpy, kJ/kg
H	Percentage of hydrogen in the fuel
i	Inlet condition
$\dot{I}$	Irreversibility
k	Siegert constant
L_4	Loss due to unburned carbon in ash and riddling
L_5	Loss due to unburned carbon in grit and dust
m	Mass/ kg
m_{H_2O}	Percentage of moisture in the fuel as fired (% m/m)
$\dot{m}$	Mass flow rate, kg/s
$\dot{m}_{fw}$	Mass flow rate of feedwater
$\dot{m}_{cw}$	Mass flow rate of cooling water
$\dot{m}_F$	Mass flow rate of fuel
$\dot{m}_s$	Mass flow rate of steam
P_o	Ambient pressure
q	Energy radiated
Q	Heat transfer per unit mass kJ/kg

Q_k	Heat transfer through the boundary
$\dot{Q}$	Heat transfer rate kg/s
s	Specific entropy
S_{gen}	Total entropy generation, kJ/K
t	time
T	Temperature
T_a	Inlet air temperature
T_o	Ambient temperature
T_r	Boiler room temperature (K)
T_s	Surface temperature (K)
U	Body's internal energy
v	Specific volume, m^3/kg
V	Volume
Vco_2	Percentage of CO_2 in the dry flue gases (% v/v)
w	Work per unit mass kJ/kg
W	work
x	Specific exergy, kJ/kg
X	Total exergy, kJ/kg
$\dot{X}_{gen}$	Rate of total exergy destruction
z	Elevation, m
μ_{io}	Chemical potential of substance "i"
n_i	Number of mole of substance "i"
$\in$	Emissivity of the surface = 0.2
σ	Stefan-Boltzman constant (5.669×10^{-11} kW/m^2K^4)
ρ	Density
ε_F	Chemical exergy of fuel
η_I	First law efficiency
η_{II}	Second law efficiency
η_{comb}	Combustion efficiency
ψ	Stream of flow availability per unit mass

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CHAPTER 1

INTRODUCTION

The available energy or exergy function has been introduced to enhance our understanding of thermal and chemical processes. This function allows us to examine any process, no matter how complex, in relation to the theoretically most efficient manner by which that process could be carried out within the environment.

The science and thermodynamics is built primarily on two fundamental natural laws which is known as the first law and the second law of thermodynamic. The first law of thermodynamic is simply an expression of the conservation of energy principle. It asserts that energy is a thermodynamic property and that during the interaction, energy can change from one form to another form but the total amount of energy remains constant. The second law of thermodynamic asserts that energy has quality as well as quantity and actual processes occur in the direction of decreasing quality of energy.

Energy balances treat all forms of energy as equivalent, without differentiating between the different grades of energy crossing the system boundary. Thus heat transfer to the environment from a pipe carrying high temperature steam will be treated in the same way as low grade thermal energy rejected in the condenser of a steam plant. In generally energy balances provide no information about internal losses. An energy balance for an adiabatic system such as a throttling valve, a heat exchanger or a combustion chamber, could lead one to believe that these processes are free of losses of any kind.

The Exergy Method is an alternative, relatively new technique based on the concept of exergy, loosely defined as universal measure of the work potential or quality of different forms of energy in relation to a given environment. An exergy balance applied to a process or a whole plant tells us hoe much of the usable work potential, or exergy, supplied as an input to the system under consideration has been consumed by the process.

The main purpose of exergy analysis is to detect and evaluate quantitatively the causes of the thermodynamic imperfection of thermal processes. Exergy analysis can, therefore, give information about the possibilities of improving thermal processes, but cannot state whether or not the possible improvement is practicable. The majority of the causes of thermodynamic imperfection of thermal and chemical processes cannot be detected by means of an energy balance. For example, irreversible heat transfer, throttling, and adiabatic combustion are not associated with any energy loss, but they lead to decrease of the energy quality, reduce its ability to be transformed into other kinds of energy, and therefore, increase the operational costs.

Exergy analysis is highly effective method of analysis for thermal processes because it provides that cannot be obtained from energy analysis alone. Furthermore, exergy analysis is a tool for identifying that types, locations and magnitudes of thermal losses. Identification and quantification of these losses allows us to evaluate and improve the design of thermodynamic system.

The exergy of the system is defined as the maximum shaft work that could be produced by the composite of the system and a specified reference environment that is assumed to be infinite in equilibrium an ultimately to enclose all other system.

In particular, exergy analysis takes into account the different thermodynamic values of work and heat. The exergy transfer is associated with shaft work is equal to the shaft work. The exergy transfer associated with heat transfer, however depends on the temperature level at which it occurs in relation to the temperature of the environment.

1.1 Problems of Statement

The first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed. The first law also gives no information about direction which it merely states that when one form of energy is converted into another, identical quantities of energy are involved regardless of feasibility of the process. The second law of thermodynamics, however, deals with the quality of energy. It is concerned with the degradation of energy during a process and the lost opportunities to do work. The exergy method of analysis overcomes the limitations of the first law of thermodynamics. The exergy analysis is based on both the First and the Second Laws of Thermodynamics. Exergy analysis can clearly indicate the locations of energy degradation in a process that may lead to improved operation. The main purpose of exergy analysis is to identify the causes and to calculate the true magnitudes of exergy losses.

1.2 Objectives of the project

The objectives of the project are given as follows:-

a) To develop an understanding of the concept of exergy analysis applied to thermal systems.

b) To apply exergy analysis concept to evaluate the performance of an educational of steam boiler-turbine system.

c) To perform an exergy balance on each component of the plant and evaluate the second law efficiency of the entire plant.

d) To identify locations in the plant where exergy destruction due to irreversibility occurs.

1.3 Scopes of the Project

The scopes of the project are as follows:-

a) Literature review on the application of exergy analysis on thermal systems.

b) Experimental data are obtained from the educational steam generating plant available in the Thermodynamic laboratory, Faculty of Mechanical Engineering, KUITTHO.

c) Steam at boiler exit is dry saturated and a superheater unit is included in this study.

d) The steam generating plant uses diesel fuel as the chemical exergy source.

1.4 Project Methodology

The following are the methodology adapted in this project:

1. Literature review on the exergy analysis of the steam power plant.
2. Carry out steady-state experiments on the educational steam power plant.
3. Perform the energy and exergy analysis with the data obtained from the experiments and generate the MATLAB program to perform all the calculations.
4. Carry out parametric study to investigate the effects of boiler pressure and superheater temperature on the performance of the steam power plant.

CHAPTER 2

LITERATURE REVIEW

Goran Wall [1] studied on exergy concept and exergy method. The purpose of this study is to discuss the basic concept which hopefully could help in social and economy. Exergy represents the useful part of energy for a system in its environment such as the maximum quantity of work that the system can execute in its environment. Basically the exergy concept derives from the entropy concept. Instead of saying the quality decreases, we can say that the lack of quality increases, or that the entropy increases. This paper also discusses the conversion of energy on earth. The exergy reaches the earth by means of sunlight, which is then converted and thus maintains the living conditions for almost all living things on the earth's surfaces.

Furthermore, Goran Wall [2] studied on the exergy flows in industrial processes. The concept of exergy is applied to industrial processes. The aim of this report is to show the concept of exergy when analyzing industrial processes and to develop conventions and standards within the field. The study establishes the energy flow in processes and exergy losses. The losses which are revealed in an exergy treatment of a process should take as a guide to achieve technical improvement in industrial process.

Ibrahim Dencer and Cengel [3] studied the energy, entropy and exergy concepts and their roles in thermal engineering. The purpose of this article is to provide background for better understanding of these concepts and their differences among various classes of life support systems with a diverse average. Some illustrative examples are presented to highlight the importance of energy, entropy and exergy and their roles in thermal engineering. During the past decade exergy related studies have receive considerable attention for various disciplines ranging from chemical engineering to mechanical engineering, from environmental engineering to ecology and so on. As a consequence of this, recently, international exergy community has expanded greatly.

H Struchup and M A Rosen [4] studied the lost work in an adiabatic turbine due to irreversibility. They discussed on basis of the isentropic efficiency and exergy efficiency and application of each basis. The turbine is considered as open system of constant volume with one inlet and one exit. The result is the second law efficiency, η_{II} of an adiabatic turbine normally is larger than the isentropic efficiency, η_T. For a given isentropic efficiency, η_T and pressure ratio, the work loss according to the exergy method is independent of the turbine temperature. The exergetic work loss is smaller than the isentropic work loss that was computed for the adiabatic turbine. There are few possibilities to reduce the lost work of turbine:

a) Reduce the irreversibility inside the turbine

b) Add recovery devices to the turbine.

Marc A Rosen [5] studied on clarifying thermodynamic efficiencies and losses via exergy. Most peoples, who work or appreciate exergy, realize that there exist numerous problems associated with the meaning of energy efficiencies and losses. Exergy efficiencies do provide measures of approach to ideality and exergy losses do provide measures of the deviation from ideality. The losses occur when the efficiency of a device or process deviates from the efficiency that would occur if the device or processes are ideal. This paper stated that the exergy losses can be divided into two types: the losses associated with waste exergy effluents, and the losses associated with the internal irreversibilities in a system or process.

In their studied, G. P Verkhivker and B.V Kosoy [6] presented the exergy analysis of power plant. They indicated that the thermal performance of power generating and consuming devices can be improved by combining exergy and economic analysis. They performed their study on the nuclear power plant. The objective of this study is to draw attention to a nuclear power plant with a high temperature nuclear reactor. From this study, it is realized that the exergy analysis of power plant have some advantages. Among the advantages are: identify method for improving the effectiveness of a power plant, assess the influence of every process (component) of the system on the overall efficiencies and eliminate the major process (components) of the system that diminish its performance. The quantitative analysis of exergy destruction showed that the principal irreversibilities are associated with the chemical transformation of exergy into heat and the subsequent transfer of this heat to the working fluid. A reduction in exergy destruction is achieved by increasing the values of the thermodynamic parameters of the working fluid supplied to the turbine and by reducing the temperature difference of the net heater. To improve the thermal design and optimization methodology for nuclear power plant, it was proposed to evaluate the entire nuclear plant efficiency based on the system coefficient of performance (SCOP).

CHAPTER 3

EXERGY ANALYSIS

When a new energy source, such as a geothermal well, is discovered, the first thing the explorers do is estimate the amount of energy contained in the source. This information alone, however, is of little value in deciding whether to build a power plant on that site. What we really need to know is the work potential of the source where the amount of energy we can extract as useful work. The rest of the energy will eventually be discarded as waste energy and is not worthy of our consideration. Thus, it would be very desirable to have a property to enable us to determine the useful work potential of a given amount of energy at some specified state. This property is exergy, which is also called the availability.

The work potential of the energy contained in a system at a specified state is simply the maximum useful work that can be obtained from the system. The work done during a process depends on the initial state, the final state, and the process state.

In an exergy analysis, the initial state is specified, and thus it is not a variable. The work output is maximized when the process between two specified states is executed in a reversible manner. Therefore, all the irreversibilities are disregarded in determining the work potential. Finally, the system must be in the dead state at the end of the process to maximize the work output.

A system is said to be dead state when it is in thermodynamic equilibrium with the environment. At the dead state, the system is at the temperature and pressure of its environment where there is no kinetic or potential energy relative to the environment and it does not react with the environment. A system has zero availability at the dead state.

Distinction should be made between the surrounding, immediate surroundings and the environment. Surroundings are everything outside the system boundaries. The immediate surroundings refer to the portion of the surroundings that is affected by the process. Environment refers to the region beyond the immediate surroundings whose properties are not affected by the process at any point. Therefore, any irreversibilities during a process occur within the system and its immediate surroundings, and the environment is free of any irreversibilities.

The system will deliver the maximum possible work as it undergoes a reversible process from the specified initial state to the state of its environment that is the dead state. This represents the useful work potential of the system at the specified state and is called exergy.

3.1 Exergy or Availability

A very important class of problems in engineering thermodynamics concerns systems or substances that can be modeled as being in equilibrium or stable equilibrium, but that are not mutual stable equilibrium with the surroundings. Exergy is not simply a thermodynamic property, but rather is a co-property of a system and the reference environment. The term exergy comes from the Greek words *ex* and *ergon* [8], meaning from and work: the exergy of a system can be increased if work is done on it. The following are some terms found in the literature that is equivalent to exergy: available energy, essergy, utizable energy, available work and availability.

Exergy has the characteristic that it is conserved only when all processes of the system and the environment are reversible. Exergy is destroyed whenever an irreversible process occurs. When an exergy analysis is performed on a plant such as an entire power station, a chemical processing plant, the thermodynamic imperfection can be quantified as exergy destruction, which is wasted work or wasted potential for the production work. Like energy, exergy can be transferred or transported across the boundary of the system.

Exergy analysis is a tool for identifying the types, location and magnitude of thermal losses. The exergy method of analysis is a technique of using the second law of thermodynamics in actual system analysis. It is necessary to realize that work can be performed only under conditions that are not at rest in the surrounding environment. More work can be performed when the conditions are farther from equilibrium with the surrounding environment. Therefore, when a system is in equilibrium with its surrounding, it is not possible to use the energy within the system to produce work. At this point, the exergy of the system has been completely destroyed. The state in which the system is in equilibrium with its surrounding is known as the dead state. The exergy analysis is concerned with how well we use the available work that is generated from our energy resources.

The exergy of a substance is the function of its temperature, pressure and composition, as well as of the temperature, pressure and chemical form of this substance when in physical and chemical equilibrium with human environment. Exergy can be also the function of the substance location and velocity. Therefore, the exergy can consist of the following components:

a) **physical exergy** resulting from the temperature and pressure of the substance measured with respect to the temperature and pressure of the environment. The physical exergy is used for analysis of physical processes, in which the kind of the considered substance is unchanged

b) **chemical exergy** resulting from the difference in the substance composition with respect to the common components of this substance in the environment. The chemical exergy is used for analysis of chemical processes, in which unchanged are the chemical elements. The chemical exergy corresponds to the substance calorific value;

c) **kinetic exergy** of the substance, which results from its velocity relative to the environment.

d) **potential exergy** of the substance resulting from the substance location above the ground level.

Most often, in the practical engineering considerations, only the thermal exergy, which is the sum of the physical and chemical exergy, is taken into account. The chemical exergy is important particularly for fuels. The physical exergy is possessed by any substance, whose temperature and/or pressure deviate from the environmental conditions.

3.2 Exergy Change of the System

The property exergy is the work potential of a system in a specified environment and represents the maximum amount of useful work that can be obtained as the system is brought to equilibrium with the environment. Unlike energy, the value of exergy depends on the state of the environment as well as the state of the system. Therefore, exergy is a combination system. The exergy of a system that is in equilibrium with its environment is zero where at this state its called dead state.

The system at this dead state will be at the temperature and pressure of the environment and it will have no kinetic or potential energies relative to the environment. However, it may have a different chemical composition then the environment.

3.2.1 Exergy of a Flow Steam

The flowing fluid has an additional form of energy, its called the flow energy, which is the energy needed to maintain flow in a pipe or duct, and was expressed as $w_{flow} = Pv$ where v is the specific volume of the fluid, which is equivalent to the volume change of a unit mass of the fluid as it is displaced during flow. The flow work is essentially the boundary work done by a fluid on the fluid downstream, and thus the exergy of flow work is equivalent to the exergy of the boundary work, which is the

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