Energy and Exergy Based Performance Analysis of Westinghouse AP1000 Nuclear Power Plant

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By

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DECLARATION

I hereby declare that with the exception of references to other people's work which have been duly acknowledged, this compilation is the result of my own research work and no part of it has been presented for another degree in this university or elsewhere.

………………………….   Date……………………………..

Robert Benjamin Eshun

I hereby declare that the preparation of this project was supervised in accordance with the guidelines of the supervision of thesis work laid down by the University of Ghana.

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Date…………………………..   Date……………………………..

DEDICATION

I dedicate this thesis to my parents Madam Leticia Akuffo and Mr Jacob Kofi Eshun, my siblings Fifi, Angie, Emelia (Ewuradwoa), Isaac (Owuraku), and Naa Ayele, and also Mrs Nana Adwoa Eshun, and my colleagues Gadri, Nti-Agyemang, Djangmah, Darko, Nunoo and Yaa-Takyiwaa.

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LIST of SYMBOLS and ABBREVIATIONS

c	speed of light (m/s)
c	common specific heat capacity (J/kg K) in Eqs. (2.32 and 3.6)
c_{wi}, c_{wo}	condenser cooling water inlet and outlet streams respectively
e	specific energy (J/kg)
E_{cv}	energy transfer in a control volume (J)
E_{in}	energy input (J)
E_{sys}	total energy of system (J)
E_{out}	energy output (J)
Ex	exergy (J)
$\dot{E}_{fuel}$	fuel energy rate (W)
$\dot{Ex}_{fuel}$	fuel exergy rate (W)
g	acceleration due to gravity (m/s^2)
h	specific enthalpy (J/kg)
h_{co}	enthalpy of condenser cooling water outlet (J/kg)
h_{ci}	enthalpy of condenser cooling water inlet (J/kg)
H	enthalpy (J)
I_d	exergy destruction (J)
I	irreversibility (J)
$\dot{I}_d$	exergy destruction (irreversibility) rate (W)
$\dot{I}_{fission}$	irreversibility of fission (W)
$\dot{I}_{fuel}$	Irreversibility in heating fuel centreline (W)
$\dot{I}_{pellet}$	irreversibility rate of heating fuel pellet surface (W)
$\dot{I}_{clad}$	irreversibility rate of clad (W)
$\dot{I}_{coolant}$	irreversibility rate of coolant (W)

$\dot{I}_{reactor}$	irreversibility rate of reactor core (W)
k	Boltzmann constant (J/K)
M	molecular weight (g/g mole)
M'	molecular weight of fission fragments (g/g mole)
m_{sys}	mass of system (kg)
$\dot{m}_i$	mass flow rate of inlet stream(kg/s)
$\dot{m}_{cw}$	mass flow rate of condenser cooling water stream
P	pressure (Pa or atm)
Q	heat flow (J)
$\dot{Q}_{cv}$	rate of heat flow in a control volume (W or J/s)
$\dot{Q}_j$	rate of heat transfer rate at boundary j (W)
$\dot{Q}_{net}$	net heat flow rate (W)
$\dot{Q}_{loss}$	rate of heat loss (W or J/s)
s	specific entropy (entropy per unit mass) (J/kg. K)
S	entropy (J/K)
S_{gen}	entropy generation (J/K)
S_{cv}	net entropy transfer in a control volume (J/K)
T	temperature (K or ^{o}C)
T_a	Temperature of fission fragments (K)
U	internal energy of fluid (J)
u_a	Internal energy of fission fragments (J)
u_i	internal energy of inlet stream(J)
u_e	internal energy of exit stream(J)
v	velocity of stream (m/s)
V	volume (m^3)
W	mechanical work (J)

W_{cv}	net work output in a control volume (J)
w_{flow}	flow work (J)
$W_{rev,out}$	reversible work (J)
$W_{u,out}$	useful work (J)
$\dot{W}_{net}$	net work output rate (W)
$W_{u,total}$	total useful work(W)
$\dot{W}_{u,max}$	maximum useful work (W)
$\dot{W}_{actual}$	actual work rate (W)
$(\dot{W}_{u,\max})_{fission}$	maximum work obtainable from fission (W)
$(\dot{W}_{u,\max})_{fuel}$	maximum work available from fuel centreline (W)
$(\dot{W}_{u,\max})_{pellet}$	maximum work available from fuel pellet surface (W)
$(\dot{W}_{u,\max})_{clad}$	maximum work available from clad surface (W)
$(\dot{W}_{u,\max})_{coolant}$	maximum work obtainable from coolant (W)
$\dot{W}_{HPT}$	work output by high pressure turbine (W)
$\dot{W}_{LPT}$	work output by low pressure turbine (W)
$\dot{W}_{T}$	work rate $W_{rev,out}$ reversible work (J)
x	specific exergy (J/kg)
x_f	specific flow exergy (J/kg)
z	elevation (m)
δW_{surr}	differential change in surrounding work (J)
δW_u	differential change in useful work (J)
δW	differential change in work (J)
ds	differential change in entropy (J/K)
dQ	differential change in heat (J)
dQ_R	reversible heat transfer (J)

ϕ_{th}	thermal neutron flux (n/cm^{2}s)
Σ_f	macroscopic fission cross-section (cm^{-1})
η	energy efficiency (%)
η_s	isentropic efficiency (%)
η_{th}	Carnot efficiency (%)
η_R	energy efficiency of reactor core (%)
η_{plant}	overall energy efficiency of plant (%)
ψ	exergy efficiency (%)
ψ_R	exergy efficiency of reactor core (%)
ψ_{plant}	overall exergy efficiency of plant (%)

FLT	first law of thermodynamics
SLT	second law of thermodynamics
PE	potential energy
KE	kinetic energy
int, rev	internally reversible process

ABSTRACT

Energy and exergy analyses of the performance of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP1000) was conducted with the primary objectives to identify and quantify the operational locations having the largest energy and exergy losses under normal operating conditions.

The energy and exergy losses in the reactor units were determined from formulations of the energy and exergy rate balances based on the Gouy-Stodola theorem. The performance of the overall AP1000 plant was estimated by component wise modeling and detailed break-up of energy and exergy losses in the various plant sections.

Operating at maximum core power of 3400 MW, the AP1000 reactor core experienced moderately small thermal loss of 125.1 MW and very substantial exergy consumption of 1814.8 MW, achieving energy and exergy efficiencies of 96.3 % and 46.6 % respectively.

For the entire AP1000 plant, energy losses occurred mainly in the condenser where 1849.8 MW was lost to the environment. Exergy analysis, however, revealed lost energy in the condenser was thermodynamically insignificant due to the low quality and that irreversible losses in the reactor and steam generator assembly (1868.4 MW) were the major source of irreversibilities in the plant.

The study confirmed that the major heat transfer inefficiencies occurring in nuclear reactor plants resided in the reactor cores, and efforts to increase the efficiency of the station should concentrate on the design of the core components.

CHAPTER ONE

INTRODUCTION

1.1 Background

The current emphasis on energy resource conservation and environmentally sustainable developmental efforts in energy resource extraction, processing, and production endeavours have generated increased interest and prompted both researchers and industries to find high efficiency and low emission solutions to energy related problems.

Conventional energy analysis is based on the first law of thermodynamics which quantifies energy on quantity only. Energy, however, is fully quantified by the quantity and quality (referred to as exergy). Generally, mathematical models based on the first and second laws of thermodynamics are the foundations for any comprehensive analysis of energy related engineering systems.

The exergy concept, derived from the second law of thermodynamics, is poorly understood and applied for performance assessment of energy related systems. Exergy analysis is a recent and rigorous technique that has found increasingly widespread acceptance as a useful tool in the design, assessment, optimization and improvement of energy systems [1].

Exergy is useful for providing a detailed breakdown of the losses for plants and components, in terms of waste emissions and irreversible losses, and quantifies the types, causes and locations of the losses, such that inefficiencies in processes are better pinpointed. In exergy analysis, more meaningful efficiencies are evaluated since exergy efficiencies are always a measure of the approach to the physically ideal output.

1.2 Research Problem

A complete energy analysis of thermal power and other energy intensive systems requires a combination of the first and second laws of thermodynamics to account for the quality and quantity of the energy flows [2].Various irreversible losses exist within the systems, which transform part of the total energy to forms unavailable for power production [3].

The research problem investigated was to develop a mathematical model of the thermodynamic efficiency of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP1000) using energy and exergy methods in order to quantify the locations, types and magnitude of operational losses, and determine the overall performance of the plant.

Mathematical formulations of energy and exergy balances were derived for the primary circuit operating under steady state conditions, and for the individual components of the steam supply system of the AP1000 plant.

1.3 Justification

This study of the energy and exergy characteristics of the nuclear power reactor will contribute and offer a deeper insight into the energy and fuel use profile of nuclear stations.

Further, the study will yield operational data on the sources and magnitude of losses in the reactor systems, and the extent to which each component approaches the ideal output. Thus sites of inefficiencies would be pinpointed to inform on future improvement in the design of new systems for more efficient energy conversion and reduced fuel usage.

Facing a huge shortfall in the supply of energy, Ghana plans to augment its energy production mix with nuclear power in the foreseeable future. With the AP1000 being one of the likely choice of reactors [4], the study would serve as a fundamental thermodynamic assessment of the various components of the reactor plant, and provide the platform for conducting further performance and efficiency research on the plant.

A comprehensive energy and exergy analyses of the Westinghouse AP1000 thermodynamic systems would provide valuable performance data as presently no literature exists on the exergetics and performance levels of the AP1000 plant.

1.4 Research Objectives

The objectives of the research included:

- Formulation of energy and exergy balances for the Westinghouse AP1000 power reactor system under steady state conditions.
- Determination of the magnitude of energy losses and dissipations (or exergy consumptions) in the energy conversion processes within the components of the reactor assembly.
- Identification of the locations and types of irreversibilities within the systems, and specification of the sites or components that contribute significant losses to the system.
- Determination of the energy and exergy efficiency of the reactor components and the overall operating efficiencies under nominal conditions.
- Contributing to a comprehensive understanding of the thermodynamic characteristics of reactor systems.

1.5 Energy Analysis

Conventional energy analysis is based primarily on the first law of thermodynamics (FLT), which stipulates the principle of energy conservation. Energy is conserved by the amounts of energy of various forms (mass flows, heat and work) transferred between a system and surroundings, and in the changes in the energy stored within the system [5].

Energy analysis of thermal systems is essentially an accounting of the energies entering and exiting the system. The exiting energy can be broken down into products and wastes. The only inefficiencies detected by the energy analysis of a system are the energy transfers out of the system that are not further used in the installation [6, 7].

Energy efficiencies thus emphasize reducing energy emissions or wastes to improve efficiency. The thermodynamic losses which occur within systems due to the irreversible nature of real processes are often not accurately identified and assessed.

Consequently, energy analysis provides no information on the degradation of energy or resources during a process and does not quantify the usefulness of the various energy and material streams flowing through a system and exiting as products and wastes.

The results of energy analysis can therefore indicate the main inefficiencies to be within the wrong sections of the system, and a state of technological efficiency different than actually exists. Therefore, energy analysis does not always provide a measure of how nearly the performance of a system approaches ideality [6].

1.6 Exergy Analysis

Energy is conserved in all interactions. However, all real processes involve energy losses. In real processes, energy is not destroyed but rather transformed into other forms, less suitable for feeding and driving real processes. Hence beside energy, the concept of exergy was introduced to characterize the quality of the energy under consideration [8].The exergy method of analysis, based on the second law of thermodynamics and the concept of irreversible production of entropy, overcomes the limitations of energy analysis.

Exergy is the maximum work potential of energy in relation to the environment and is a measure of the ability to do work by the variety of energy streams (mass, heat, and work) that flow through a system [9].The key principle of exergy is the provision of common grounds for the comparison of the various energy streams based on the mechanical work obtainable from the energy stream.

The term exergy comes from the Greek words '*ex'* and '*ergon'*, meaning 'external' work. Exergy is conserved only when all processes occurring in a system and the environment are reversible. Exergy is destroyed whenever an irreversible process occurs due to the generation of entropy in a system [6].

The elementary irreversible phenomena that generate entropy are mechanical or hydraulic friction, heat transfer with a finite temperature gradient, diffusion with a finite gradient of concentration, and the mixing of substances with different parameters and chemical composition [8].

In systems analysis, the irreversibilities associated with combustion, heat transfer, mixing and pressure losses are considered separately to estimate the contribution of each to the total exergy destruction in a system [10].

Exergy losses represent the true losses of potential that exist to generate a desired energy output by accurately quantifying the entropy generation of the components [11].Exergy efficiency therefore provides a measure of how nearly the operation of a system approaches the ideal or theoretical upper limit and gives clear insights into process performance, as energy flows are weighted according to exergy contents and losses are separated into heat losses to surroundings and energy dissipations within the system[6].

1.7 Nuclear Power Plants

Nuclear reactors produce and control the release of energy from fission chain reactions. The energy released from continuous fission of the atoms of the fuel is harnessed as heat in either a gas or water (which is used to produce steam). The steam is used to drive the turbines which produce electricity, as in most fossil fuel plants.

Uranium is the basic fuel. Pellets of uranium oxide (UO_2) are typically arranged in long zirconium alloy (zircaloy) tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core. Moderator material in the core slows down the neutrons released from fission so that they cause more fission. The material is usually water, but may be heavy water or graphite.

Control rods made with neutron-absorbing material such as cadmium, hafnium or boron, are inserted or withdrawn from the core to control the reaction rate, or to halt it. A coolant fluid circulating through the core transfers the heat to the steam generator where the heat from the core is used to make steam for the turbine.

The main power reactor designs are the pressurized water reactor (PWR) and boiling water reactor (BWR). PWRs are the most common power reactor type. The PWR

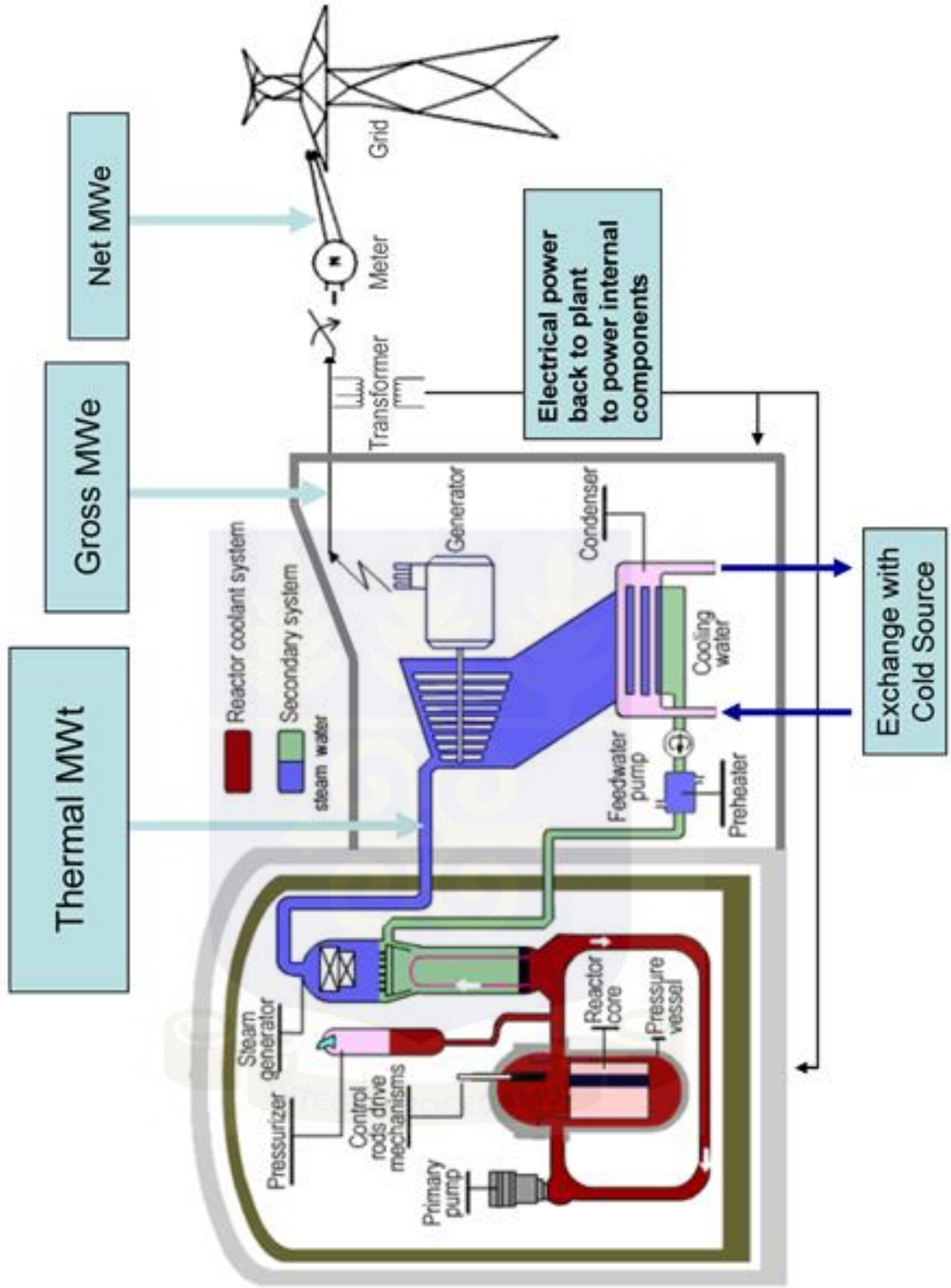


Fig. 1.1 The components and cycles of a PWR nuclear power plant [12].

design (see Fig. 1.1) is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure, and a secondary circuit in which steam is generated to drive the turbine.

A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies with 80-100 tonnes of uranium. Water in the reactor core reaches about 325°C, hence it must be kept under about 150 times atmospheric pressure (15 MPa) to prevent it boiling. Pressure is maintained by steam in a pressurizer. In the primary cooling circuit the water is also the moderator, and if any of it turned to steam the fission reaction would slow down. The secondary circuit is under less pressure and the water here boils in the heat exchangers which are thus steam generators. The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit.

The BWR design has many similarities to the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C.

The reactor is designed to operate with 12-15% of the water in the top part of the core as steam, and hence with less moderating effect and thus efficiency there. The steam passes through drier plates (steam separators) above the core and then directly to the turbines, which are thus part of the reactor circuit [12].

1.8 Description of AP1000 Plant

The AP1000 is an advanced pressurized water reactor (PWR) plant developed by Westinghouse Electric Company of USA. It is based on a conventional 2-loop, 2-

steam generator primary system configuration. AP1000 is rated at 3400 MWt core power and contains 157 fuel assemblies, similar to Doel 4 and Tihange 3[13].

The fuel rods consist of enriched uranium, in the form of cylindrical pellets of uranium dioxide (UO_2), contained in ZIRLO™ tubing. The tubing is plugged and seal welded at the ends to encapsulate the fuel.

The fuel rods in the AP1000 fuel assemblies contain additional gas space below the fuel pellets, compared to other previous fuel assembly designs to allow for increased fission gas production due to high fuel burnups. A cross-sectional view of the fuel rod is shown in Fig. 1.2.

The thermal-hydraulic design parameters described in Table 1.1, establish that adequate heat transfer is provided between the fuel clad and the reactor coolant. The reactor core is cooled and moderated by light water at a pressure of 15.5 MPa. Soluble boron in the moderator/coolant serves as a neutron absorber. The concentration of boron is varied to control reactivity changes that occur relatively slowly, including the effects of fuel burnup [14].

AP1000 features passive emergency core cooling and containment cooling systems. The active systems required to mitigate design basis accident conditions have been replaced by simpler, passive systems relying on gravity, compressed gases, or natural circulation instead of pumps [13].

The reactor coolant system consists of two heat transfer circuits, each with a steam generator, two reactor coolant pumps, and a single hot leg and two cold legs for circulating reactor coolant. In addition, the system includes the pressurizer,

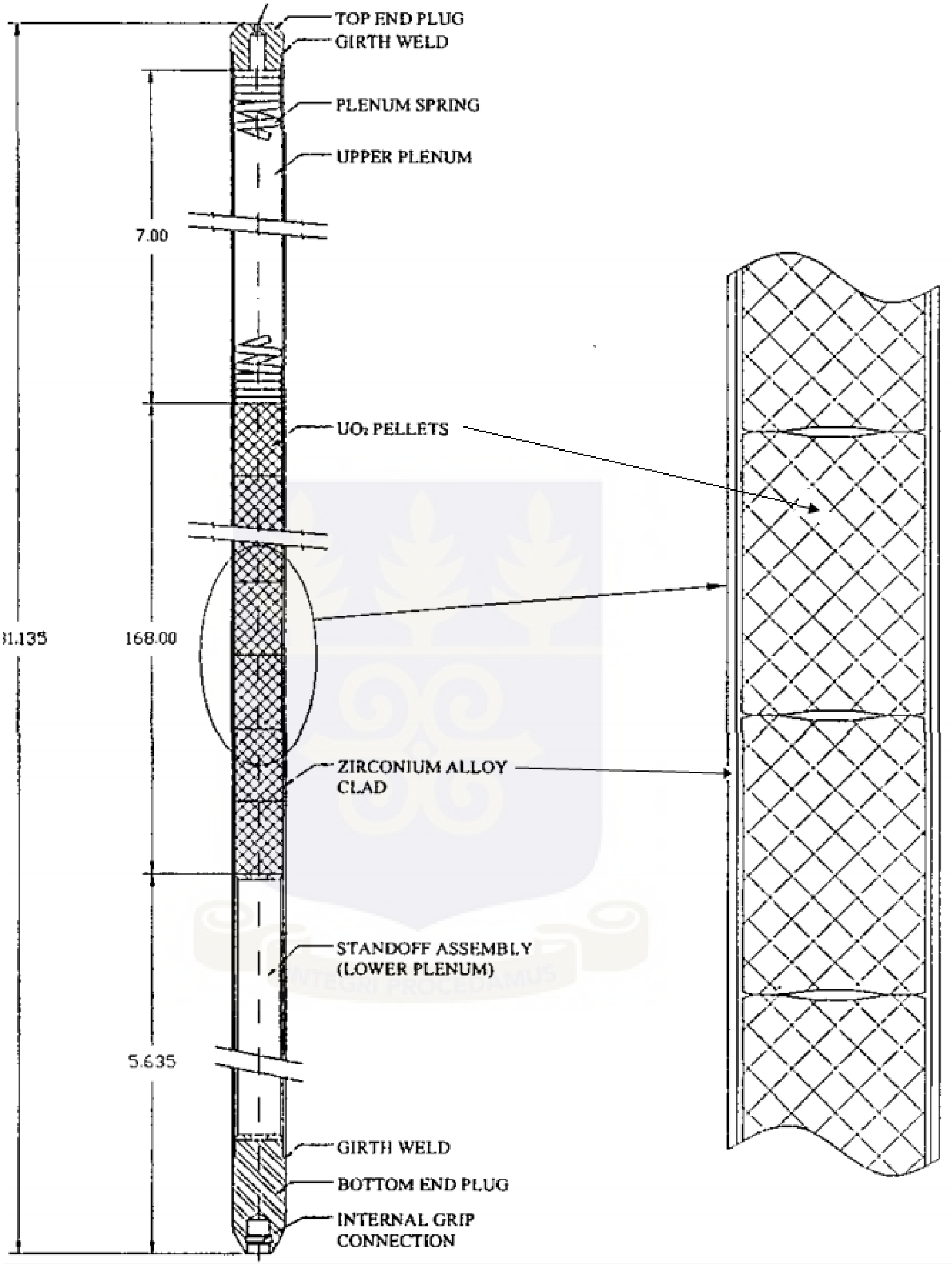


Fig. 1.2 Fuel rod schematic of AP1000 reactor [15].

Table 1.1 Thermal-hydraulic parameters of AP1000 [14].

Thermal and Hydraulic Design Parameters	**AP1000**
Fuel assembly design	17x17 XL Robust Fuel
Number of fuel assemblies	157
Uranium dioxide rods per assembly	264
Rod pitch (in.)	0.496 (1.26 cm)
Overall dimensions (in.)	8.426 x 8.426 (21.40 x 21.40 cm)
Fuel weight, as uranium dioxide (lb)	211,588 (95974.7 kg)
Clad weight (lb)	43,105 (19552.1 kg)
Number of grids per assembly Top and bottom – (Ni-Cr-Fe Alloy 718) Intermediate Intermediate flow mixing	 2 8 ZIRLO™ 4 ZIRLO™
Loading technique, first cycle	3 region non uniform
Fuel Rods	
Number	41,448
Outside diameter (in.)	0.374 (0.95 cm)
Diametral gap (non-IFBA) (in.)	0.0065 (0.016 cm)
Clad thickness (in.)	0.0225 (0.057 cm)
Clad material	ZIRLO™
Fuel Pellets	
Material	UO_2 sintered
Density (% of theoretical)	95.5
Diameter (in.)	0.3225 (0.819 cm)
Length (in.)	0.387 (0.98 cm)

Interconnecting piping, valves, and instrumentation for operational control and safeguards actuation. All reactor coolant system equipment is located in the reactor containment.

During operation, the reactor coolant pumps circulate pressurized water through the reactor vessel then the steam generators. The water serves as coolant, moderator, and solvent for boric acid (chemical shim control) and is heated as it passes through the core. It is transported to the steam generators where the heat is transferred to the secondary coolant. It is then returned to the reactor vessel by the pumps to repeat the process [16].

The reactor coolant system pressure is controlled by operation of the pressurizer, where water and steam are maintained in equilibrium by the activation of electrical heaters or a water spray, or both. Steam is formed by the heaters or condensed by the water spray to control pressure variations due to expansion and contraction of the reactor coolant. The reactor coolant system arrangement is shown in Fig. 1.3.

The steam and power conversion system is designed to remove heat energy from the reactor coolant system via the two steam generators and to convert it to electrical power in the turbine-generator. The main condenser de-aerates the condensate and transfers heat that is unusable in the cycle to the circulating water system. The regenerative turbine cycle heats the feedwater, and the main feedwater system returns it to the steam generators.

The steam generated in the two steam generators is supplied to the high-pressure turbine by the main steam supply system. After expansion through the high-pressure turbine, the steam passes through the two moisture separator/ reheaters (MSRs) and is

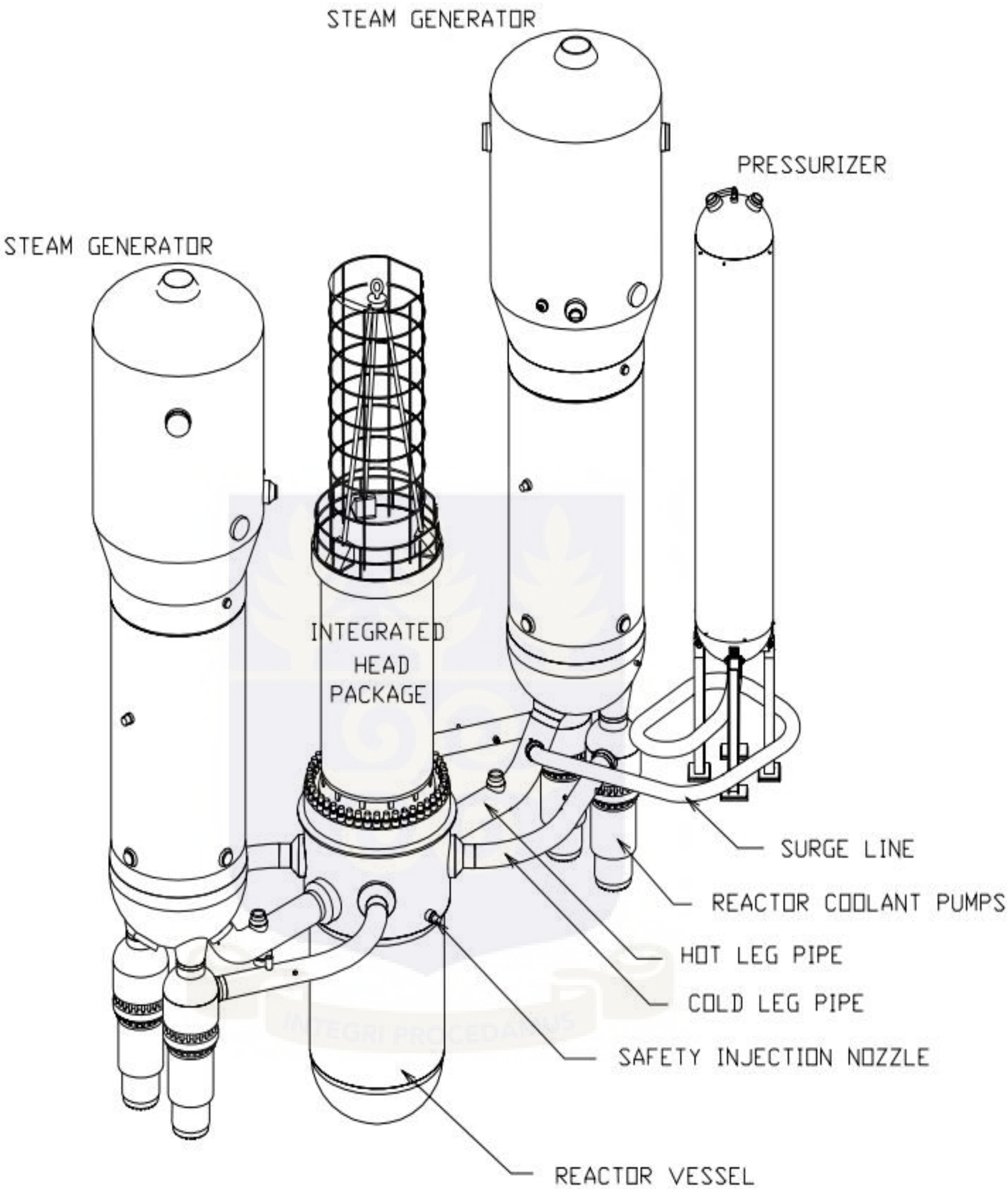


Fig.1.3 AP1000 reactor coolant system showing the reactor and steam generator assembly [16].

then admitted to the three low-pressure turbines. A portion of the steam is extracted from the high- and low-pressure turbines for six stages of feedwater heating.

Exhaust steam from the low-pressure turbines is condensed and deaerated in the main condenser. The heat rejected in the main condenser is removed by the circulating water system (CWS). The condensate pumps take suction from the condenser hotwell and deliver the condensate through four stages of low-pressure closed feedwater heaters to the fifth stage, open deaerating heater.

Condensate then flows to the suction of the steam generator feedwater booster pump and is discharged to the suction of the main feedwater pump. The steam generator feedwater pumps discharge the feedwater through one stage of high-pressure feedwater heating to the two steam generators. The turbine-generator has an output of about 1,199,500 kW for the Westinghouse nuclear steam supply system (NSSS) thermal output of 3,415 MWt [17].

1.9 Scope of the Research

The research investigated the energy and exergy characteristics of the AP1000 power reactor under normal operating conditions. Chapter 1 introduced the background to the study, the distinction between energy and exergy methods and gave a brief description of the AP1000 reactor system.

Chapter 2 provided the general definitions, basic principles and implications, and practical applications of energy and exergy whilst Chapter 3 presented the methodologies for the energy and exergy evaluation of water cooled nuclear reactors.

Chapter 4 presented the results of the energy and exergy analyses of AP1000, and discussion of the findings in relation to other published works. Finally, Chapter 5 summarized the research work as conclusions and presented recommendations for further investigation of the processes and concepts.

CHAPTER TWO

LITERATURE REVIEW

Normal energy analysis evaluates energy on quantity basis only [18]. However, the concept of exergy complements and enhances an energetic analysis by calculating the true thermodynamic value of an energy carrier, the real inefficiencies and variables that unambiguously characterize performance of the system (or its components) [7].Performing energy and exergy analyses therefore give a complete depiction of system characteristics [19].

The energy and exergy methods stem from thermodynamics and are applicable to divergent schemes of energy processes. For instance Mady et al. [20] applied exergy analysis to the human body to assess the quality of the energy conversion processes that take place in its several organs and systems and, Hepbasli [21] undertook an exergetic analysis review and performance evaluation of solar, wind, geothermal and other renewable energy resources.

In the literature, there exist a number of publications on the exergetic analysis of thermal systems. Rashad & Maihy [1] analyzed the system components of the Shobra El-Khima power plant in Cairo to quantify the sites having largest energy and exergy losses. Ebadi & Gorji-Bandpy [11] performed a thermo-mechanical and chemical exergy analysis for a116MW gas-turbine power plant located in Mahshahr, Iran.

Reddy et al. [5] performed thermodynamic analysis of coal based thermal power plants and gas based cogeneration power plants using energy and exergy methods. Lebele & Alawa [22] used energy and exergy models to evaluate the optimal performance parameters of the 20MWgas turbine plant at Kolo-Creek power station, and Kaushik et al. [19] presented a comparison between energy and exergy analysis of thermal power plants stimulated by coal and gas. In Ghana, Mborah and Gbadam [18] evaluated the exergetic performance of the 500kW steam power plant operated at the Benso Oil Palm plantation in Ghana.

The principles of using the second law of thermodynamics (SLT) and exergy methods in the performance analyses of nuclear systems have been elaborated in literature review. Lahey & Moody [3] used formulations of the SLT and entropy to analyze energy processes found in BWRs in order to determine the loss of available power.

Todreas & Kazimi [23] developed working forms of the first law of thermodynamics (FLT) and SLT to analyze control volume and control mass schemes and processes of nuclear systems. Dincer [6] presented energy and exergy based comparison of coal fired and nuclear steam power plants, detailing the stepwise breakdown of the energy and exergy losses in the reactor core.

2.1 The First Law of Thermodynamics (FLT)

The first law of thermodynamics defines energy as a conserved quantity and is expressed as:

$$E_{in} - E_{out} = \Delta E_{sys} \tag{2.1}$$

where E_{in} is the energy input, E_{out} is the energy output and ΔE_{sys} is the energy change in the system.For a closed system, the only forms of energy that can be supplied or removed from the system are heat and work. But the change in the total energy of the system during a process is the sum of the changes in its internal, kinetic, and potential energies. Therefore the closed system energy balance can be expressed as:

$$Q - W = \Delta U + \Delta KE + \Delta PE \tag{2.2}$$

Where Q is thermal energy, W is work, ΔU is change in internal energy, ΔKE and ΔPE are respectively change in kinetic and potential energies. For a stationary system, in which no velocity and elevation change during a process, the change of the total energy of the system is due to the change of the internal energy only, i.e.

$$Q - W = \Delta U \tag{2.3}$$

In an open flow system there are three types of energy transfer across the control surface, namely, work transfer, heat transfer, and energy associated with mass transfer or flow [19].

2.1.1 Energy and Work

The fluid entering or leaving a control volume (V) possess additional energy known as flow work w_{flow} which is the work done due to pushing the entire fluid element across the boundary into the control volume, and on a unit mass basis is given as,

$$w_{flow} = PV \tag{2.4}$$

where P is pressure. Thus the total specific energy (e) of a flowing fluid becomes [24],

$$e = PV + u + \frac{v^2}{2} + gz \tag{2.5}$$

where$v$ is velocity, g is acceleration due to gravity and z is elevation.

Since the specific enthalpy(h) is defined as,

$$h = u + PV \tag{2.6}$$

then,

$$e = h + \frac{v^2}{2} + gz \tag{2.7}$$

2.1.2 Energy Balance

The conservation of energy principle applied to control volumes states that the time rate of change in the total energy of a system $\frac{dE_{cv}}{dt}$ equals the net rate at which energy is being transferred in by heat transfer and mass flow less the net rate at which energy is being transferred out by work and is expressed as [25],

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(u_i + p_i V_i + \frac{v_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(u_e + p_e V_e + \frac{v_e^2}{2} + gz_e \right) \tag{2.8}$$

where $\dot{m}$ is mass flow rate, $\dot{Q}$ is heat transfer rate and $\dot{W}$ is the rate of mechanical energy transfer. Equation (2.8) is rewritten as

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right) \tag{2.9}$$

For one dimensional flow through a single inlet and exit stream, the energy rate balance reduces to:

$$\frac{dE_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i \left(h_i + \frac{v_i^2}{2} + gz_i \right) - \dot{m}_e \left(h_e + \frac{v_e^2}{2} + gz_e \right) \tag{2.10}$$

The conservation of mass principle is therefore expressed as,

$$\frac{dm_{sys}}{dt} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \tag{2.11}$$

At steady state there is no accumulation of mass within the control volume

$(dm_{cv}/dt = 0)$. The mass rate balance takes the form

$$\dot{m}_i = \dot{m}_e \tag{2.12}$$

Further, at steady state $dE_{cv}/dt = 0$, therefore the energy rate balance can be written as,

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{v_e^2}{2} + gz_e\right) \tag{2.13}$$

For the steady state flow from state 1→2, the mass flow balance reduces to,

$$\dot{m}_1 = \dot{m}_2 \tag{2.14}$$

and the energy rate balance becomes

$$\dot{Q}_{cv} - \dot{W}_{cv} = \dot{m}\left[(h_2 - h_1) + \left(\frac{v_2^2 - v_1^2}{2}\right) + g(z_2 - z_1)\right] \tag{2.15}$$

2.2 The Second Law of Thermodynamics (SLT) and Entropy

Entropy is a randomized energy state that is unavailable to do work [6].According to the SLT, it is impossible for any system to operate in a way that entropy is destroyed [25].Entropy is an abstract property. However, its gradient, or change, can be used to determine the loss of available power [3].

The definition of entropy change (dS) for a system undergoing an internally reversible process, expressed on a differential basis is [24]:

$$dS = \left(\frac{dQ}{T}\right)_{\substack{int\\rev}} \tag{2.16}$$

where dQ is differential heat and T is temperature.

For a fixed mass system, as shown in Fig. 2.1, which contains an amount of entropy, S, with heat inflow $dQ_{R,in}$ and outflow $dQ_{R,out}$ at temperatures T_{in} and T_{out} respectively, the differential change of entropy is given as[3],

$$dS = \frac{dQ_{R,in}}{T_{in}} - \frac{dQ_{R,out}}{T_{out}} \tag{2.17}$$

where dQ_R designates idealized reversible heat transfer without temperature gradients.

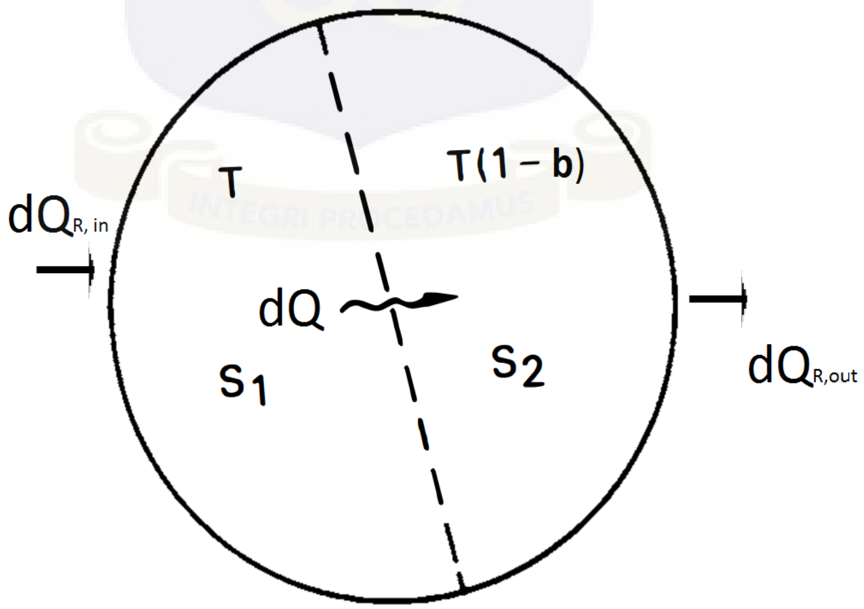


Fig. 2.1 A fixed mass, isolated system with heat transfer dQ from region 1 at temperature $T$and entropy S_1, and region 2 at $T(1-b)$ and S_2 respectively [3].

If we assume one region of the isolated system is at uniform temperature T , and the other region is at $T(1-b)$ where b is a small quantity, the temperature difference causes a differential amount of heat transfer dQ to occur from the region at higher temperature to the lower one over an unspecified period of time. Since entropy is an extensive property, the total system entropy is,

$$S = S_1 + S_2 \tag{2.18}$$

Its differential dS is given as [3]

$$dS = dS_1 + dS_2 = -\frac{dQ}{T} + \frac{dQ}{T(1-b)} = \frac{dQ}{T}(b + b^2 \ldots) \geq 0 \tag{2.19}$$

which shows that the system's total entropy increases. Viewed from the microscopic standpoint, the system becomes more disorderly as entropy increases.

As system undergoing a thermodynamic process from state 1→2 (See the temperature-entropy diagram of Fig. 2.2) the increase of entropy principle states that,

$$\Delta S = S_2 - S_1 \geq \int_1^2 \frac{\delta Q}{T} \tag{2.20}$$

The above expression can be expanded as:

$$\Delta S \; = \; S_2 - S_1 \; = \; \int_1^2 \frac{\delta Q}{T} \; + \; S_{gen} \tag{2.21}$$

$$\begin{pmatrix} entropy \\ change \end{pmatrix} \qquad \begin{pmatrix} entropy \\ transfer \end{pmatrix} \begin{pmatrix} entropy \\ generation \end{pmatrix}$$

where S_{gen} is the entropy generated (or produced) within the system by the action of irreversibilities [24]. Thus,

$$S_{gen} = \Delta S_{total} = \Delta S_{sys} + \Delta S_{\text{surr}} \tag{2.22}$$

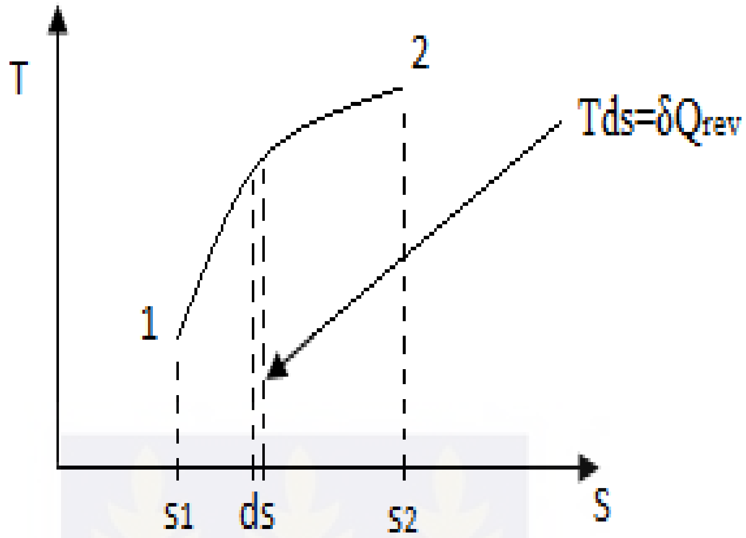


Fig. 2.2 T-S diagram of entropy change of internally reversible cycle.

2.2.1 Entropy Analysis

The elementary phenomena that generate entropy are: mechanical or hydraulic friction, heat transfer with a finite temperature gradient, diffusion with a finite gradient of concentration, and the mixing of substances with different parameters and chemical composition [8].

Entropy is transferred by two mechanisms: heat transfer and mass flow. The entropy transfer associated with heat transfer process is;

$$S_{heat} = \int_1^2 \frac{\delta Q}{T} \tag{2.23}$$

With constant boundary temperature T, the above equation can be simplified as

$$S_{heat} = \frac{Q}{T} \tag{2.24}$$

The entropy transfer associated with mass flow is given by,

$$S_{mass} = ms \tag{2.25}$$

The general balance for entropy is stated as [6],

$entropy\ change = entropy\ input - entropy\ output + entropy\ generation,$

ie. $$\Delta S = S_{in} - S_{out} + S_{gen} \tag{2.26}$$

For a control volume, the rate form of the entropy balance is derived as:

$$\frac{dS_{cv}}{dt} = \sum_j \frac{\dot{Q}_j}{T_j} + \sum_i \dot{m}_i s_i - \sum_e \dot{m}_e s_e + \dot{S}_{gen} \tag{2.27}$$

where the term $\frac{\dot{Q}_j}{T_j}$ represents the time rate of entropy transfer through the portion of the boundary whose instantaneous temperature is T_j [25].

At steady state, $\frac{dS_{cv}}{dt} = 0$. For a control volume having a single inlet and outlet stream, this leads to,

$$0 = \frac{\dot{Q}}{T} + \dot{m}(s_i - s_e) + \dot{S}_{gen} \tag{2.28}$$

The combined statement of the FLT and SLT, in differential form, for a closed system undergoing an internally reversible process gives

$$dU = \delta Q_{rev} - \delta W_{rev} \tag{2.29}$$

From equation (2.16) $\delta Q_{rev} = Tds$, and the only significant work in an internally reversible process is associated with volume change and given as $\delta W_{rev} = pdV$.

Thus equation (2.29) can be rewritten on a unit mass basis as Gibbs equation:

$$du = Tds - pdv \tag{2.30}$$

Introducing enthalpy, $h = u + pv$, the differential yields

$$dh = du + pdv + vdp$$

Replacing $du + pdv$ with Tds gives

$$dh = Tds + vdp \tag{2.31}$$

For the incompressible model, $v = constant$ and $u = u(T)$. Thus,

$$h(T, p) = u(T) + pv$$

Differentiating $h(T, p)$ with respect to temperature at fixed pressure gives $c_p = c_v = c$, the common specific heat.

As equation (2.30) reduces to $du = Tds$ and $du = c(T)dT$, the change in specific entropy is [24]

$$\Delta s = \int_{T1}^{T2} \frac{c(T)}{T} dT$$

$$= c \ln \frac{T_2}{T_1} \tag{2.32}$$

2.3 Exergy

Energy conservation, expressed by the energy balance, can determine energy supply requirements in the form of streams of matter, heat and work, but fails to provide accurate information on how efficiently the supplied energy is used in a system.

An entropy balance determines the entropy generation within a system which is a measure of the inefficiencies within it. However, entropy is an abstract concept which does not allow us to develop objective measures of the efficiency with which energy is used in a system.

In thermodynamics the true thermodynamic value (or quality) of an energy carrier is characterized by its exergy**.** The ability to perform mechanical work has been accepted as a measure of the quality of the energy form, characterizing its ability to be transformed to into other kinds of energy**.** The concept of exergy is derived from the SLT and defined as the maximum theoretical work obtainable from an overall system consisting of a system and the environment as the system comes into equilibrium with the environment [25].

In comparison with energy, exergy is a function of state of the considered matter and of the environment [26], and identifies the loss of available energy in conversion systems by accurately quantifying the entropy generation or irreversibilities within it**.**

There are many effects whose presence during a process renders it irreversible. These include but are not limited to [24] (i) heat transfer through a finite temperature difference, (ii) unrestrained expansion of a gas or liquid to a lower pressure, (iii) spontaneous chemical reaction, (iv) mixing of matter at different compositions or states, (v) friction, (vi) electric current flow through a resistance, (vii) magnetization, (viii) inelastic deformation.

Exergy is evaluated with respect to a reference environment which acts as a sink for heat and materials. The reference environment is a large equilibrium system, in which the state variables(T_o andP_o) and the chemical potential of the chemical components contained in it remain constant [7]. Thus, the intensive properties of the reference environment determine the exergy of a system. [6].

2.3.1 Exergy and Work

A system will deliver the maximum possible work if it undergoes a reversible process from the specified initial state to its dead state. This work represents the useful work potential of the system at the specified initial state and is called exergy of the specified initial state [27].

A system contains energy in numerous forms such as kinetic energy, potential energy, internal energy, flow work and enthalpy. The exergy of a system is the sum of the exergies of different forms of energy it contains. The relations between the exergy associated with different energy forms are developed below.

Kinetic energy and potential energy are forms of mechanical energy and can be completely converted to work regardless of the surroundings. Thus the specific exergy (x) of these forms is given by

$$x_{ke} = ke = v^2/2 \tag{2.33}$$

$$x_{pe} = pe = gz \tag{2.34}$$

Useful work is defined as the difference between the actual work and the surrounding work and expressed in differential form as,

$$\delta W_u = \delta W - \delta W_{surr} \tag{2.35}$$

where,

$$\delta W_{surr} = P_o dV \tag{2.36}$$

From the entropy relation (equation 2.30),

$$TdS = dU + \delta W \tag{2.37}$$

This implies that,

$$\delta W_u = TdS - dU - P_o dV \tag{2.38}$$

Integrating from the initial to the final state gives the exergy associated with internal energy as:

$$W_{u,total} = (U - U_o) + P_o(V - V_o) - T_o(S - S_o) \tag{2.39}$$

Flow work is essentially boundary work, and the exergy of flow work equals the exergy of boundary work, which is the difference between the boundary work PV and the surroundings work $P_o V$. On a unit mass basis,

$$x_{pv} = PV - P_o V \tag{2.40}$$

where V is the specific volume.

Enthalpy is defined as the sum of internal energy and flow work. The specific enthalpy is given as

$$h = u + PV \tag{2.41}$$

Thus the exergy associated with enthalpy is given as

$$Ex_h = Ex_u + Ex_{pv} \tag{2.42}$$

On a unit mass basis [27],

$$x_h = (u - u_o) + P_o(V - V_o) - T_o(s - s_o) + (PV - P_o V)$$

$$= (h - h_o) - T_o(s - s_o) \tag{2.43}$$

The total exergy of a system is made up of four components namely physical exergy, kinetic exergy, potential exergy and chemical exergy [21].

$$Ex = Ex_{ph} + Ex_{ke} + Ex_{pe} + Ex_{ch} \tag{2.44}$$

Neglecting chemical energy, the exergy of a steady flow stream of matter (Ex_f) is the sum of kinetic, potential and physical exergy respectively [19]. This is also known as the thermo-mechanical exergy. The kinetic and potential energy are almost equivalent to exergy, and were given from equations (2.33) and (2.34) as,

$$Ex_{ke} = KE \tag{2.45}$$

$$Ex_{pe} = PE \tag{2.46}$$

The physical exergy of a flow process is given from equation (2.43) as,

$$Ex_{ph} = (H - H_o) - T_o(S - S_o) \tag{2.47}$$

Thus the specific exergy (x_f) of a steady flow stream is given as,

$$x_f = (h - h_o) - T_o(s - s_o) + v^2/2 + gz \tag{2.48}$$

2.3.2 Exergy, Heat Transfer and Work

Heat transfer is always accompanied by exergy transfer. The maximum work that can be obtained from a heat source at constant temperature T is the work output from a Carnot heat engine which works between this heat source and the environment at T_o [27]. The Carnot efficiency of the Carnot heat engine is given as,

$$\eta_{th} = 1 - \frac{T_o}{T} \tag{2.49}$$

Therefore, the exergy of the heat Q transferred is given as,

$$Ex_q = \left(1 - \frac{T_o}{T}\right) Q \tag{2.50}$$

When the temperature at the location of heat transfer is not constant, the exergy transfer accompanying heat transfer is

$$Ex_q = \int \left(1 - \frac{T_O}{T}\right) \delta Q \tag{2.51}$$

Exergy transfer by shaft work or electric work is equal to the work itself and is given as

$$Ex_w = W \tag{2.52}$$

The exergy transfer accompanying boundary or expansion work equals the difference between the expansion work and the surrounding work. That is:

$$Ex_{w,b} = W - P_o(V_2 - V_1) \tag{2.53}$$

Mass contains exergy as well as energy and entropy. The rate of exergy transfers to or from a system is proportional to the flow rate. When a mass m enters or leaves a system, exergy mx_{flow} enters or leaves a system as well. Thus

$$Ex_m = mx_{flow} = m[(h - h_o) - T_o(s - s_o) + v^2/2 + gz] \tag{2.54}$$

2.3.2 Exergy Destruction and Irreversibility

The exergy destruction represents the exergy destroyed I_d due to irreversibilities within a system. Irreversibilities are effects whose presence during a process renders it irreversible. A process is irreversible if there is no way to restore the system and its surroundings to their exact initial states [24].

There are many effects whose presence during a process renders it irreversible. These include mechanical or hydraulic friction, heat transfer with a finite temperature gradient, diffusion with a finite gradient of concentration, and the mixing of substances with different composition [8].

The exergy destruction (or irreversibility) I_d within a system is related to the entropy generation by the Gouy-Stodola theorem given as [19],

$$I_d = T_o S_{gen} \tag{2.55}$$

There are two types of irreversibilities created within a system. These are internal and externally generated irreversibilities. Internal exergy losses appear inside the analyzed process. The primary contributors to internal exergy destruction are irreversibilities associated with chemical reaction, heat transfer, mixing of streams, and friction [10].

External exergy losses occur after the rejection of waste products of the process to the environment [26]. When a material or energy stream is rejected to the surroundings (eg. flue gas, cooling water and heat loss), the exergy associated with this stream is an external exergy loss for the overall system.

For component analysis, the transfer of thermal exergy to the surroundings is the only external exergy loss in the system. Let the term $\dot{Q}_L$ denotes the heat transfer to the surroundings and T_L the temperature on the boundary where heat transfer occurs.

The control volume enclosing the system component can be selected to encompass the system component and enough of its nearby surroundings so that the heat loss occurs at the ambient temperature T_o and the term $\dot{E}x_{q,L}$ in an exergy balance vanishes. Thus the thermodynamic inefficiencies in a system component consist exclusively of internal exergy destruction [10].

$$\dot{E}x_{q,L} = \left(1 - \frac{T_o}{T_L}\right)\dot{Q}_L \tag{2.56}$$

Irreversibility (total exergy loss) is defined as the difference between the reversible work and the useful work. It is expressed as [27]

$$I = W_{rev,out} - W_{u,out}$$

$$= \dot{W}_{u,max} - \dot{W}_{actual} \tag{2.57}$$

Where the useful work is defined as

$$W_u = W - W_{surr}$$

Alternatively exergy consumption (or destruction) is expressed as the difference between the total exergy flows into and out of the system, less the exergy accumulation in the system (or component) and given mathematically as [6].

Exergy consumption =Exergy input – Exergy output – Exergy accumulation

At steady state, the accumulation term vanishes and the irreversibility of a process can be defined as the difference between the desired exergy outputs and the total exergy inputs [28], i.e.

$$I = \sum Ex_{in} - \sum Ex_{out} \tag{2.58}$$

The exergy destruction in the overall system is equal to the sum of the exergy destruction in all system components [7]

2.3.3 Exergy Balance

By combining the conservation law for energy and the non-conservation law for entropy for a system with inlet i and outlet e streams, the exergy balance can be expressed as:

$$\Delta Ex = \sum_j Ex_{Qj} - Ex_W + \sum_i Ex_{mi} - \sum_e Ex_{me} - I_d \tag{2.59}$$

The exergy balance is expanded in rate form for a control volume as [25],

$$\frac{dEx_{cv}}{dt} = \sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_j - \left(\dot{W}_{cv} - p_o \frac{dV_{cv}}{dt}\right) + \sum_i \dot{m}_i\, x_{fi} - \sum_e \dot{m}_e\, x_{fe} - \dot{I}_d \tag{2.60}$$

At steady state, $dEx_{cv}/dt = dV_{cv}/dt = 0$, giving the steady-state exergy rate balance as,

$$0 = \sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \sum_i \dot{m}_i\, x_{fi} - \sum_e \dot{m}_e\, x_{fe} - \dot{I}_d \tag{2.61}$$

For a single inlet and exit stream, denoted by process 1→2, the steady-state exergy rate balance reduces to,

$$0 = \sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_j - \dot{W}_{cv} + \dot{m}(x_{f1} - x_{f2}) - \dot{I}_d \tag{2.62}$$

or,

$$\sum_j \left(1 - \frac{T_o}{T_j}\right) \dot{Q}_j = \dot{W}_{cv} + \dot{m}(x_{f2} - x_{f1}) + \dot{I}_d \tag{2.63}$$

where the change in specific flow exergy is expanded as,

$$x_{f1} - x_{f2} = (h_1 - h_2) - T_o(s_1 - s_2) + \frac{v_1^2 - v_2^2}{2} + g(z_1 - z_2)$$

Closed systems only have heat transfer and work interactions with no mass flow out of the system. The exergy rate balance therefore reduces to

$$\dot{W} = \sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j - \dot{I}_d \tag{2.64}$$

2.4 First and Second Law Efficiency Ratios

The energy balance for a system undergoing a thermodynamic cycle with no net change in its energy is given by,

$$\dot{W}_{cycle} = \dot{Q}_{in} - \dot{Q}_{out} \tag{2.65}$$

where $\dot{W}_{cycle}$ is the net work output by the cycle.

The thermal or energy efficiency η of such a system is defined as [23],

$$\eta = \frac{\dot{W}_{cycle}}{\dot{Q}_{in}} = \frac{\dot{W}_{actual}}{\dot{Q}_{in}} \tag{2.66}$$

where $\dot{Q}_{in}$ is the rate of heat addition to the system, and $\dot{W}_{actual}$ is the useful, actual work done by the cycle .

For adiabatic systems the thermal efficiency is not a useful measure of system performance [23]. The thermodynamic or exergy efficiency of a system is defined as,

$$\psi = \frac{\dot{W}_{actual}}{\dot{W}_{u,max}} \tag{2.67}$$

An adiabatic process is isentropic when the process is reversible. In this case the quantity $\dot{W}_{u,max} \quad |_{\dot{Q}=0}$ represents the useful, maximum work associated with the reversible adiabatic (and hence isentropic) process [23].

The isentropic efficiency η_s of the process is therefore expressed as [23]:

$$\eta_s = \frac{\dot{W}_{actual}}{\dot{W}_{u,max} \quad |_{\dot{Q}=0}} \tag{2.68}$$

2.5 Heat Engines

Heat engines are systems which convert heat to work. Operating on a cycle, heat received from a high-temperature source is partially converted to work, while the remaining energy is rejected as waste heat to a low-temperature sink [27].

A steam power plant is an example of a heat engine. The steam cycle of the plant consists of the following processes.

- Heat (Q_{in}) is transferred to the steam in the boiler orheat exchanger from a furnace, which is the energy source;
- The turbine produces work (W_{out}) when steam passes through it;
- A condenser transfers the waste heat (Q_{out}) from steam to the energy sink, such as the atmosphere;
- A pump is used to carry the water from the condenser back to the boiler. Work (W_{in}) is required to compress water to boiler pressure [27].

The Carnot Cycle is the most efficient cycle for any given source and sink temperatures of a heat engine and represents a reversible power cycle in which heat is added from an external source at a constant temperature T_H (process 2-3 of Fig. 2.3) and rejected to the surroundings at a constant temperature T_C (process 4-1of Fig. 2.3) [24, 29].

The Carnot efficiency for a cycle operating between two thermal reservoirs at high temperature T_H and low temperature T_C is obtained from equation (2.49) as,

$$\text{Carnot efficiency,} \qquad \eta_{th} = 1 - \frac{T_C}{T_H}$$

Thus the Carnot efficiency can predict the operating characteristics of a plant since efficiency of the cycle will be increased if the value of T_H is increased or the value of T_C is reduced [29].

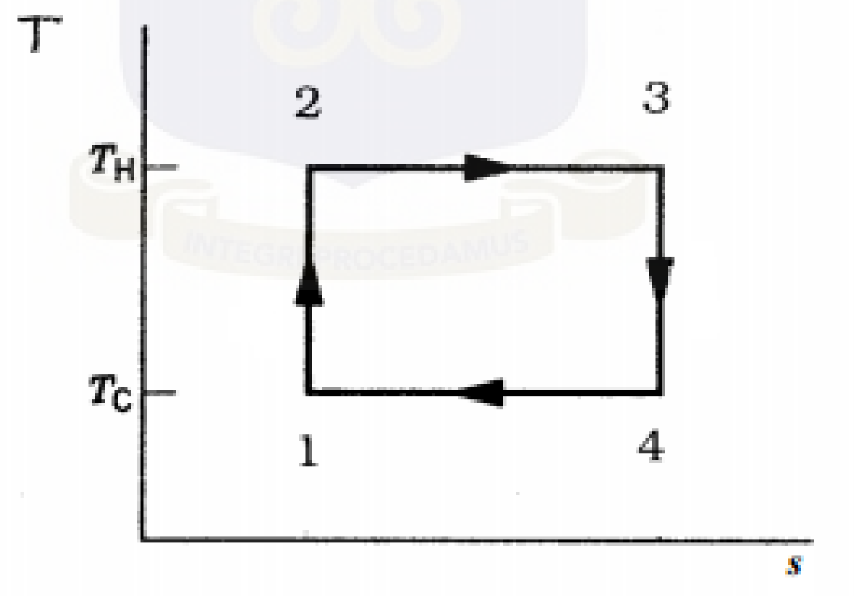


Fig.2.3 T-S diagram of the Carnot Cycle [24].

2.5.1 Rankine and Brayton Cycles

In their simplest configurations vapour and gas turbine power plants are represented in terms of four components in series forming, respectively, the Rankine cycle and the Brayton cycle shown schematically in Fig. 2.4.

The ideal cycle through the four components, devoid of irreversibilities and pressure drops [27], consists of four internally reversible processes in series: two isentropic processes in a turbine and pump alternated with two constant pressure processes in a boiler and condenser as illustrated in Fig. 2.4.

2.7 Nuclear Energy Production

The energy released in a nuclear reactor is produced by exothermic nuclear reactions in which an atomic nucleus of initial mass M is transformed into nuclei of mass M' and the difference in mass is released as energy [30]. This is expressed mathematically as:

$$E = (M - M')c^2$$

where c is the speed of light.

A typical nuclear reaction equation for fission resulting from neutron absorption in U-235 is represented by [30]:

$$n + {}^{235}_{92}U \rightarrow {}^{236}_{92}U^* \rightarrow {}^{139}_{54}Xe + {}^{95}_{38}Sr + 2n + \gamma \quad (2.69)$$

The fission of U-235 yields about 200 MeV of energy (corresponding to a mass loss of nearly 0.2 u). This appears as kinetic and decay energy of the fission fragments,

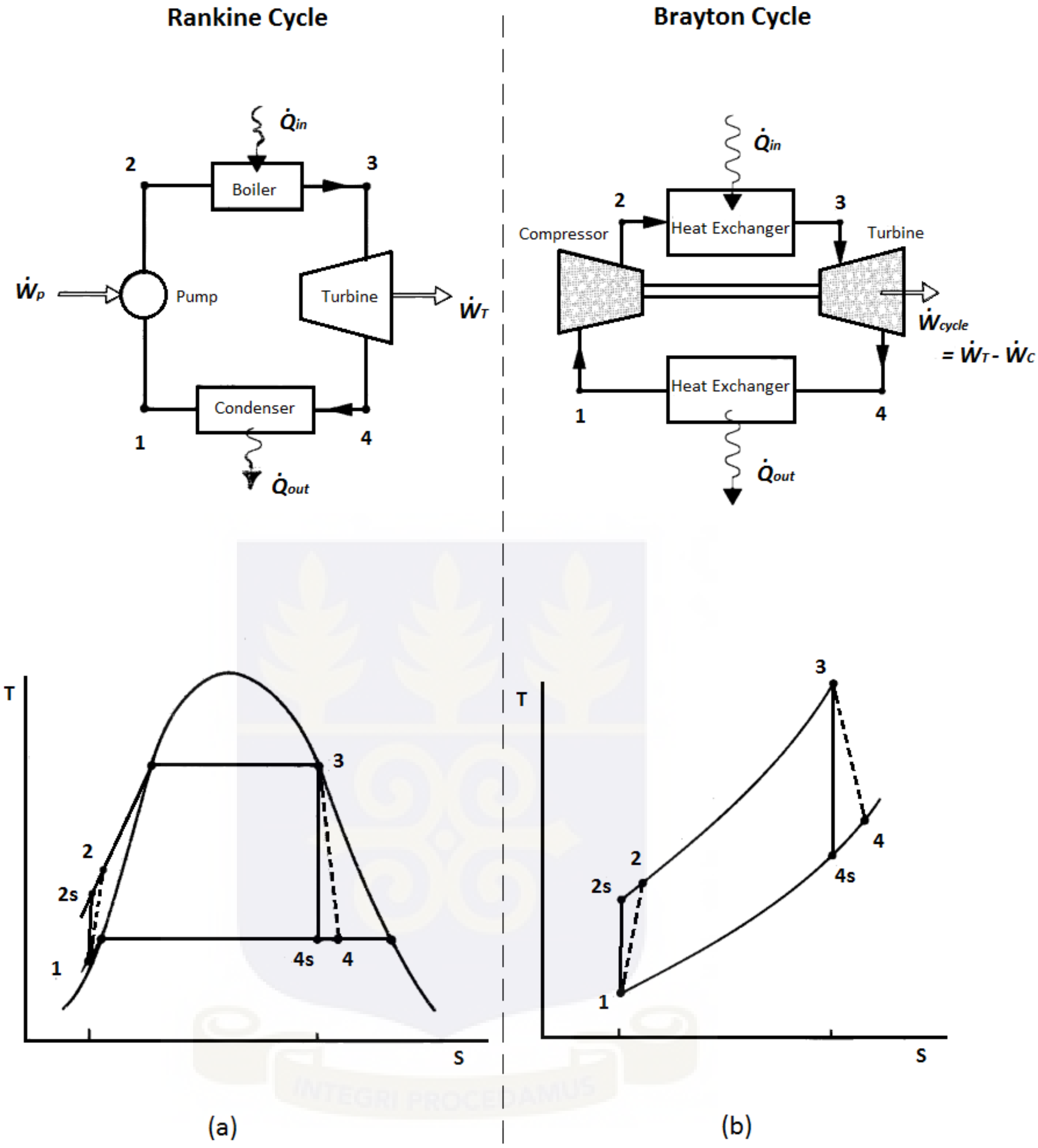


Fig. 2.4 Schematic and process diagrams of Rankine (a) and Brayton (b) cycles [24].

kinetic energy of the newborn neutrons, and energy of emittedγ-rays and neutrinos [23].

The fission products moving through the reactor impart thermal energy to the core through interactions with the surrounding matter. The distribution of energy released over the reaction products, and the principal positions of energy deposition within the various parts of the reactor is shown in Table 2.1.

The energy produced in a reactor core is expressed by the core power, which represents the fraction of recoverable energy deposited in the fuel. In thermal reactors, assuming average values for thermal flux ϕ_{th} and macroscopic fission Σ_f cross section for fissile atoms in a reactor of volume $V(m^3)$ [31],

$$total\ number\ of fissions = V\overline{\sum\nolimits_f \phi_{th}} \tag{2.70}$$

Given that a fission rate of 3.1*10^{10} $fissions/s$ is required to produce 1 watt of thermal power, the thermal reactor power P_{th} is expressed as [31]:

$$P_{th} = \frac{V\overline{\sum_f \phi_{th}}}{3.1 * 10^{10}} \tag{2.71}$$

On the whole, the energy, entropy, exergy and nuclear principles and theorems formulated thus far, form the foundations for the comprehensive analysis of energy systems. The applications of these derivations in nuclear heat conversion systems and other heat exchanger assemblies were pursued in subsequent chapters to determine the energy and exergy utilization characteristics of nuclear power systems.

Table 2.1 Approximate energy distribution and deposition resulting from a typical U-235 fission [23, 30].

Energy Source	**Energy Released**	**Energy Deposited in Core**		**Principal Position of Energy Deposition**
	(MeV)	**(MeV)**	**(%)**	
Fission				
I. Instantaneous Energy				
Kinetic energy of lighter fission fragment	100	100	50	Fuel
kinetic energy of heavier fission fragment	67	67	33.5	Fuel
Kinetic energy of fission neutrons	5	5	2.5	Moderator
Energy of prompt gamma rays	6	6	3	Fuel and structures
II. Delayed Energy				
Beta particle energy gradually released from fission products		8	4	Fuel
Gamma ray energy gradually released from fission products	22	6	3	Fuel and structures
Neutrinos		-	-	Non-recoverable
Neutron Capture				
III. Instantaneous and delayed Energy				
Radiative capture of excess fission neutrons	-	8	4	Fuel and structures
Total	200	200	100	

CHAPTER THREE

RESEARCH METHODOLOGY

Analysis of the nuclear power plant was done in two stages. Firstly, analysis of the reactor core was carried out to determine the efficiencies of the nuclear heat conversion systems, and then the entire power cycle (steam cycle) of the power plant was assessed to establish the efficiencies of various plant components.

3.1 Analysis of Energy and Exergy Loss in a Generic Nuclear Reactor Core

3.1.1 Reactor Energy Analysis

The steady state form of the energy rate balance for the reactor was derived from the energy balance for an open flow system as,

$$0 = \dot{Q}_{net} - \dot{W}_{net} + \dot{m}_i\left(h_i + \frac{v_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{v_e^2}{2} + gz_e\right) \qquad (2.13)$$

The reactor core has zero shaft work. Thus the steady state form of the energy rate balance for the reactor core was obtained by equating the net rate of heat transfer to the coolant to the net rate of coolant mass transfer across the reactor, expressed as,

$$\dot{Q}_{net} = \dot{m}(h_e - h_i) \qquad (3.1)$$

where $\dot{m}$ is the steady state coolant mass flow rate, and h_i and h_e are the inlet and exit enthalpy values respectively. Operating at full power ($\dot{Q}_{fission}$) the energy rate balance was expressed as,

$$\dot{Q}_{fission} - \dot{Q}_{loss} = \dot{m}(h_e - h_i) \qquad (3.2)$$

where the energy loss rate was given by $\dot{Q}_{loss}$. Thus,

$$\dot{Q}_{loss} = \dot{Q}_{fission} - \dot{m}(h_e - h_i) \qquad (3.3)$$

From the definition of the first law of thermodynamics, the energy efficiency of the reactor core (η_R) was written as,

$$\eta_R = \frac{\dot{m}(h_e - h_i)}{\dot{Q}_{fission}} = 1 - \frac{\dot{Q}_{loss}}{\dot{Q}_{fission}} \tag{3.4}$$

3.1.2 Reactor Exergy Analysis

The energy and exergy utilization processes that occur within a water cooled nuclear reactor, assuming typical power reactor fuel meat of Fig. 3.1, are illustrated in Fig. 3.2. Ignoring fission heat deposition outside the fuel element, the process consists of heating of the fuel pellets to their maximum temperature, transfer of the heat within the fuel pellets to the surface of the pellets, transfer of heat from the surface of the fuel pellets to the cladding outer surface, and the transfer of heat from the cladding surface to the primary coolant. The breakdown of the energy and exergy losses in the reactor core therefore is modelled according to flow schematic of Fig. 3.2.

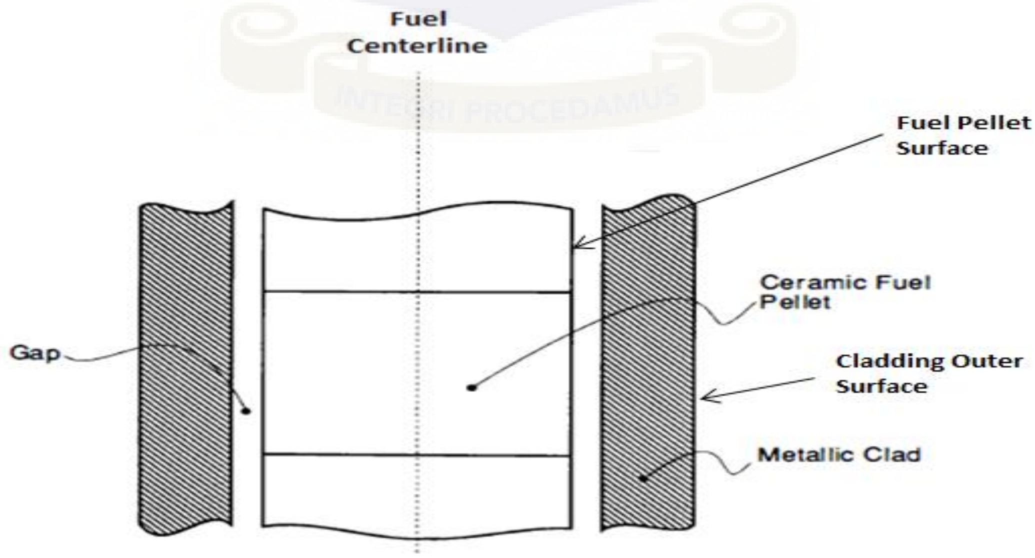


Fig. 3.1 Typical power reactor fuel [23].

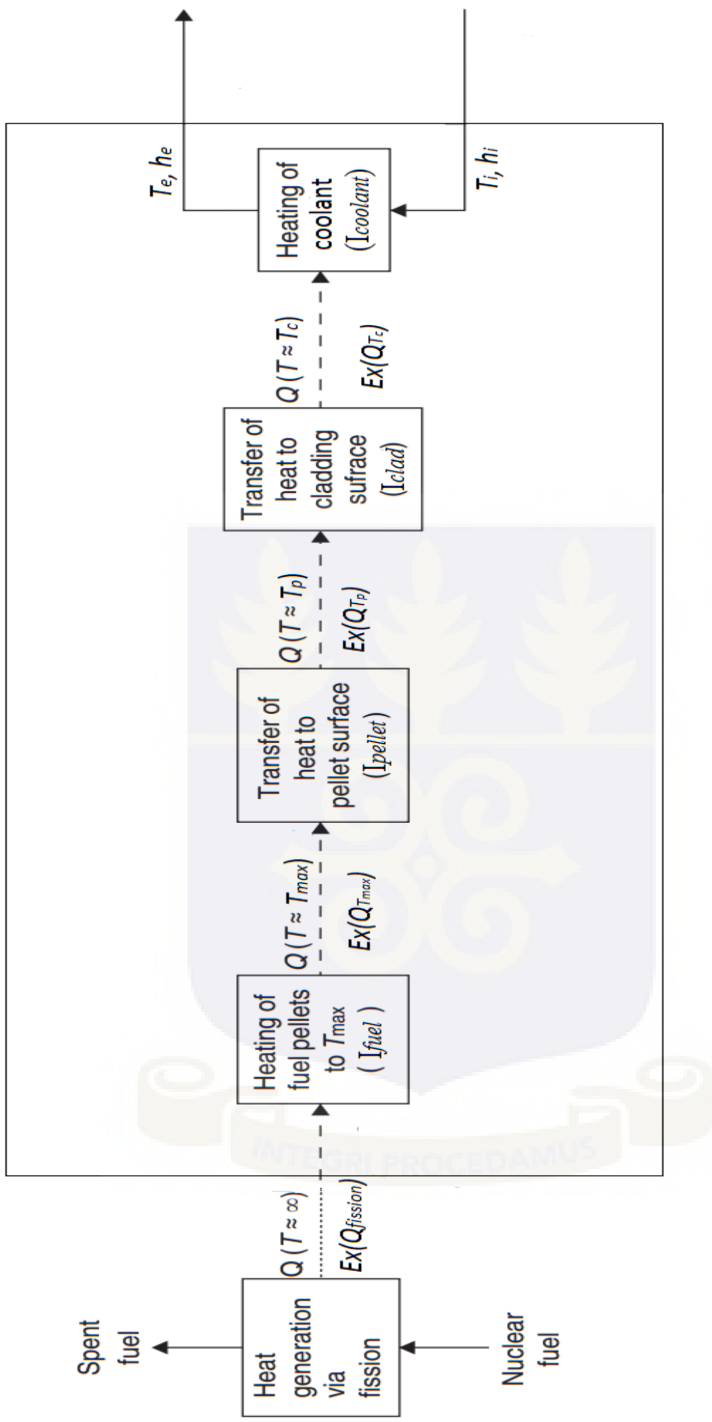


Fig. 3.2 Energy (Q) and exergy (Ex) flows in a generic nuclear reactor with inlet and exit coolant temperatures given as T_i and T_e respectively [6].

The total irreversible loss ($\dot{I}_{reactor}$) experienced by the reactor core was derived as a summation of the exergy losses at the various stages of energy transfer in the core. Assuming a reference- environment temperatureT_o, $\dot{I}_{reactor}$ was evaluated as follows:

Upon fissioning and with respect to fission products, each fission fragment at steady was regarded as having a kinetic energy of about 100 MeV [23], and if considered a perfect gas in a thermodynamic equilibrium state, the fragment would have a temperature T_a such that $\frac{3}{2}kT_a = 100\ MeV$ [23].

The maximum work done by the fragment in a reversible process brings the fragment to a state of mutual equilibrium with the environment at $T_o = 298^o K$ or $kT_o = 0.025\ eV$. At the environment state, the energy of the fragment is $u_o = 0.0375\ eV$. The maximum work per unit mass of fission fragment was expressed as [23]:

$$W_{u,max} = (h_a - h_o) - T_o(s_a - s_o) \tag{3.5}$$

which was approximated as:

$$W_{u,max} = u_a - u_o - cT_o \text{In} \frac{T_a}{T_o} \tag{3.6}$$

Since $T_a >> T_o$,

$$W_{u,max} \approx u_a \tag{3.7}$$

i.e.

$$(\dot{W}_{u,\max})_{fission} \approx \dot{Q}_{fission} \tag{3.8}$$

Thus the maximum useful power available as a result of fission equalled the fission power and the irreversibility of fission $\dot{I}_{fission}$ was zero.

The maximum power available from the fuel rod at maximum operating temperature T_{max} was obtained from equation (2.50) as:

$$(\dot{W}_{u,\max})_{fuel} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_{max}}\right) \tag{3.9}$$

The irreversibility in heating the fuel rod was derived from equation (2.57) as,

$$\dot{I}_{fuel} = (\dot{W}_{u,\max})_{fission} - (\dot{W}_{u,max})_{fuel} = (\dot{W}_{u,max})_{fission}\left(\frac{T_o}{T_{max}}\right) \tag{3.10}$$

The maximum useful work available from the outer surface of the fuel pellet surface at temperature T_p was:

$$(\dot{W}_{u,\max})_{pellet} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_p}\right) \tag{3.11}$$

The exergy loss or irreversibility in heating the fuel clad was given as,

$$\dot{I}_{pellet} = (\dot{W}_{u,\max})_{fuel} - (\dot{W}_{u,\max})_{pellet} \tag{3.12}$$

The maximum useful work available from the outer surface of the fuel clad at temperature T_c was:

$$(\dot{W}_{u,\max})_{clad} = \dot{Q}_{fission}\left(1 - \frac{T_o}{T_c}\right) \tag{3.13}$$

The irreversible loss in heating the fuel clad was given by,

$$\dot{I}_{clad} = (\dot{W}_{u,\max})_{pellet} - (\dot{W}_{u,\max})_{clad} \tag{3.14}$$

From the fuel rods, all the fission power was transferred to the coolant. The maximum work available from the coolant was derived from equation (2.54), assuming negligible kinetic and potential energy changes, as:

$$(\dot{W}_{u,\max})_{coolant} = \dot{m}\,[(h_e - h_i) - T_o(s_e - s_i)] \quad (3.15)$$

The exergy loss or irreversibility in heating the coolant was:

$$\dot{I}_{coolant} = (\dot{W}_{u,\max})_{clad} - (\dot{W}_{u,\max})_{coolant} \quad (3.16)$$

Hence the total irreversibility of the reactor core was given as:

$$\dot{I}_{reactor} = \dot{I}_{fission} + \dot{I}_{fuel} + \dot{I}_{pellet} + \dot{I}_{clad} + \dot{I}_{coolant} \quad (3.17)$$

Given the total reactor irreversibility, the exergy efficiency of the reactor core ψ_R was derived as,

$$\psi_R = 1 - \frac{\dot{I}_{reactor}}{(\dot{W}_{u,\max})_{fission}} \quad (3.18)$$

3.3 Analysis of Energy and Exergy Loss in AP1000 Reactor Core

Operating under full power conditions, the steady state fuel temperature distribution within the AP1000 reactor core was assumed to be maximum at the fuel centerline at *Tmax* (1339.9^{o}C) [4], and fell to temperature *Tc* (315.75^{o}C) [4] at the fuel cladding surface.Taking the coolant flow as a single inlet and single exit stream, denoted by states 1 and 2 respectively, the AP1000 reactor core was modeled as depicted in Fig. 3.3, based on a simplification of the generic flow diagram of Fig. 3.2. The main operational data for the AP1000 reactor core was presented in Table 3.1.

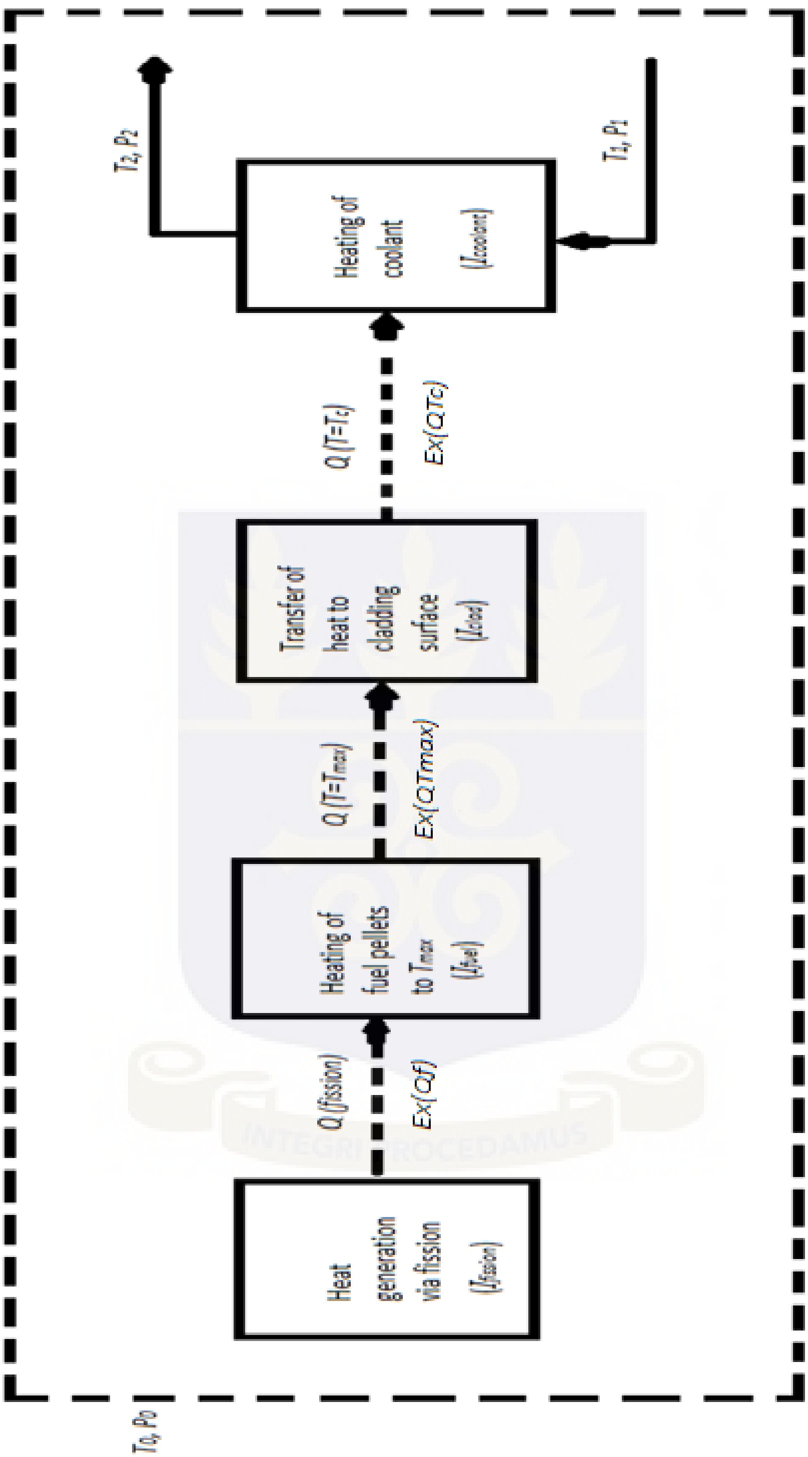


Fig.3.3 Schematic of energy and exergy flows in AP1000 reactor core, where $T_1 \neq T_2$ and $P_1 = P_2$.

Table 3.1 AP1000 plant data [32]

Technical data

General plant data		
Power plant output, gross	1200	MWe
Power plant output, net	1115	MWe
Reactor thermal output [core power 3400 MWt]	3415	MWt
Power plant efficiency, net	33	%
Cooling water temperature	30.5	°C
Nuclear steam supply system		
Number of coolant loops	2 hot legs/4 cold legs	
Steam flow rate at nominal conditions	1886	kg/s
Feedwater flow rate at nominal conditions	1887	kg/s
Steam temperature/pressure	272.9/5.76	°C/MPa
Feedwater temperature	226.7	°C
Reactor coolant system		
Primary coolant flow rate, per loop	9.94	m^3/s
Reactor operating pressure	15.5	MPa
Coolant inlet temperature, at RPV inlet	280.7	°C
Coolant outlet temperature, at RPV outlet	321.1	°C
Mean temperature rise across core	40.4	°C
Reactor core		
Active core height	4.267	m
Equivalent core diameter	3.04	m
Heat transfer surface in the core	5268	m^2
Fuel inventory	84.5	t U
Average linear heat rate	18.7	kW/m
Average fuel power density	40.2	kW/kg U
Average core power density (volumetric)	109.7	kW/l
Thermal heat flux, F_q	2.60	kW/m^2
Enthalpy rise, F_H	1.65	
Fuel material	Sintered UO_2	
Fuel assembly total length	4 795	mm
Rod array	square, 17×17 (XL)	
Number of fuel assemblies	157	
Number of fuel rods/assembly	264	
Number of control rod guide tubes	24	
Number of structural spacer grids	10	
Number of intermediate flow mixing grids	4	
Enrichment (range) of first core	2.35-4.45Wt% U-235	
Enrichment of reload fuel at equilibrium core	4.8	Wt% U-235
Operating cycle length (fuel cycle length)	18	months
Average discharge burnup of fuel (nominal)	60 000	MWd/t
Cladding tube material	ZIRLO ™	
Cladding tube wall thickness	0.57	mm
Outer diameter of fuel rods	9.5	mm
Overall weight of assembly	799.7	kg
Burnable absorber, strategy/material	Discrete burnable absorber, Integral fuel burnable absorber	
Number of control rods	69 (53 black, 16 gray)	
Absorber rods per control assembly	24	
Absorber material	Ag-In-Cd (black), Ag-In-Cd/304SS (gray)	
Drive mechanism	Magnetic jack	
Positioning rate [in steps/min or mm/s]	45	steps/min
Soluble neutron absorber	Boric acid	
Reactor pressure vessel		
Cylindrical shell inner diameter	3 988	mm
Wall thickness of cylindrical shell	203	mm
Total height	12056	mm
Base material: cylindrical shell	Carbon steel	
RPV head	Carbon steel	
Liner	Stainless steel	
Design pressure/temperature	17.1/ 343.3	MPa/°C
Steam generators		
Type	Delta 125, vertical, U-tube	
Number	2	
Heat transfer surface	11477	m^2
Number of heat exchanger tubes	10025	
Tube dimensions	17.5/15.4	mm
Maximum outer diameter	5575.3	mm

The energy rate balance for the AP1000 reactor operating at core power ($\dot{Q}_{fission}$) was given by equation (3.2) as,

$$\dot{Q}_{loss} = \dot{Q}_{fission} - \dot{m}(h_2 - h_1) \tag{3.19}$$

From equation (3.4) the energy efficiency was derived as,

$$\eta_R = 1 - \frac{\dot{Q}_{loss}}{\dot{Q}_{fission}} = \frac{\dot{m}(h_2 - h_1)}{\dot{Q}_{fission}} \tag{3.20}$$

The steady state form of the exergy rate balance for the AP1000 reactor core at the clad-coolant boundary was derived from equation (2.62) as,

$$(\dot{W}_{u,max})_{clad} = \dot{m}(x_{f2} - x_{f1}) + \dot{I}_{coolant} \tag{3.21}$$

From equation (3.13) and equation (3.8),

$$\left(1 - \frac{T_o}{T_c}\right)(\dot{W}_{u,max})_{fission} = \dot{m}(x_{f2} - x_{f1}) + \dot{I}_{coolant} \tag{3.22}$$

which was expanded as,

$$(\dot{W}_{u,max})_{fission} - \left(\frac{T_o}{T_c}\right)(\dot{W}_{u,max})_{fission} = \dot{m}(x_{f2} - x_{f1}) + \dot{I}_{coolant} \tag{3.23}$$

The irreversibility in heating the clad was given as,

$$\dot{I}_{clad} = (\dot{W}_{u,\max})_{fuel} - (\dot{W}_{u,max})_{clad} \tag{3.24}$$

and expanded as,

$$\dot{I}_{clad} = \left(1 - \frac{T_o}{T_{max}}\right)(\dot{W}_{u,max})_{fission} - \left(1 - \frac{T_o}{T_c}\right)(\dot{W}_{u,max})_{fission}$$

which reduced to,

$$\dot{I}_{clad} = \left(\frac{T_o}{T_c}\right)(\dot{W}_{u,max})_{fission} - \dot{I}_{fuel} \tag{3.25}$$

Thus from equation (3.25), equation (3.23) was rewritten as,

$$(\dot{W}_{u,max})_{fission} = \dot{m}(x_{f2} - x_{f1}) + \dot{I}_{coolant} + \dot{I}_{clad} + \dot{I}_{fuel} \tag{3.26}$$

and expanded as,

$$(\dot{W}_{u,max})_{fission} = \dot{m}\,[(h_2 - h_1) - T_o(s_2 - s_1)] + \dot{I}_{fuel} + \dot{I}_{clad} + \dot{I}_{coolant} \tag{3.27}$$

or,

$$\dot{I}_{reactor} = \dot{Q}_{fission} - \dot{m}\,[(h_2 - h_1) - T_o(s_2 - s_1)] \tag{3.28}$$

where, $\dot{I}_{reactor} = \dot{I}_{fuel} + \dot{I}_{clad} + \dot{I}_{coolant}$

From equation (3.18) the exergy efficiency of the AP1000 reactor core was given as,

$$\psi_R = 1 - \frac{\dot{I}_{reactor}}{(\dot{W}_{u,\max})_{fission}} \tag{3.29}$$

3.4 Analysis of Energy and Exergy Loss in Simulation Model of AP1000 Plant.

The AP1000 power plant utilizes a regenerative vapour cycle whereby steam produced in the steam generation section was passed through a series of high and low pressure turbine generators attached to a transformer. Extraction steam from several points on the turbine preheats feedwater in several low and high pressure heat exchangers and one open deaerating heat exchanger. The process cycle for the AP1000 power cycle was idealized with the simulation model shown in Fig. 3.4, which was derived from the complete heat balance presented in Fig. 3.5 [17].

The thermodynamic modelling of the subsystems of the AP1000 plant was initiated by considering in turns the major components working under steady state. The analyses were performed based on the following assumptions and simplifications:

- Kinetic and potential energy changes were negligible for all processes.
- Pump work as a contribution to net work output was insignificant
- Frictional irreversibilities in the turbines were ignored (i.e. turbines had mechanical efficiencies of 100 %.)
- The reference environment model used had the following property values: temperature T_o =32 °C and pressure P_o=1atm.

Thus the only irreversibilities considered for all the plant components were internal irreversibilities due to heat transfer.

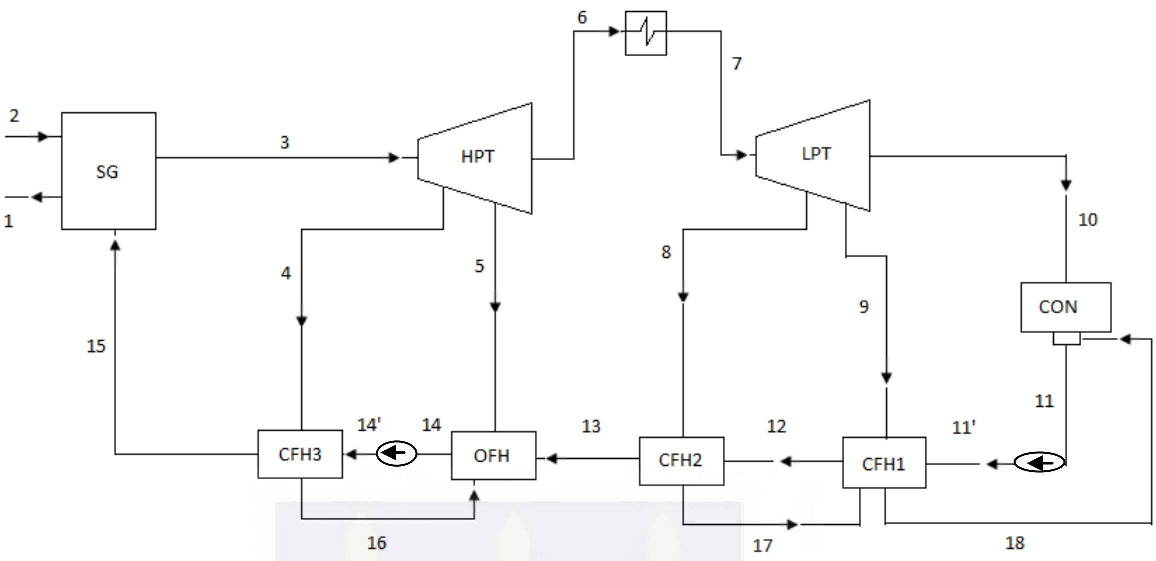
3.4.1 Energy Analysis of AP1000 Components

The energy rate balances used to determine the energy losses in the components were developed as presented below.

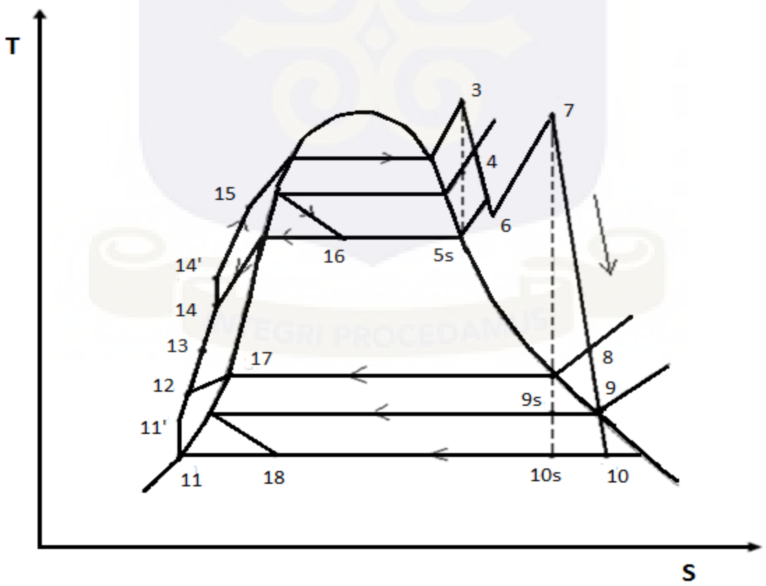
(a) The Energy Balance for the Turbine:

The turbine was made up of two sections: a high pressure stage (HPT) and a low pressure stage (LPT). The energy rate balance for the high pressure turbine was given as,

$$\dot{W}_{HPT} = \dot{m}_3(h_3 - h_4) + (\dot{m}_3 - \dot{m}_4)(h_4 - h_5) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(h_5 - h_6) - Energy\ loss_{hpt} \quad (3.30)$$



(a)



(b)

Fig. 3.4 (a) Simplified model of the AP1000 process cycle (b) T-S diagram of the regenerative vapour cycle. The property data for the flow streams are listed in Table 4.1.

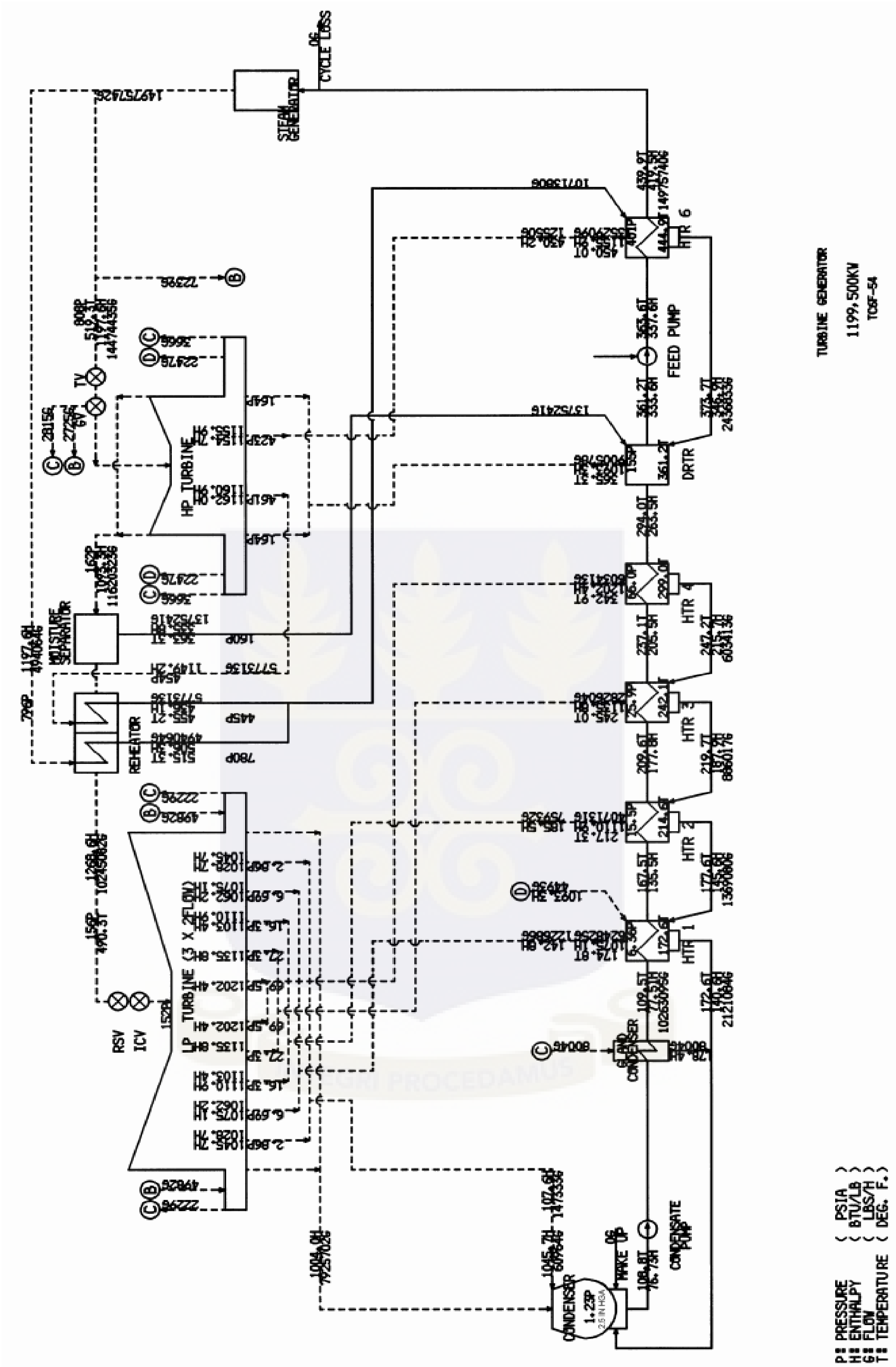


Fig. 3.5 AP1000 steam and power conversion system with process data [17].

The energy rate balance for the low pressure turbine was given by:

$$\dot{W}_{LPT} = \dot{m}_7(h_7 - h_8) + (\dot{m}_7 - \dot{m}_8)(h_8 - h_9) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(h_9 - h_{10}) - Energy\ loss_{lpt} \tag{3.31}$$

The total turbine work rate $\dot{W}_T$ was expressed as,

$$\dot{W}_T = \dot{W}_{HPT} + \dot{W}_{LPT}$$

Combining equations (3.30) and (3.31), the energy rate balance for the entire turbine was derived as,

$$\begin{aligned}\dot{W}_T = {} & \dot{m}_3(h_3 - h_4) + (\dot{m}_3 - \dot{m}_4)(h_4 - h_5) \\ & +(\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(h_5 - h_6) + \dot{m}_7(h_7 - h_8) \\ & +(\dot{m}_7 - \dot{m}_8)(h_8 - h_9) \\ & +(\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(h_9 - h_{10}) - Energy\ loss\end{aligned} \tag{3.32}$$

where $Energy\ loss$ was the total energy loss for the turbines.

(b) Steam Generator Energy Balance:

The energy rate balance for the steam generator was deduced as:

$$0 = \dot{m}_1(h_2 - h_1) - \dot{m}_3(h_{15} - h_3) - \text{Energy loss}$$

and the

$$\text{Energy loss} = \dot{m}_1(h_2 - h_1) - \dot{m}_3(h_{15} - h_3) \tag{3.33}$$

(c) Energy balance of Closed Feedwater Heater No. 1 (CFH1):

The energy rate balance for the low pressure closed feedwater heater (1) was given by:

$$0 = \dot{m}_9 h_9 + \dot{m}_{17} h_{17} - \dot{m}_{11'}(h_{12} - h_{11'}) - \dot{m}_{18} h_{18} - \text{Energy loss}$$

and the

$$\text{Energy loss} = \dot{m}_9 h_9 + \dot{m}_{17} h_{17} - \dot{m}_{11'}(h_{12} - h_{11'}) - \dot{m}_{18} h_{18} \tag{3.34}$$

(d) Energy Balance of Closed Feedwater Heater No. 2 (CFH2):

The energy rate balance for the low pressure closed feedwater heater (2) was given by:

$$0 = \dot{m}_8(h_8 - h_{17}) - \dot{m}_{12}(h_{13} - h_{12}) - \text{Energy loss}$$

and

$$\text{Energy loss} = \dot{m}_8(h_8 - h_{17}) - \dot{m}_{12}(h_{13} - h_{12}) \tag{3.35}$$

(e) Energy Balance of Open Feedwater Heater (OFH):

The energy rate balance for the open feedwater heater was given by:

$$0 = \dot{m}_5 h_5 + \dot{m}_{16} h_{16} + \dot{m}_{13} h_{13} - \dot{m}_{14} h_{14} - \text{Energy loss}$$

This gives:

$$\text{Energy loss} = \dot{m}_5 h_5 + \dot{m}_{16} h_{16} + \dot{m}_{13} h_{13} - \dot{m}_{14} h_{14} \tag{3.36}$$

(f) Energy Balance of Closed Feedwater Heater No. 3 (CFH3):

The energy balance for the high pressure closed feedwater heater was given by,

$$0 = \dot{m}_4(h_4 - h_{16}) - \dot{m}_{14}(h_{15} - h_{14'}) - \text{Energy loss}$$

and the

$$\text{Energy loss} = \dot{m}_4(h_4 - h_{16}) - \dot{m}_{14}(h_{15} - h_{14'}) \quad (3.37)$$

(g) Condenser Energy Balance:

The energy rate balance for the condenser was given by:

$$0 = \dot{m}_{10}(h_{10} - h_{11}) - \dot{m}_{cw}(h_{co} - h_{ci}) - Energy\ loss$$

and the

$$\text{Energy loss} = \dot{m}_{10}(h_{10} - h_{11}) - \dot{m}_{cw}(h_{co} - h_{ci}) \quad (3.38)$$

where the quantity $\dot{m}_{cw}(h_{co} - h_{ci}) + Energy\ loss$ represented the total energy rejected by the condenser.

3.4.2 Exergy Analysis of AP1000 Components

The exergy rate balances were developed using the Gouy-Stodola relationship [19] to determine the exergy losses in the components.

(a) Exergy Balance for the Turbine:

The total exergy consumed by the turbine was the sum of the exergy losses in the low and high pressure stages. The exergy rate balance for the high pressure turbine (HPT) was derived from the energy rate balance as:

$$\dot{W}_{HPT} = \dot{m}_3(x_{f3} - x_{f4}) + (\dot{m}_3 - \dot{m}_4)(x_{f4} - x_{f5}) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(x_{f5} - x_{f6}) - \dot{I}_d \tag{3.39}$$

Where x_f is the flow exergy of the listed stream, and $\dot{I}_d = T_o\dot{S}_{gen}$

Equation (3.39) was expanded as,

$$T_o\dot{S}_{gen} = \dot{m}_3[(h_3 - h_4) - T_o(s_3 - s_4)] + (\dot{m}_3 - \dot{m}_4)[(h_4 - h_5) - T_o(s_4 - s_5)]$$

$$+(\dot{m}_3 - \dot{m}_4 - \dot{m}_5)[(h_5 - h_6) - T_o(s_5 - s_6)] - \dot{W}_{HPT}$$

The irreversibility or exergy loss was represented as,

$$T_o\dot{S}_{gen} = T_o[\dot{m}_3(s_4 - s_3) + (\dot{m}_3 - \dot{m}_4)(s_5 - s_4) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(s_6 - s_5)] \tag{3.40}$$

where the entropy generation rate was,

$$\dot{S}_{gen} = [\dot{m}_3(s_4 - s_3) + (\dot{m}_3 - \dot{m}_4)(s_5 - s_4) + (\dot{m}_3 - \dot{m}_4 - \dot{m}_5)(s_6 - s_5)]$$

For the low pressure turbine (LPT) the exergy rate balance was given by:

$$\dot{W}_{LPT} = \dot{m}_7(x_{f7} - x_{f8}) + (\dot{m}_7 - \dot{m}_8)(x_{f8} - x_{f9}) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(x_{f9} - x_{f10}) - T_o\dot{S}_{gen}$$

and expanded as,

$$T_o\dot{S}_{gen} = \dot{m}_7[(h_7 - h_8) - T_o(s_7 - s_8)] + (\dot{m}_7 - \dot{m}_8)[(h_8 - h_9) - T_o(s_8 - s_9)]$$

$$+(\dot{m}_7 - \dot{m}_8 - \dot{m}_9)[(h_9 - h_{10}) - T_o(s_9 - s_{10})] - \dot{W}_{LPT}$$

which gave the exergy loss rate as:

$$T_o\dot{S}_{gen} = T_o[\dot{m}_7(s_8 - s_7) + (\dot{m}_7 - \dot{m}_8)(s_9 - s_8) + (\dot{m}_7 - \dot{m}_8 - \dot{m}_9)(s_{10} - s_9)] \tag{3.41}$$

(b) Steam Generator Exergy Balance:

The exergy flow equation for the steam generator was given as,

$$0 = \dot{m}_1(x_{f2} - x_{f1}) - \dot{m}_3(x_{f15} - x_{f3}) - T_o\dot{S}_{gen}$$

and expanded as,

$$T_o\dot{S}_{gen} = [\dot{m}_1(h_2 - h_1) - \dot{m}_3(h_{15} - h_3)] - T_o[\dot{m}_1(s_2 - s_1) - \dot{m}_3(s_{15} - s_3)]$$

where irreversibility was rewritten as,

$$T_o\dot{S}_{gen} = T_o[\dot{m}_1(s_1 - s_2) - \dot{m}_3(s_{15} - s_3)] \tag{3.42}$$

(b) Exergy Balance of Closed Feedwater Heater No.1 (CFH1):

The exergy flow equation for the low pressure closed feedwater heater (1) was given as,

$$0 = \dot{m}_9 x_{f9} + \dot{m}_{17} x_{f17} - \dot{m}_{11'}(x_{f12} - x_{f11'}) - \dot{m}_{18} x_{f18} - T_o\dot{S}_{gen}$$

Since,

$$\dot{m}_{18} = \dot{m}_9 + \dot{m}_{17} \quad and \quad \dot{m}_{12} = \dot{m}_{11'}$$

this gave,

$$T_o\dot{S}_{gen} = \dot{m}_9[(h_9 - h_0) - T_o(s_9 - s_0)] + \dot{m}_{17}[(h_{17} - h_0) - T_o(s_{17} - s_0)]$$
$$- \dot{m}_{11'}[(h_{12} - h_{11'}) - T_o(s_{12} - s_{11'})]$$
$$- \dot{m}_{18}[(h_{18} - h_0) - T_o(s_{18} - s_0)]$$

and the entropy generation rate was:

$$\dot{S}_{gen} = [\dot{m}_{18}s_{18} + \dot{m}_{11'}(s_{12} - s_{11'}) - \dot{m}_9 s_9 - \dot{m}_{17}s_{17}]$$

The irreversibility or exergy loss becomes,

$$T_o\dot{S}_{gen} = T_o[\dot{m}_{18}s_{18} + \dot{m}_{11'}(s_{12} - s_{11'}) - \dot{m}_9 s_9 - \dot{m}_{17}s_{17}] \tag{3.43}$$

(c) Exergy Balance of Closed Feedwater Heater No.2 (CFH2):

The exergy rate balance for the low pressure closed feedwater heater (2) was given as,

$$0 = \dot{m}_8(x_{f8} - x_{f17}) - \dot{m}_{12}(x_{f13} - x_{f12}) - T_o\dot{S}_{gen}$$

This gave the exergy loss as,

$$T_o\dot{S}_{gen} = [\dot{m}_8(h_8 - h_{17}) - \dot{m}_{12}(h_{13} - h_{12})] - T_o[\dot{m}_8(s_8 - s_{17}) - \dot{m}_{12}(s_{13} - s_{12})] \tag{3.44}$$

(e) Exergy Balance of Open Feedwater Heater (OFH):

The exergy rate balance for the open feedwater heater system was expressed as:

$$0 = \dot{m}_5 x_{f5} + \dot{m}_{16}x_{f16} + \dot{m}_{13}x_{f13} - \dot{m}_{14}x_{f14} - T_o\dot{S}_{gen}$$

where,

$$\dot{m}_{14} = \dot{m}_5 + \dot{m}_{16} + \dot{m}_{13}$$

giving

$$T_o\dot{S}_{gen} = \dot{m}_5 x_{f5} + \dot{m}_{16} x_{f16} + \dot{m}_{13} x_{f13} - \dot{m}_{14} x_{f14}$$

which was expanded as

$$T_o\dot{S}_{gen} = \dot{m}_5[(h_5 - h_0) - T_o(s_5 - s_0)] + \dot{m}_{16}[(h_{16} - h_0) - T_o(s_{16} - s_0)] + \dot{m}_{13}[(h_{13} - h_0) - T_o(s_{13} - s_0)] - \dot{m}_{14}[(h_{14} - h_0) - T_o(s_{14} - s_0)]$$

and the entropy generation rate was given as,

$$\dot{S}_{gen} = [\dot{m}_{14} s_{14} - \dot{m}_5 s_5 - \dot{m}_{16} s_{16} - \dot{m}_{13} s_{13}]$$

The irreversibility or exergy loss thus becomes,

$$T_o\dot{S}_{gen} = T_o[\dot{m}_{14} s_{14} - \dot{m}_5 s_5 - \dot{m}_{16} s_{16} - \dot{m}_{13} s_{13}] \quad (3.45)$$

(f) Exergy Balance of Closed Feedwater Heater No.3 (CFH3):

The exergy rate balance for the high pressure closed feedwater heater was given as,

$$0 = \dot{m}_4(x_{f4} - x_{f16}) - \dot{m}_{14}(x_{f15} - x_{f14}) - T_o\dot{S}_{gen}$$

And the irreversibility was,

$$T_o\dot{S}_{gen} = [\dot{m}_4(h_4 - h_{16}) - \dot{m}_{14}(h_{15} - h_{14})] - T_o[\dot{m}_4(s_4 - s_{16}) - \dot{m}_{14}(s_{15} - s_{14})] \quad (3.46)$$

(g) Condenser Exergy Balance:

The exergy rate balance for the condenser was derived as:

$$0 = \dot{m}_{10}(x_{f10} - x_{f11}) - \dot{m}_{cw}\left(x_{fco} - x_{fci}\right) - T_o\dot{S}_{gen}$$

which was expanded as,

$$T_o\dot{S}_{gen} = [\dot{m}_{10}(h_{10} - h_{11}) - \dot{m}_{cw}(h_{co} - h_{ci})] - T_o[\dot{m}_{10}(s_{10} - s_{11}) - \dot{m}_{cw}(s_{co} - s_{ci})]$$

This gave the irreversibility as,

$$T_o\dot{S}_{gen} = T_o[\dot{m}_{10}(s_{10} - s_{11}) - \dot{m}_{cw}(s_{co} - s_{ci})] \tag{3.47}$$

3.5 Overall Energy and Exergy Efficiencies and Losses of AP1000 Plant

For the simplified model of AP1000 (Fig. 3.4 (a)), the net power output was approximated as:

$$\dot{W}_{net} = \dot{W}_{HPT} + \dot{W}_{LPT} = \dot{W}_T \tag{3.48}$$

which was obtained from literature as the turbine generator power output and found to be 1199.5 MW [17]. Thus,

$$\dot{W}_T = 1199.5\ MW \tag{3.49}$$

The overall plant energy efficiency was expressed as:

$$\eta_{plant} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}} \tag{3.50}$$

where fission heat was treated as the only input source of energy. The overall efficiency definition differentiates from thermal efficiency defined as the ratio of net electrical power to reactor thermal power or heat transferred from the fuel to the coolant. Thus equation (3.49) was rewritten as,

$$\eta_{plant} = \frac{\dot{W}_T}{\dot{Q}_{fission}} \tag{3.51}$$

The overall thermodynamic or exergy efficiency was expressed as [1, 6]:

$$\psi_{plant} = \frac{\dot{W}_{net}}{\dot{E}x_{fuel}} \tag{3.52}$$

where fission heat was taken as the only input source of fuel exergy. From equations (3.8) and (3.48), the exergy efficiency was rewritten as,

$$\psi_{plant} = \frac{\dot{W}_T}{(\dot{W}_{u,max})_{fission}} = \frac{\dot{W}_T}{\dot{Q}_{fission}} \tag{3.53}$$

Equations (3.51) and (3.53) stated directly that the energy and exergy efficiency values of the nuclear power cycle were similar.

The energy loss η_{loss} and exergy loss ψ_{loss} values for the entire plant were, consequently, derived as,

$$\eta_{loss} = \psi_{loss} = \dot{Q}_{fission} - \dot{W}_T \tag{3.54}$$

3.6 Computation of Energy and Exergy Loss Rates

The energy and exergy rate balances for the AP1000 power cycle presented in equations (3.30 - 3.47) were solved using a Matlab script named ExergyCalc (see Appendix A) developed for the purpose of computing the energy and exergy loss rates specified for the various plant components. The solution algorithm for the program was specified according to the steps described below.

3.6.1 Solution Algorithm (Structured Program)

Step 1 – Parameters and Initialization

T_o - temperature of reference environment = 32°C

$\dot{W}_T$ – turbine output = 1199.5MW

h – enthalpy value of streams, kJ/kg

s – entropy value of streams, $kJ/kg\ K$

$\dot{m}$ – mass flow rate of listed streams, kg/s

Step 2 – Computation of Energy Loss Values

For the energy loss values**,** the mass flow rates and enthalpy values listed in the process streams were computed by substituting into the energy rate balances formulated for the various components comprising the steam generator, turbine, pre-heaters and condenser.

Step 3 – Computation of Exergy Loss Values

Computation of the exergy loss values were obtained by inputting flow rates, the reference environment temperature, enthalpy and entropy values into the exergy rate balances given by equations (3.30- 3.47).

Step 4 – Total Energy and Exergy Loss Values

The total energy and exergy loss values were obtained from an aggregation of the energy and exergy loss values computed in Step 2 and Step 3 for the various plant components.

Step 5- Program Structure

The program structure consisted of declaration stage where the symbols were defined and physical parameters declared. Program run consisted of initializing the parameters and constants, calculating the energy and exergy loss values by section, and summing the energy and exergy values obtained.

3.6.2 Numerical Flow Chart for Solution Algorithm

A diagrammatic representation of the numerical flow chart algorithm is shown below.

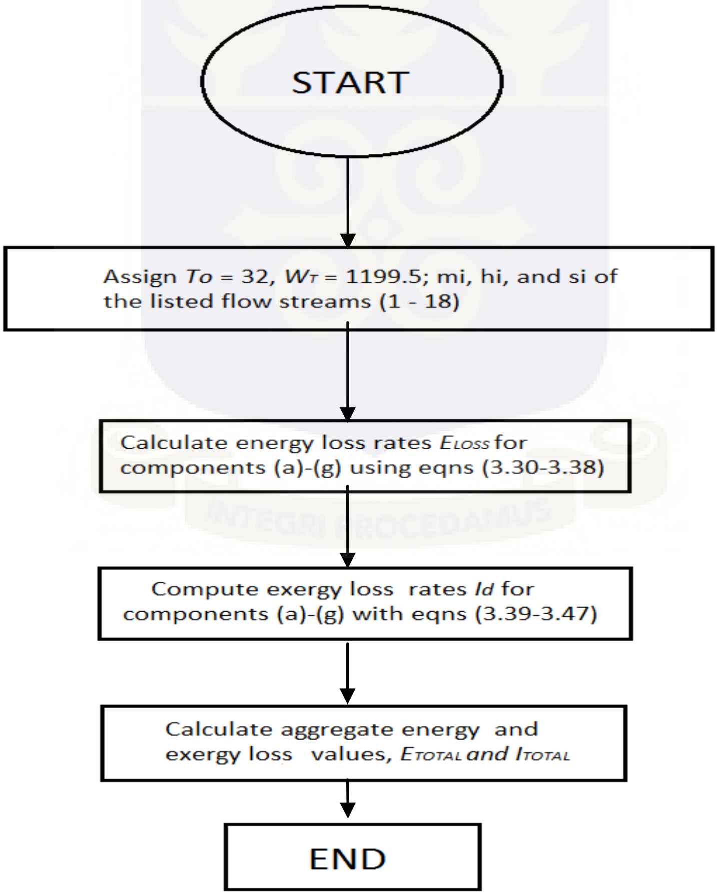


Fig. 3.6 Numerical flow chart algorithm for computation of energy and exergy loss rates.

3.6.3 Matlab Program Development and Implementation

The energy loss and exergy consumption Matlab computer code named ExergyCalc.m (shown in Appendix A) was developed from the energy and exergy rate balances of equations (3.30 - 3.47), implemented and executed using a high speed Dell Optiplex 780 series PC workstation in the Computational Laboratory of the School of Nuclear and Allied Sciences, University of Ghana. The PC had the specifications: Intel(R) Core(TM) 2 Quad CPU Q9400 processor @ 2.66 GHz (4 CPUs), 2.7 GHz,4096 MB of Memory (RAM), 500 GB Hard Disk, and Windows7 professional64-bit Operating System. After coding, the program was debugged and run to obtain the results, which were checked for errors.

3.7 Validation, Verification and Errors

The mathematical formulations of overall plant energy efficiency developed for the research were derived from simplifications of the original system based on indications from operational data. The theoretical value of overall energy efficiency predicted for the simulation model was comparable to the value specified from literature data.

The simulation values obtained from the ExergyCalc code were verified by undertaking comprehensive manual calculations of a selection of energy and exergy balances, and through rigorous testing of the ExergyCalc code with data from process diagrams of similar systems (streams) reported in the literature.

The computational error estimated for the simulation results was obtained as the percentage error calculated as,

$$\%\ error = \frac{(theoretical\ loss\ value - simulated\ loss\ value)}{theoretical\ loss\ value}(100\%) \qquad (3.55)$$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results

The operational data used in the analysis of the processes within the AP1000 power cycle have been presented in Table 4.1 [17]. The AP1000 plant was assessed according to a reference environment temperature of 32°C taken as the approximate mean temperature of the condenser cooling water.

4.1.1 Energy and Exergy Losses in AP1000 Reactor Core

The thermodynamic properties for the AP1000 reactor core operating at 3400 MWt nominal power was given as,

$$\dot{Q}_{fission} = 3400\ MW$$

$$T_o = 32C + 273.15 = 305.15\ K$$

$$T_f = 1339.9C + 273.15 = 1613.15\ K$$

$$T_c = 315.75C + 273.15 = 588.9\ K$$

$$\dot{m} = 14275.8\ kg/s$$

$$h_1 = 1239.52\ kJ/kg, h_2 = 1468.87\ kJ/kg$$

$$s_1 = 3.0731\ kJ/kg\ K, \quad s_2 = 3.45997\ kJ/kg\ K$$

The energy output and loss values for the reactor were calculated as follows:

$$\dot{Q}_{loss} = 3400MW - 14275.8\ (1468.87 - 1239.52) = 125.1\ MW$$

Table 4.1.Property data for flow streams listed in Fig. 3.4 (a).

State	Mass flow rate	Enthalpy[1]	Entropy[1]	Temp	Pressure	Condition	Vapour fraction[3]
	kg/s	kJ/kg	kJ/kg. K	°C	MPa		
0				32.0	0.101		
1	14275.8[2]	1239.5	3.073	280.7	15.513	Subcooled liquid	0.0
2	14275.8[2]	1468.9	3.503	321.1	15.513	Subcooled liquid	0.0
3	1886.7	2765.8	5.924	270.7	5.571	Saturated vapour	1.0
4	170.4	2688.6	7.257	232.2	2.916	Two phase mixture	0.56
5	113.4	2543.0	5.840	229.4	1.103	Two phase mixture	0.40
6	1464.1	2543.0	5.840	184.1	1.117	Two phase mixture	0.90
7	1290.9	2950.8	7.980	254.6	1.075	Saturated vapour	1.0
8	172.5	2695.4	6.901	152.3	0.191	Saturated vapour	1.0
9	94.8	2146.0	7.830	79.3	0.046	Two phase mixture	0.84
10	1025.9	2252.0	8.407	42.7	0.008	Two phase mixture	0.98
11	1293.1	178.4	0.606	42.7	0.008	Saturated liquid	0.0
11'	1293.1	180.7	0.570	43.1	0.043	Subcooled liquid	0.0
12	1293.1	315.2	1.070	95.7	0.247	Subcooled liquid	0.0
13	1293.1	612.9	1.795	145.6	1.068	Subcooled liquid	0.0
14	1886.7	776.0	2.166	182.9	1.068	Subcooled liquid	0.0
14'	1886.7	785.3	2.187	184.2	2.764	Subcooled liquid	0.0
15	1886.7	975.8	2.578	226.6	5.570	Subcooled liquid	0.0
16	306.9	806.9	2.900	189.8	1.068	Subcooled liquid	0.0
17	172.5	338.7	1.080	80.9	1.190	Subcooled liquid	0.0
18	267.2	327.0	1.081	78.1	0.043	Subcooled liquid	0.0
Cwin	37665.8	137.0	0.453	32.0	0.101	Subcooled liquid	0.0
Cwout	37665.8	185.0	0.663	46.8	0.101	Subcooled liquid	0.0

[1] Enthalpy and entropy values were obtained by finding the mass weighted average enthalpy and entropy values of streams specified for components in the AP1000 Design Control Document [17].

[2] The mass flow rate for the primary coolant was derived from the best estimate core flow provided in AP1000 Design Control Document [16].

[3] Vapour fraction is listed as 0.0 for liquids and 1.0 for superheated vapours.

The energy efficiency of the reactor core was,

$$\eta_R = \left(1 - \frac{125.1\ MW}{3400\ MW}\right) 100\ \% = 96.3\ \%$$

The exergy output and loss values were calculated as follows,

$$(\dot{W}_{u,\max})_{fuel} = \left(1 - \frac{305.15\ K}{1613.15\ K}\right) 3400\ MW = 2756.8\ MW$$

$$\dot{I}_{fuel} = 3400\ MW - 2756.8\ MW = 643.1\ MW$$

$$(\dot{W}_{u,\max})_{clad} = \left(1 - \frac{305.15}{588.9}\right) 3400 = 1638.1\ MW$$

$$\dot{I}_{clad} = 2756.8 - 1638.2 = 1118.6\ MW$$

$$(\dot{W}_{u,\max})_{coolant} = 14275.8[(1468.87 - 1239.52) - 305.15(3.4599 - 3.0731)]$$

$$= 1585.1\ MW$$

$$\dot{I}_{coolant} = 1638.2\ MW - 1585.1\ MW = 53.1\ MW$$

The total irreversibility of the reactor was,

$$\dot{I}_{reactor} = \dot{I}_{fuel} + \dot{I}_{clad} + \dot{I}_{coolant} = 1814.8\ MW$$

From the definition of the second law, the exergy efficiency of the reactor core was calculated as,

$$\psi_R = \left(1 - \frac{1814.8\ MW}{3400\ MW}\right) 100\% = 46.6\ \%$$

The results of the energy and exergy analysis of the AP1000 reactor core are summarized in Table 4.2 and Table 4.3 respectively.

Table 4.2 Energy balance (input, output and loss rates) of AP1000 reactor core.

Reactor core (rate)	AP1000	
	(MW)	(% of total energy)
Energy loss	125.1	3.7
Energy output rate (coolant)	3274.9	96.3
Fission heat input	3400.0	100.0

Table 4.3 Exergy output and consumption values for AP1000 reactor core.

Reactor core	AP1000	
	(MW)	(% of total exergy)
Exergy consumption rate		
Heating of fuel centerline	643.2	18.9
Transfer of heat to cladding surface	1118.6	32.9
Heating of coolant	53.1	1.6
Total	1814.8	53.4
Exergy output rate		
Exergy available from coolant	1585.2	46.6
General Total	3400.0	100.0

4.1.2 Energy and Exergy losses in AP1000 Power Cycle

The energy and exergy values obtained for the power cycle of the AP1000 plant were evaluated using the Matlab script ExergyCalc developed and implemented for the analyses and presented in Appendix A. The energy loss and exergy consumption values computed for the overall processes and process subsections with ExergyCalc are presented in Table 4.4

From first law analysis, a large quantity of energy (1808MW) entered the condensation section, of which close to 100% was rejected to the environment. In the power production section of the AP1000 unit (consisting of the turbines), the combined energy loss from the high and low pressure turbines was found to be very small at 17.6 MW. The preheating sections consisting of two low pressure closed heat exchangers, a high pressure closed heat exchanger and a de-aerating chamber, were are found to have an aggregate energy loss of 31.2 MW.

The energy losses in the steam generation sections, consisting of the reactor core and steam generator devices, were found to be moderate at 227.4 MW with the reactor core contributing 125.1 MW of the total, and the steam generator device experiencing the remaining 102.3 MW loss.

The exergy analysis of components revealed that, the condenser consumed only 28.4 MW of exergy during heat transfer to the cooling water. In the power production section of the AP1000 unit, the total exergy losses were found to be moderate at 99.3 MW. Of this total, the low pressure turbine was observed to account for the highest loss of 72.4 MW, with the high pressure turbine contributing a loss of 26.9 MW.

Table 4.4 Simulated energy and exergy loss rates in sections of AP1000 power cycle.

Section/device	**Energy loss rate**		**Exergy loss rate**	
	(MW)	**% of total energy loss**	**(MW)**	**% of total exergy loss**
Steam generation section				
Reactor				
Fuel Centerline	-		643.2	31.7
Cladding surface	-		1118.6	55.1
Coolant	-		53.1	2.6
Total	125.1	6.0	1814.8	89.4
Steam generator	102.3	4.9	53.6	2.6
Section Total	227.4	10.9	1868.4	92.0
Power production section				
High-pressure turbine	-		26.9	1.3
Low-pressure turbine	-		72.4	3.6
Total	17.6	0.8	99.3	4.9
Condensation section				
Condenser(rejected)	1808.0		28.5	
Total	1808.0	86.7	28.5	1.4
Preheat section				
Low-pressure heat exchanger (CFH1)	0.6	0.0	2.0	0.1
Low-pressure heat exchanger (CFH2)	21.5	1.0	1.2	0.1
Deaerating heat exchanger (OFH)	7.9	0.4	10.9	0.5
High-pressure heat exchanger (CFH3)	1.2	0.1	19.5	1.0
Total	31.2	1.5	33.6	1.7
General Total	2084.2	100.0	2029.8	100.0

The preheating sections were found to have small exergy consumptions adding up to a total loss of 33.6 MW. The exergy consumption associated with the reactor core and steam generator assembly, collectively called the steam generation sections, was substantial contributing 1868.4 MW of exergy loss, thereby accounting for 92% of the total exergy consumed.

The main energy process in the steam generation sections was heat transfer, and of the total exergy consumed, 1814.8 MW was consumed in the heat transfer processes of the reactor core, and 53.6 MW internally consumed in the steam generator device.

The overall energy and exergy efficiency values were calculated using $\dot{W}_T = 1199.5\ MW$ and equations (3.51) and (3.53) respectively for the AP1000 plant, and modeled as the theoretical energy and exergy efficiency values.

$$\eta_{plant} = \frac{1199.5\ MW}{3400\ MW}(100\%) = 35.3\ \% \qquad (3.51)$$

$$\psi_{plant} = \frac{1199.5\ MW}{3400\ MW}(100\%) = 35.3\ \% \qquad (3.53)$$

Consequently, the theoretical energy and exergy loss values calculated from equation (3.54) were found to be same as

$$\eta_{loss} = \psi_{loss} = 3400\ MW - 1199.5\ MW = 2200.5\ MW \qquad (3.54)$$

4.1.3 Error Analysis

Sources of error encountered in the research were the model assumptions, or simplifications, computational errors and rounding off errors. The errors caused deviations of the simulated total energy and exergy loss values from the theoretical loss values for the model. The computational error associated with the simulated energy and exergy results was estimated as the percentage error calculated as follows:

From equation (3.55), the computational error estimated for total energy loss rate was,

$$\%\, error = \frac{(2200.5 - 2084.2)\ MW}{2200.5\ MW}(100\%) = 5.3\ \% \qquad (3.55)$$

And the computational error estimated for the total exergy consumption rate was obtained as,

$$\%\, error = \frac{(2200.5 - 2029.8)\ MW}{2200.5\ MW}(100\%) = 7.8\ \% \qquad (3.55)$$

Thus, the simulated total energy loss and exergy consumption values fall within 10% of the theoretically predicted values.

4.2 Discussion

The energy analysis of the AP1000 reactor core indicated that operating at nominal core power of 3400 MW, energy was lost at the rate of 125.1 MW to the surroundings, and transferred at the rate of 3274.9 MW to the primary coolant. On percent basis, only 3.7 % of the total heat (energy) generated from the fuel was wasted, yielding a reactor energy efficiency of 96.3 %.

The exergy consumption in the AP1000 reactor core was separated into irreversible losses in heating the fuel centerline to the maximum temperature of 1339.9 ^{o}C, transferring of heat to the cladding surface at 315.75 ^{o}C [4], and heating of the primary coolant.

Of the 1814.8 MW total exergy consumption observed in the reactor core, 643.2 MW was consumed in heating the fuel centerline to the maximum temperature, 1118.6

MW in transferring heat to the cladding surface, and 53.1 MW was destroyed in heating the primary coolant. The maximum work available from the coolant was observed to be 1585.2 MW, thereby achieving exergy efficiency of 46.6 %.

The high thermal efficiency and moderate exergy efficiency achieved by the AP1000 reactor core was ascribed to the high temperatures of heat generation in the fuel, and heat-transfer under high temperature and pressure to the coolant. By this mechanism, the primary circuit maintained a high average temperature of heat addition to the working fluid in the secondary circuit.

The exergy destruction profile of the AP1000 reactor, which detailed the sectional contributions to total consumption within the core, showed that a substantial proportion (97 %) of total exergy consumption in the core was associated with heat transfer processes occurring within the fuel meat. This attribute was consistent with the exergy consumption profile observed for the nuclear reactor of the Pickering Nuclear Generating Station in Canada [6].

For the AP1000 power cycle, the theoretical values of the plant overall energy and exergy efficiencies were found to be similar. However, the energy and exergy analysis revealed that individual component contributions to the total energy and exergy losses differed significantly for most plant sections as depicted in Fig. 4.1.

Although, from energy analysis, energy loss in the condensers seemed high (1808 MW), the losses were associated with emissions at a temperature very near that of the environment. While the energy loss was large in quantity, it was thermodynamically insignificant due to its low quality, indicated by the low exergy consumption of 28.5 MW.

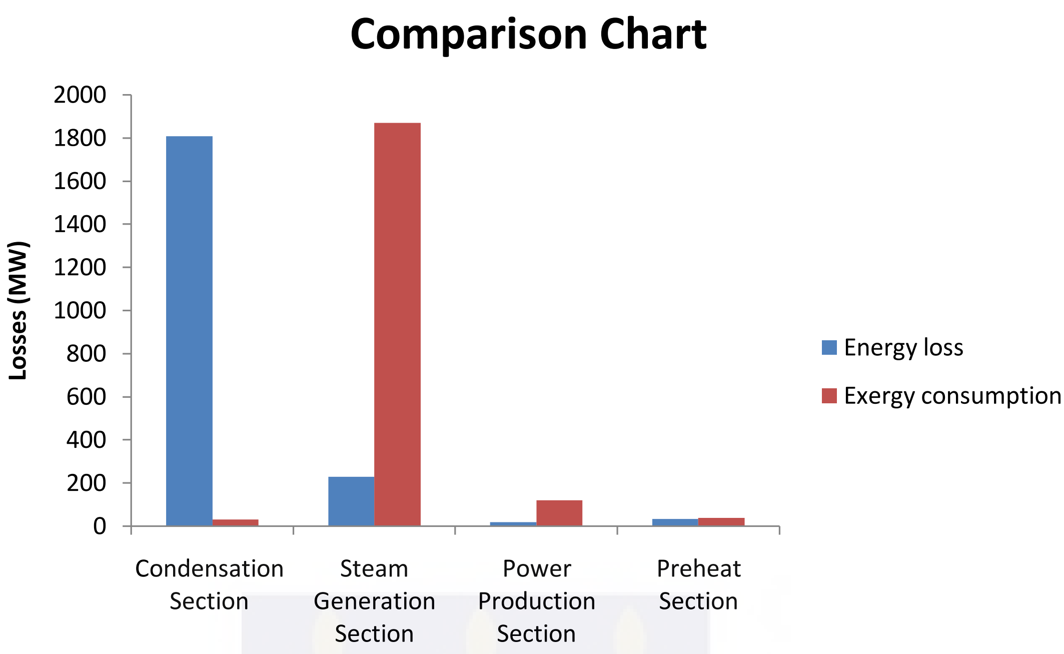


Fig. 4.1 Comparison of sectional energy and exergy losses within the AP1000 plant

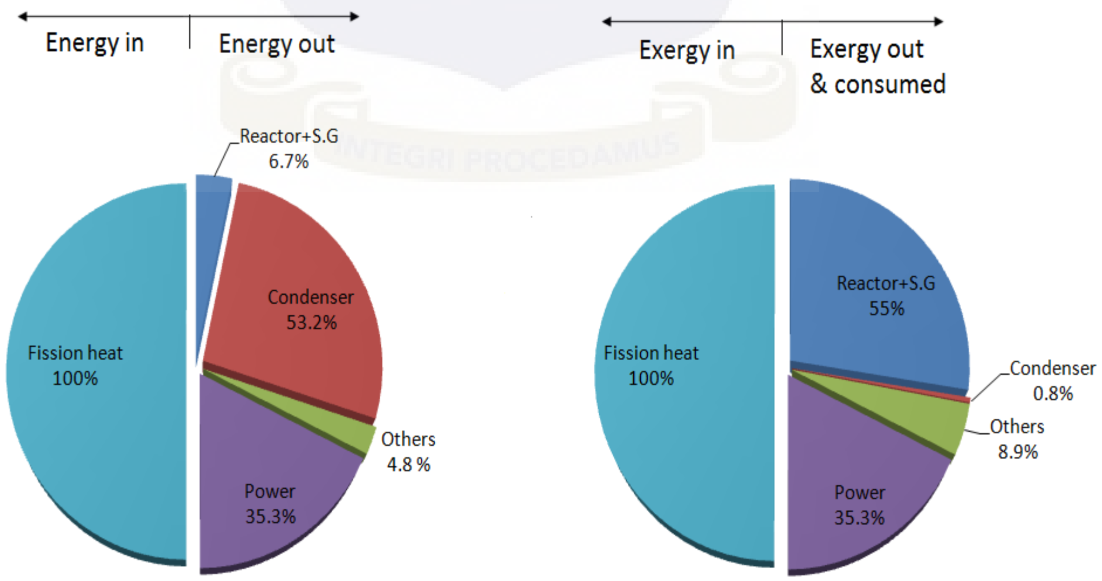


Fig. 4.2 Energy and exergy balances for the entire AP1000 plant indicating power input, output and sectional losses.

The largest irreversible losses (1868.4 MW) occured in the steam generation sections which experienced the largest exergy destruction (92 %) in the plant. The exergy analysis, therefore, quantitatively demonstrated that condensers were responsible for little of useful or quality energy losses. This discrepancy was highlighted in Fig. 4.2.

Energy analysis, thus, leads to the erroneous conclusion that almost all losses in net work output were associated with heat rejected by the condensers. However, as reported by Dincer [6], the sources for majority of useful losses were the steam generation sections which experienced the largest irreversible losses or internal consumptions.

The steam generation sections of the AP1000 unit appeared significantly more efficient on an energy basis than on an exergy basis. The implication was that although a large quantity of the input energy was transferred to the coolant, and subsequently to the working fluid, the quality of energy was degraded as it was transferred.

The overall energy efficiency value calculated for the AP1000 plant was observed to be comparable to the value specified from literature [32]. The marginal deviation was ascribed to the assumptions, simplifications and idealizations adopted for the study.

Generally, the energy loss and exergy consumption values obtained for the AP1000 plant were found to be in broad agreement with other published works on nuclear power plants, and indicated the operational locations with the biggest potential for efficiency improvements as reported by the researchers [6, 33].

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, energy and exergy analysis of the Westinghouse Advanced Passive 1000-MWe Nuclear Plant (AP1000) was presented**.** The primary objectives of the study were to analyze the AP1000 reactor core and power cycle separately, and to identify and quantify the sites having the largest energy and exergy losses under normal operating conditions.

Mathematical models of the energy and exergy rate balances for the AP1000 plant were formulated under steady state normal operating conditions and evaluated using process data sourced from literature and AP1000 design documents. A Matlab software script called ExergyCalc was implemented to compute the energy loss and exergy consumption rates in the various subsections of the AP1000 power cycle.

Of the 3400 MW core power generated by the AP1000, heat was lost at the rate of 125.1 MW to the environment, and transferred at a rate of 3274.9 MW to the reactor coolant, yielding a thermal efficiency of 26.7 %. Exergy analysis, on the other hand, revealed that of the total exergy (3400 MW) input to the reactor, 1814.8 MW was consumed in the reactor core.

The total exergy consumption in the core consisted of 643.2 MW consumed in heating the center of the fuel element, 1118.6 MW in transferring heat to the cladding surface, and 53.1 MW of exergy destroyed in heating the primary coolant. The maximum work obtainable from the primary coolant was found to be 1585.2 MW, resulting in exergy efficiency of 46.6 %**.**

The AP1000 core achieved very high energy efficiency and modest exergy efficiency which was comparable to other power reactor cores. This was attributable to the high temperatures associated with heat generation in the fuel and heat-transfer to the coolant.

For the AP1000 plant, maximum energy loss was observed in the condenser where close to 100 % of energy entering this section was rejected. The condenser alone accounted for 86.7 % of the total energy loss by the power cycle to the environment. The overall energy efficiency of the plant based on fission power generated was found to be 35.3 %.

Exergy analysis of the AP1000 station showed that energy loss in the condenser was thermodynamically insignificant due to the low quality of the ejected heat. In terms of exergy consumption (or irreversible losses), major loss was found in the steam generation sections (consisting of reactor core and steam generator assembly) where a substantial 1868.4 MW of exergy, constituting 55 % of the fission exergy input, was destroyed. In contrast, the percent exergy destruction in the condenser was 0.8 %, with the turbines and pre-heaters consuming 2.9 % and 1.0 % respectively of total exergy input.

From the definition of the second law, the overall exergy efficiency for the power cycle was found to be the same as the overall energy efficiency at 35.3 %, while energy and exergy analyses gave markedly different accounts of the component contributions to the total losses in the plant. Thus, while energy analysis gave only the energy emissions from processes without providing information about internal losses, exergy analysis highlighted the degradations in energy quality as it was transferred.

Generally, the energy and exergy loss and efficiency values evaluated for the process subsections and overall plant were found to be comparable to modern power plants and were in broad agreement with other published works on nuclear power reactors.

In conclusion, the exergy consumption rate of the nuclear reactor core was dominant over all other irreversible losses in the nuclear power cycle. However, parts of this irreversibility could not be avoided due to physical limitations. The study demonstrated that nuclear reactor cores have the largest potential for efficiency improvement in nuclear plants and, therefore, efforts to increase station efficiency should concentrate on this section.

5.2 Recommendations

As a tool that has found increasingly widespread use in the design, assessment, optimization, improvement and economic analysis of energy systems, the topic of exergy analysis should be incorporated in the school's engineering curriculum on thermodynamic analysis of power plants.

Investigations of the complete, full scale model of the AP1000 power cycle was not performed for reasons of time and scale of the work required. The simplified model adapted for the study had inherent limitations in comprehensively accounting for the energy and exergy losses in the various plant components. A holistic research would involve group work and the use of thermodynamic process simulators (e.g. Aspen Plus) which were not available for this study.

Subsequently, an advanced exergy analysis is envisaged, where the interactions among components will be considered and the exergy destruction within each component is split to better reveal the sources in terms of endogenous/exogenous exergy, and the potential for reduction in terms of avoidable and unavoidable exergy.

Finally, the exergy method should be applied to the Takoradi Thermal Power Station (Aboadze) and other thermal power systems operational in Ghana in order to assess the true thermodynamic performance of the energy conversion systems and determine the sections that contribute to the greatest losses in energy quality.

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APPENDICES

Appendix A. ExergyCalc _ code.

```
%-----------------------------------------------------------
%Matlab script 'ExergyCalc.m' to compute the energy
%and exergy loss values in the simulation model of AP1000 power cycle
%------------------------------------------------------------

%Parameters

%------------------------------------------------------------
To=32+273.15
Wt=1199500
%---------------------------------------
h1= 1239.5;
h2= 1468.9;
h3= 2765.8;
h4= 2688.6;
h4bar=  1981.8;
h5= 2543.0;
h5bar=  1506.1;
h6= 2543.0;
h7= 2950.8;
h8= 2695.4;
h9= 2146.0;
h10=    2252;
h11 =178.4;
h11bar= 180.7;
h12 =315.2;
h13 =612.9;
h14=    776.0;
h14bar=785.3
h15 =975.8;
h16 =806.9;
h17 =338.7;
h18=    327.0;
hci =137;
hco =185;
%---------------
s1= 3.0731;
s2= 3.503;
s3= 5.9242;
s4= 7.2574;
s4bar = 5.2236;
s4bar2 = 6.6;
s5 =    5.84;
s5bar=  4.7784;
s5bar2=6.6;
s6= 5.84;
s7= 7.98;
s8= 6.9;
s9= 7.83;
s10=    8.4071;
s11 =0.6062;
s11bar= 0.57;
s12=    1.07;
s13=    1.795;
s14=    2.1667;
s14bar= 2.1875
s15=    2.5785;
```

```
s16=    2.9;
s17=    1.08;
s18=    1.08;
sci=  0.453;
sco=    0.663;
%---------------------------------------
m1= 14275.8;
m2= 14275.8;
m3bar=  1886.7;
m3= 1823.7;
m4= 170.4;
m4bar=  306.9;
m5= 113.4;
m5bar=  286.7;
m6= 1464.1;
m7= 1290.9;
m8= 172.5;
m9= 94.8;
m10=    1025.9;
m11=    1293.1;
m11bar= 1293.1;
m12=    1293.1;
m13=    1293.1;
m14=    1886.7;
m15=    1886.7;
m16=    306.9;
m17=    172.5;
m18=    267.2;
mcwi=   37665.8;
mcwo=   37665.8;
clc
%-------------------------------------

% Energy and Exergy  Analysis of Station Components
%--------------------------------------------------


%Steam Generator Energy and Exergy Balance Analysis

RCoolantFlow = m1*(h2-h1 )

SGFlow = m15*(h3-h15)

ESG =RCoolantFlow - SGFlow

IdSG =To*(m15*(s3-s15)-m1*(s2-s1))


% Energy and Exergy Balance for HPT

EHPT = m3*(h3-h4)+(m3-m4)*(h4-h5 )+(m3-m4-m5)*(h5-h6)

Idhpt=To*(m3*(s4-s3 )+(m3-m4)*(s5-s4)+(m3-m4-m5 )*(s6-s5))


%Energy and exergy balance for LPT

ELPT = m7*(h7-h8 )+(m7 -m8)*(h8-h9)+(m7-m8-m9)*(h9-h10)
```

```
IdLPT = To*(m7*(s8-s7)+(m7-m8)* (s9-s8)+(m7-m8-m9)*(s10-s11))

%Total Turbine Energy and Exergy Losses

IdTURB = IdLPT + IdHPT

ETUR = ELPT + EHPT

Wloss = ETUR - Wt


% Energy and Exergy balance of CFH1

ECFH1 = m9*h9 + m17*h17- m11* (h12-h11bar)- m18*h18

IdCFH1 = To*(m11*(s12-s11bar)+m18*s18-m9*s9-m17*s17)

%  Energy and Exergy balance of CFH2

ECFH2 = m8*(h8-h17)- m12*(h13-h12)

IdCFH2 = m8*(h8-h17)-m12*(h13-h12)-To*(m8*(s8-s17)-m12*(s13-s12))

%  Exergy balance of OFH

EOFH = m5bar*h5bar+ m16*h16 + m13*h13 - m14*h14

IdOFH = To*(m14*s14bar-m5bar*s5bar-m16*s16-m13*s13)

%  Energy and Exergy balance of CFH3

ECFH3 = m4bar*(h4bar-h16) - m14*(h15-h14bar)

IdCFH3=m4bar*(h4bar-h16) - m14*(h15-h14bar)-To*(m16*(s15-s4bar)-
m14*s14+m14*s15)

% Energy and Exergy balance of Condenser


QCON = mcwi*(hco-hci)

IdCON=To*(m10*(s10-s11)-mcwi*(sco-sci))

% Total energy loss by components
Wloss
ECFH1
ECFH2
EOFH
ECFH3
QCON

%--------total energy loss by pre-heaters----------

NTotal=ECFH1+ECFH2+EOFH+ECFH3
```

```
%-------grand total of energy losses---------------

ETOTAL=Wloss+ECFH1+ECFH2+EOFH+ECFH3+QCON-ESG

%Total exergy loss in components
IdCON
IdCFH3
IdOF
IdCFH2
IdCF1
IdHPT
IdLPT
IdSG

%-----grand total of losses--------------------------

IdTOTAL=IdLPT+IdHPT+IdCF1+IdCFH2+IdOF+Id3+IdCON+IdSG
```