CHAPTER 6

Performance Assessment of a Magnetohydrodynamic Power Generation System on the basis of Advanced Exergy Analysis

6.1 Introduction

Performance evaluation of the conventional and non-conventional energy systems requires the use of suitable methods and approaches to propose means for improvement. In recent times exergy analysis has evolved as a useful way of predicting the performances of various systems. Such analysis has been able to provide qualitative information about the cause and location of inefficiencies in the thermodynamic system [1]. The exergy method utilizes the first and second law principles of thermodynamics for the purpose of analysis. It thus enabled the determination of meaningful efficiencies [2]. Exergy balances can be used to analyze multi-component systems that will indicate the distribution of the entire plant's irreversibility indicating the most inefficient component of the overall plant [3]. An exergy balance applied to a process or an overall plant helps one know the quantity of exergy that has been consumed by the process against its supply in the form of input to the investigated system [4].

Exergy appeared to be an evaluative criterion in system analysis to attain further development by providing an effective means to measure the potential to cause environmental degradation by a substance or energy form [5]. Exergy played a significant role in evaluating and improving the efficiencies of electrical power technologies and systems by clear identification of the locations that show sufficient potential for lowering thermodynamic losses and improving efficiency [6]. Energy systems can be evaluated using the method of exergy to obtain useful and meaningful information about energy utilization and understanding of the use of green energy [7].

The real thermodynamic inefficiencies in a system though are related to exergy desolation and exergy losses, the use of conventional exergy analysis can only point out the related system units having maximum exergy desolation and their causative processes. Moreover, only a portion of the exergy desolation in a component is avoidable in actual situation and the non-avoidable part is mostly caused by different physical, technological, and economic constraints. Hence the benefits of the conventional exergy analysis are often countered by a few essential information that could not be derived from such analysis [8]. The conventional exergy approach lacks completeness as it can mainly determine the energy and exergy rates, exergy desolations, and the thermodynamic inefficiencies of a component and the overall system.

The general exergy method cannot distinguish between what amount of exergy desolation is unrecoverable and those that can be avoided or minimized. Moreover, information regarding the nature of strength of the interactions that may exist among the various components of the system and the exactness of enhancement capabilities of either the components or the overall system cannot be obtained through the use of the conventional exergy method [9]. These drawbacks can be suitably eliminated by using the advanced method of splitting of the exergy desolations.

The advance method of exergy analysis splits the total desolation in exergy rates into a number of sub destructive components namely the endogenous and exogenous parts that are either avoidable or unavoidable. The endogenous part of exergy destruction is attributed to the irreversibilities that occurs inside a component itself while it is operating with its real efficiency while other components function under ideal conditions. The exogenous part is affected by both the internal irreversibility within a component and the irreversibilities occuring within other components of the system. Informations on endogenous and the exogenous parts of exergy desolation under the avoidable conditions are essential while considering performance improvement of systems as observed by Tsatsaronis and Morosuk [10].

The splitting of exergy destruction in energy systems have been a topic of research interest in recent times. Investigation of the improvement potential of thermal systems was one of the primary goal of advanced exergy analysis. Application of advanced exergy method for the analysis of a Kalina cycle driven by a geothermal system augmented with reduced temperature showed that the endogenous avoidable exergy desolation rate of the overall system was higher than the total endogenous unavoidable exergy destruction rate [11].

The endogenous exergy desolation provides a measure of self-inefficiency or internal irreversibility of a system or its component while the environmental components continue operating with zero irreversibilities. From the advanced exergy analysis for a combined organic Rankine cycle (ORC) and internal combustion engine (ICE), it was further observed that contribution to the exogenous part was because of inefficiencies external to the system or components while the given system or its components operate with maximum efficiency or zero internal irreversibility [12]. The advantages of the application of advanced exergy analysis over the conventional exergy method were evident from the available works of literature undertaking investigations on various systems [8-24].

Application of advanced exergy analysis to a coal-fired power plant (supercritical) following the standard exergy analysis helped to determine the differences in the percentage contribution of endogenous and exogenous exergy desolations among the sub-components. Among the sub-components, the boiler subsystem was found to exhibit large value of exogenous exergy destruction which also showed to possess the largest avoidable exergy destruction [13]. Application of advanced exergy analysis to a gas-turbine that was based on the consideration of real, conceptual and the unavoidable processes revealed about the improvement potential and the interactions among the system components [14].

While investigating a natural gas driven facility for electrical energy generation using the advanced exergy analysis, it was found that there were high enhancement possibilities for the combustion chamber, HPT, and the condenser. From the obtained information on the mutual relationships among the different system components, it was recommended that by prioritizing the most important system components enhancement of system efficiency can be achieved [15]. By considering the avoidable and unavoidable parts of exergy desolation together with the endogenous/exogenous parts, the splitting process will lead to a better understanding of the interactions among the components and can improve exergy conversion systems [16].

Discussing the theoretical and application aspects of both advanced and traditional exergetic analyses it was proposed that a conventional exergetic analysis identifies the magnitude, location, and causes of thermodynamic inefficiencies. However, in advanced exergy analysis, the desolation in exergy rate is split into avoidable and non-avoidable parts that will provide an idea of the actual improvement potential of the system components and the endogenous and exogenous parts will provide useful information in understanding the interactions among the components [17].

The existence of large amount of avoidable exergy desolation was observed while analysing an existing plant for ethane gas recuperation and suggested a high potential for improvement for the units [18]. A determinative method based on the splitting of exergy destructions was proposed to analyse deterioration in performance in thermal power plants. In this method, a fault was introduced in one of the component and the component was identified using an internal exergy indicator. The degradation was quantified by determination of the endogenous part of exergy destruction. In the analysis, it was found that major portion of the total exergy destruction is due to the endogenous exergy destruction in most components [19].

Exergy destruction or desolation is an useful parameter in the overall evaluation of any thermal systems. However, the advanced exergy analysis proved to be a better approach for obtaining system information and clear understanding of the enhancement potential for efficient operations [20].

Investigating a real combined cycle power plant (CCPP) with supplementary firing for varying mass flow rate of fuel in a duct burner it was shown that variations exists in the amount of different parts of the exergy destruction or their combinations among the system components. The conclusion derived stated that a rise in fuel flow rate in the duct burner has both positive and negative effects indicating increased improvement potential in most of the components in the former while reduction in thermal and exergetic efficiencies under actual, theoretical and non-avoidable situations in the latter [21].

Splitting of the exergy destruction rate into endogenous/exogenous and avoidable and/unavoidable parts showed the existence of high unavoidable exergy desolation rate for an aircraft gas turbine engine system. From the results it was observed that the gas turbine system possessed a low improvement potential and a weaker interrelationship among the components. Moreover, the combustion chamber was prioritized for having the maximum possibility of improvement due to its low avoidable exergy destruction rate [22].

In another investigation, that conducted a parametric study of an existing combined cycle power plant using the exergy splitting method showed an increase in the thermal and exergetic efficiencies with an increase in TIT and pressure ratio. It was found that the combustion chamber was the dominant component in terms of unavoidable endogenous exergy desolation and an increase in the TIT increases the endogenous avoidable exergy destruction in certain components whereas it increases the exogenous avoidable exergy desolation in some others. Similarly, they found that a rise in pressure ratio also affects the various components differently in terms of these exergy desolation parts [23].

By applying both conventional and advanced exergy methods to a drying system it was shown that the avoidable exergy destruction was the major part of the destruction of exergy in most of the components in the system. Moreover, the exergetic analysis gave an idea of the real range of exergetic efficiency for the overall system [24].

As seen from the above different studies, advanced exergy analysis can be applied to a system due to its advantages over conventional exergy analysis. In the advanced exergy analysis, the exergy desolation rates from the conventional exergy analysis are divided into smaller sub-portions to predict the exergy losses and the amount of exergy which is recoverable. Moreover, the results of advanced exergy analysis depend more on the decision of the operation strategist and decision-makers of a given system thus making it distinct from the method of conventional exergy analysis. It also provides an in-depth understanding of the improvement potential of components and the overall system and also their interactions among themselves.

As far as studies of MHD power generation systems are concerned, these were never analyzed previously for performance evaluation by splitting the exergy destruction rates and by considering the real and assumptions for the hypothetical and unavoidable cases. As such, no study on exergy destruction splitting applied to a MHD power generation system is available in the literature. Therefore, an advanced exergy analysis is performed in this paper to evaluate the exergy-based performance of a standalone MHD power plant in detail. However, for analysis, the present study considers the initial fuel-oxidant-seed and combustion data used in the system in Chapter 5. The primary goal of the present study is to evaluate the exergetic potential of the standalone MHD power plant through the method of splitting the exergy desolation rate into its corresponding endogenous/exogenous and avoidable/unavoidable parts. In doing so, the assumptions for the theoretical and unavoidable limitations have been considered. Accordingly, from the conducted analysis, the various divisions of the exergy desolation rates, the real improvement possibility of the MHD system and its related units, and the interlinkages existing among the various system units are determined in this study.

6.2 System description

The MHD power generation system in the present work is a standalone system. The overall system is divided into 9 components consisting of an air compressor, a combustion chamber, a nozzle, a power generator, an air-preheater unit, an OTSG (HRSG), and a seed recovery unit, one desulphurization unit, and the stack. The arrangement of the overall MHD system is shown in Fig.6.1. The MHD system here is similar to the one used in Fig. 4.1 with an addition of OTSG/HRSG component for better waste heat recovery. However, the present system as mentioned is a standalone system which has been considered for the purpose of advanced exergy analysis whereas the study conducted using Fig. 5.1 is on the exergetic performance evaluation of a MHD integrated gas turbine system. The system arrangement has been redrawn with component addition (OTSG) to system Fig. 4.1 in Chapter 4 . The components are interlinked with 15 different fluid flow streams. The above first 6 units are most relevant from the power generation and degradation of exergy viewpoint. For these 6 components, there are seven inlet and five exit streams. The compressed air (stream 2) is preheated to a high temperature to burn with the fuel in the combustion chamber which partially ionizes the combustion products. The partially ionized combustion stream is assumed to maintain a constant percentage of 40% with respect to the molecular species [25-26].

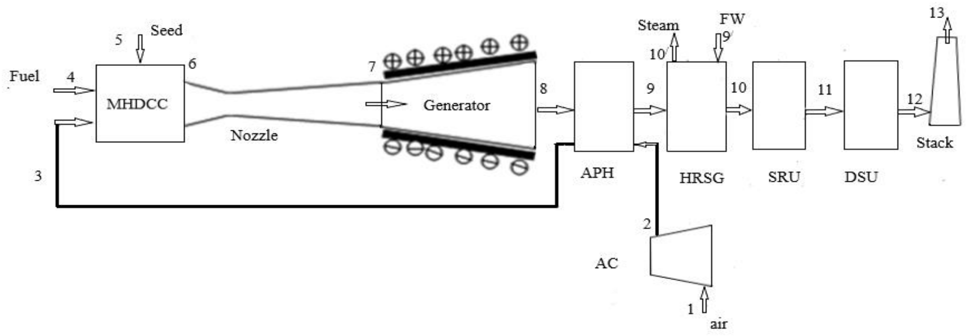

Fig. 6.1. Schematic of stand-alone MHD power plant [7].

The combustion products are accelerated through the nozzle (streams 6-7) and enter the power generator. The gas flow through the MHD generator (streams 7-8) is both conductive and in a partially ionized state. The required electrical conductivity of the ionized stream can be achieved by using alkali metals or salts as seed materials. The high-temperature exhaust gas from the MHD generator is utilized in the air-preheater (streams 8-9) to preheat the compressed gas and in the single pressure OTSG (streams 9-10). Preheating air increases the combustion temperature which assists in the ionization process. Before its release into the atmosphere, the exhaust gases from the OTSG are made to pass through a seed recovery unit for seed regeneration and seed recovery [27-28] and then through a desulphurization unit to control and capture excess sulfur dioxide. The OTSG generates superheated steam for other applications.

6.3 Methodology

As discussed in section 1, the method of advanced analysis is an extent of the method of the standard or conventional exergy analysis in which the rate of exergy destruction obtained through the conventional method is further distributed into some more distinct portions of exergy desolation rates. These distinct sub-portions are classified as endogenous, exogenous, avoidable, unavoidable, avoidable-endogenous, and exogenous and the non-avoidable endogenous and exogenous. The use of the advanced exergy method in system analysis thus requires one to first carry out the conventional exergy analysis for evaluation of the exergy degradation rate followed by its sub-class distributions in the advanced exergy analysis. These sub-portions provide a better clarity over the conventional means on the exergy utilization in a system or within its components.

6.3.1. Conventional exergy analysis

Assuming steady-state steady-flow processes and negligible kinetic and potential energy losses, the mass and energy, and the exergy balances for the control volume are given by the Eqs. (6. 1 – 6. 3) according to the relation of [4, 29] as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{6.1}$$

$$\dot{Q}_{CV} - \dot{W}_{CV} = \sum \dot{m}_{out}\bar{h}_{out} - \sum \dot{m}_{in}\bar{h}_{in} \tag{6.2}$$

$$\sum_y (1 - \frac{T_0}{T_y})\dot{Q}_y - \dot{\psi}_W = \sum \dot{m}_{out}\dot{\epsilon}_{out} - \sum \dot{m}_{in}\dot{\epsilon}_{in} + \dot{\psi}_D \tag{6.3}$$

where $\bar{h}, \dot{m},$ are the specific molar enthalpy and the mass flow rate at the entry and outlet section of a component's control volume (CV), $\dot{Q}_{CV}$ and $\dot{W}_{CV}$ are the heat and work transfer rates to and from the control volume, $\sum \dot{m}_{in}\bar{h}_{in}$ and $\sum \dot{m}_{out}\bar{h}_{out}$ are the total enthalpies (energy) entering and leaving the control volume, $\sum \dot{m}_{in}\dot{\epsilon}_{in}$ and $\sum \dot{m}_{out}\dot{\epsilon}_{out}$ are the total exergy rates entering and leaving the control volume, $\sum_y (1 - \frac{T_0}{T_y})\dot{Q}_y$ and $\dot{\psi}_W$ are the instantaneous exergy rate due to heat transfer and the exergy rate due to work transfer and $\dot{\psi}_D$ is the exergy desolation rate.

6.3.1.1. Physical and chemical exergy model of the flow streams

The determination of exergy rates requires the calculation of both thermo-mechanical and chemical exergies of the flow streams [4, 29]. The elemental chemical exergies are evaluated using the standard chemical exergy values of [30]. The physical and chemical exergy rate of a given fluid stream is given by Eqs. (6. 4- 6. 5) as:

$$\dot{\psi}^{ph} = \left(\bar{h} - \bar{h}_0\right) - T_0(\bar{s} - \bar{s}_0) \quad (6.4)$$

$$\dot{\psi}^{ch} = \sum \chi_m \,\bar{\epsilon}_m{}^{ch} + RT_0 \sum \chi_m ln\chi_m \quad (6.5)$$

6.3.1.2. Chemical exergy of ionic products of the flow streams

For computing chemical exergy of the ionized elements at a given temperature, the elemental standard molar exergies and the Gibbs free energy change are required [31] and are given by Eq.(6. 6) as:

$$\bar{\epsilon}_{ion}^{ch} = \bar{\epsilon}_{elem}^{ch} + [\Delta\bar{g}_{ion}^{0} - \Delta_f\,\bar{g}_{elem}^{0}] \quad (6.6)$$

6.3.1.3. Chemical exergy model of fuel on dry and ash free basis

For solid fuel such as coal, the standard molar chemical exergy is calculated using Eq. (6. 7) on a dry and ash-free (DAF) basis and the total molar specific chemical exergy is obtained from Eq. (6. 8) on an as-received basis taking the moisture and ash content into account [29]:

$$\bar{\epsilon}_{DAF}^{ch} = HHV_{DAF} - T_0\left[\bar{s}_{DAF} + \sum \chi_{m,\ air}\,\bar{s}_m - \sum \chi_{m,\ comb}\,\bar{s}_m\right] + [\sum \chi_{m,\ comb}\,\bar{\epsilon}_m^{ch} - \sum \chi_{m,\ air}\,\bar{\epsilon}_m^{ch}] \quad (6.7)$$

$$\bar{\epsilon}^{ch} = 0.93\bar{\epsilon}^{ch(DAF)} + \frac{0.021}{18}\,\bar{\epsilon}_{H_2O}{}^{ch}(l) \quad (6.8)$$

where, $\bar{\epsilon}_{DAF}^{ch}$ is the molar specific chemical exergy of coal on a dry and ash free basis, $\bar{s}_{DAF}$ is the molar entropy for the fuel (coal) on a dry and ash free basis, $\bar{\epsilon}^{ch}$ is the molar specific chemical exergy of coal on as–received basis, $\chi_{m,\ air}$ is the mole fraction of the constituent m present in air, $\chi_{m,\ comb}$ is the mole fraction of the constituent m present in combustion product, T_0 is the reference environment temperature, HHV_{DAF} is the higher heating value of coal obtained on a dry and ash free basis given by Eiserman et al. [32].

6.3.1.4. Enthalpy and entropy model of the product flow streams

The energy and exergy rates for a given stream are determined by computing the specific molar values of enthalpies and entropies given by Eqs. (6.9-6.11) considering the approach of Chapter 5 and is given as:

$$\bar{h}_i = x \sum \chi_m \bar{h}_{m,\,ionic} + (1-x) \sum \chi_m \bar{h}_{m,\,molecular} \quad (6.9)$$

$$\bar{s}_i = x \sum \chi_m \bar{s}_{m,\ ionic} + (1-x) \sum \chi_m \bar{s}_{m,\ molecular} \quad (6.10)$$

$$\bar{s}_{m,\ ionic/molecular} = \bar{s}^0_{m,\ ionic/molecular} - Rln\frac{\chi_m p^i}{p^0} \quad (6.11)$$

where $\bar{h}_m$, $\bar{s}_m$ are the specific enthalpy and entropy (molar), $\bar{s}^0_m$ is the specific entropy (standard molar), and the mole fraction for the stream constituent *m* is χ_m.

6.3.1.5. Composition of fuel, air and combustion products

The mole fractions of the different constituents in the air (assumed) and in the combustion products are presented in Table 6.1. These mole fractions are obtained considering the coal composition (in % wt.) and evaluating the stoichiometric combustion reaction as given and discussed in chapter 4 of the present thesis. The mole fractions of the reaction constituents help in the evaluation of fuel to air ratio and while calculating the heating values of the given fuel. Heating values and fuel air ratio are useful in the determination of the mas flow rates of the fuel and air and that of the work done rates. The fuel compositions were those of Assam colliery [34].

Table 6.1. Percentage composition of the constituents of air (*assumed)* and combustion products (*actual*) [Ref. Chapter 4]

Constituents	$\chi_{m,\ air}$ (%)	$\chi_{m,\ comb}$ (%)
N_2	77.51	77.5618
O_2	20.62	20.9
CO_2	0.03	6.6225
H_2O	1.84	4.61
SO_2	-	0.155

In the MHD power generation system, the high-velocity ionized flame with the addition of an appropriate fraction of the potassium carbonate as seed flows through the generator. The ionized gas stream experiences an electromagnetic force namely the Lorentz force under the influence of both the applied magnetic field and the induced electric field. Thus, at the generator of the MHD, the moving ions are deflected away towards the electrodes attached to the generator walls at right angles to both the gas flow and applied magnetic field in the opposite directions. At the electrodes due to the movement of these oppositely charged ions, a potential difference is created thereby current on the application of load.

The ionization mechanism at the high combustion temperature is found to be very crucial in the generation of MHD power. The air-fuel mixture or oxygen-rich-fuel mixture is partially ionized to form different ionic constituents with enhanced conductivity with the addition of seed material. The various ionic species formed are tabulated in Table 6.2 and are assumed to be formed following the stated dissociated mechanism discussed in Chapter 5 and those in Ref. [35]. The high-temperature partial ionization forms ionic species due to the dissociation of the molecular species. However, the positive ions and electrons were considered to play the primary role as these species contribute large entropy to the free energy of uniformly moving products. Moreover, the ionic formation is higher than electrons production [26]. Like mole fractions, the mass fractions are similarly obtained considering the balanced stoichiometric combustion reactions of the ionic reactions. The mass fractions of the reaction constituents then used in the evaluation of fuel to air ratio and while calculating the heating values of the given fuel. Heating values and fuel air ratio are useful in the determination of the mas flow rates of the fuel and air and that of the work done rates.

Table 6.2. Mass fractions of ionic species formed during partial ionization [Ref.Chapter 5]

Ionic species	Parent molecule (s)	Mass fraction of ions (%)
N^+	N_2	0.775618
O^+	O_2, CO_2, SO_2	0.209, 0.066225, 0.00155
C^+	CO_2	0.066225
H^+, OH^+	H_2O	0.0461, 0.0461
S^+	SO_2	0.00155

The exergy balance in the present study has been carried out considering similar operating conditions up to the air preheater as in Ref. Chapter 5 while assuming a lower value of the adiabatic flame temperature at the combustor exit.

6.3.1.6. Exergy model of fuel and product, exergetic efficiency, exergy destruction ratio, exergy loss ratio

For the overall MHD plant the exergy balance can be indicated in the form of exergy rates of the fuel and products, the exergy destruction and the exergy losses [8, 17]. The exergy losses are associated mainly with the overall system due to mass and energy transfer and are fractional portions of the overall thermodynamic inefficiencies whereas for components the thermodynamic inefficiencies can be measured as exergy destruction provided ambient boundaries are in consideration [2, 33].

Thus, for the *j*th component and the overall plant, the exergy balances are given by equations (6. 12-6. 13):

$$\dot{\psi}_{P,\ j} = \dot{\psi}_{F,\ j} - \dot{\psi}_{D,\ j} \qquad (6.12)$$

$$\dot{\psi}_{P,\ tot} = \dot{\psi}_{F,\ tot} - \dot{\psi}_{D,\ tot} - \dot{\psi}_{L,\ tot} \qquad (6.13)$$

In Eq. (6. 12), $\dot{\psi}_{P,\ j}$, $\dot{\psi}_{F,\ j}$ and $\dot{\psi}_{D,\ j}$ are the exergy rates of the product and fuel and the rate of exergetic desolation in the *j*th unit. In equation (6. 13), the terms $\dot{\psi}_{P,\ tot}$, $\dot{\psi}_{F,\ tot}$, represent the total exergy rates of the products and fuel in the overall system and $\dot{\psi}_{D,\ tot}$ *and* $\dot{\psi}_{L,\ tot}$ are the rates of total exergy desolation and total exergy losses in the overall MHD system.

In conventional exergy analysis, the thermodynamic evaluation involved the determination of the exergetic efficiency and the exergy destruction ratio in the *j*th component together with the rate of exergy destruction whereas for the overall system, the exergetic efficiency, rates of exergy desolation, and exergy loss, and the exergy loss ratio are evaluated [25]:

$$\varepsilon_j = \frac{\dot{\psi}_{P,\ j}}{\dot{\psi}_{F,\ j}} = \frac{\dot{\psi}_{F,\ j} - \dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ j}} = 1 - \frac{\dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ j}} \quad (6.14)$$

$$\gamma_{D,j} = \frac{\dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ tot}} \quad (6.15)$$

$$\varepsilon_{tot} = \frac{\dot{\psi}_{P,\ tot}}{\dot{\psi}_{F,\ tot}} = \frac{\dot{\psi}_{F,\ tot} - (\dot{\psi}_{D,\ tot} + \dot{\psi}_{L,\ tot})}{\dot{\psi}_{F,\ tot}} = 1 - \frac{(\dot{\psi}_{D,\ tot} + \dot{\psi}_{L,\ tot})}{\dot{\psi}_{F,\ tot}} \quad (6.16)$$

$$\gamma_{D,tot} = \frac{\dot{\psi}_{D,\ tot}}{\dot{\psi}_{F,\ tot}} = \sum_{j=1}^{j=m} \gamma_{D,\ j} \quad (6.17)$$

$$\gamma_{L,tot} = \frac{\dot{\psi}_{L,\ tot}}{\dot{\psi}_{F,\ tot}} \quad (6.18)$$

In the Eqs. (6. 14 – 6. 18), ε_j and $\gamma_{D,j}$ are the exergetic efficiency and the exergy destruction ratio in the *j*th component, ε_{tot} and $\gamma_{D,tot}$ are the exergetic efficiency and the exergy destruction ratio for the overall MHD system, $\gamma_{L,tot}$ is the exergy loss ratio in the overall MHD system.

6.3.1.7. Component-wise energy and exergy balance model

In the MHD system (Fig.6.1), the conventional exergy analysis is carried out using the energy and exergy balance equations which are shown in Table 6.3. From Table 6.3, it can be seen that the energy and exergy balances performed for all the components of the MHD system in Fig. 6.1 is useful in the determination of the energy losses and the exergy destructions or irreversibilities in these components. The energy losses in the MHD components are obtained considering the energy rates at the inlet and exit of each component. Likewise, the exergy destruction can be obtained by the consideration of the exergy rates at the inlet and the outlet points of these components.

Table 6.3. Energy and exergy balances for the components of the MHD plant

MHD component	Energy balance	Exergy balance
AC	$\dot{E}_2 - \dot{E}_1 = \dot{W}_{AC}$	$\dot{\psi}_1 + \dot{W}_{AC} = \dot{\psi}_2 + \dot{\psi}_{D,\ AC}$
CC	$\dot{E}_6 - (\dot{E}_3 + \dot{E}_4 + \dot{E}_5) = \dot{Q}_{CC}$	$T_0\dot{S}_{gen} = \dot{\psi}_{D,CC}$
Nozzle	$\dot{E}_6 - \dot{E}_7 = \dot{V}_7 + \dot{E}_{L,\ Nozz}$	$\dot{\psi}_6 - \dot{\psi}_7 = \dot{\psi}_{D,\ Nozz}$
GEN	$\dot{W}_G = (\dot{E}_7 + \dot{V}_7) - \dot{E}_8$	$\dot{\psi}_7 - \dot{\psi}_8 = \dot{W}_G + \dot{\psi}_{D,\ G}$
APH	$(\dot{E}_8 + \dot{E}_2) = (\dot{E}_9 + \dot{E}_3)$	$(\dot{\psi}_8 - \dot{\psi}_9) - (\dot{\psi}_3 - \dot{\psi}_2) = \dot{\psi}_{D,\ APH}$
OTSG	$(\dot{E}_9 + \dot{E}_{9'}) = (\dot{E}_{10} + \dot{E}_{10'})$	$(\dot{\psi}_9 - \dot{\psi}_{10}) - (\dot{\psi}_{10'} - \dot{\psi}_{9'}) = \dot{\psi}_{D,\ OTSG}$
SRU	$\dot{E}_{11} = \dot{E}_{10}$	$\dot{\psi}_{10} - \dot{\psi}_{11} = \dot{\psi}_{D,\ SRU}$
DSU	$\dot{E}_{12} = \dot{E}_{11}$	$\dot{\psi}_{11} - \dot{\psi}_{12} = \dot{\psi}_{D,\ DSU}$
Stack	$\dot{E}_{13} = \dot{E}_{12}$	$\dot{\psi}_{12} - \dot{\psi}_{13} = \dot{\psi}_{D,\ Stack}$

6.3.2. Division of the Exergy Desolation Rates into Sub-Portions (Advanced exergetic evaluation)

The advanced study of exergy deals with the division of the entire exergetic desolations in the system's *j*th unit or component into portions that is either avoidable or unavoidable with further divisions of each type into endogenous or exogenous categories. The destruction of exergy can be also viewed as the total of endogenous and exogenous portions [10, 16, 33]. Accordingly, the divisions of exergy desolation inside the *j*th unit are illustrated in Fig.6.2.

6.3.2.1. Exergy destruction model with avoidable and unavoidable destruction parts

The divisions of exergy destruction inside the *j*th unit are illustrated in Fig.2. The total rate of exergy reduction within the overall system can be expressed as the sum total of the avoidable and unavoidable portions of the overall destruction.

$$\dot{\psi}_{D,j} = \dot{\psi}_{D,j}^{A} + \dot{\psi}_{D,j}^{U} \tag{6.19}$$

6.3.2.2. Exergy destruction model with endogenous and exogenous destruction parts

Further, it is also expressed as the total of the endogenous and exogenous portions of destruction. However, the endogenous or exogenous by themselves do not usually reflect whether those portions of exergy reduction rate are avoidable or impossible to avoid in total.

$$\dot{\psi}_{D,j} = \dot{\psi}_{D,j}^{EN} + \dot{\psi}_{D,j}^{EX} \tag{6.20}$$

6.3.2.3. Endogenous exergy destruction model in combination with avoidable and unavoidable destruction portions

The endogenous portion of the exergy reduction rate is the sum of avoidable as well as unavoidable portions.

$$\dot{\psi}_{D,j}^{EN} = \dot{\psi}_{D,j}^{AEN} + \dot{\psi}_{D,j}^{UEN} \tag{6.21}$$

6.3.2.4. Exogenous exergy destruction model in combination with avoidable and unavoidable destruction portions

Similarly, the exogenous portion of exergy reduction rate is also the sum of avoidable as well as unavoidable portions.

$$\dot{\psi}_{D,j}^{EX} = \dot{\psi}_{D,j}^{AEX} + \dot{\psi}_{D,j}^{UEX} \tag{6.22}$$

6.3.2.5. Avoidable and unavoidable exergy destruction model in combination with endogenous and exogenous portions of exergy reduction

Morever, the total rate of destruction can be obtained when the various portions are in different combinations. The avoidable and unavoidable portions of exergy destruction are further arranged as expressed in equations (6. 23)-(6. 24):

$$\dot{\psi}_{D,j}^{A} = \dot{\psi}_{D,j}^{AEN} + \dot{\psi}_{D,j}^{AEX} \tag{6.23}$$

$$\dot{\psi}_{D,j}^{U} = \dot{\psi}_{D,j}^{UEN} + \dot{\psi}_{D,j}^{UEX} \tag{6.24}$$

Thus, from equations (6. 19)-(6. 24), it is seen that the different portions of exergy destruction can be combined in a number of ways [8, 16].

In the Eqs. (6. 19 – 6. 22) above, $\dot{\psi}_{D,j}$ is the overall rate of degradation in exergy in the *j*th unit, $\dot{\psi}_{D,j}^{A}$ and $\dot{\psi}_{D,j}^{U}$ are the portions of avoidable and non-avoidable desolation in exergetic rates in the *j*th unit, $\dot{\psi}_{D,j}^{EN}$ and $\dot{\psi}_{D,j}^{EX}$ are the portions of endogenous and exogenous desolation in exergy rates in the *j*th unit, $\dot{\psi}_{D,j}^{AEN}$ and $\dot{\psi}_{D,j}^{UEN}$ are the avoidable and non-avoidable portions of desolation in exergy in the *j*th unit and lastly $\dot{\psi}_{D,j}^{AEX}$ and $\dot{\psi}_{D,j}^{UEX}$ are the avoidable exogenous and unavoidable exogenous portions of desolation in exergy in the *j*th unit.

Thus,
$$\dot{\psi}_{D,j} = \dot{\psi}_{D,j}^{AEN} + \dot{\psi}_{D,j}^{AEX} + \dot{\psi}_{D,j}^{UEN} + \dot{\psi}_{D,j}^{UEX} \tag{6.25}$$

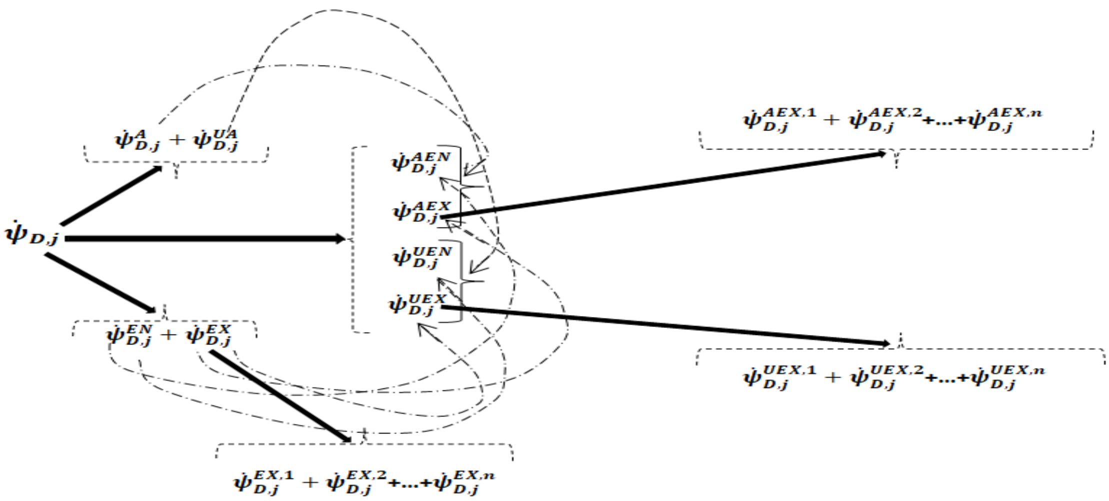

Fig.6.2. Division of exergy destructions inside the *j*th unit of the system [23, 33].

Fig. 6.2 shows the splitting of the exergy destruction rate in its major sub-portions and their different combinations which are also given by the equations (6.19- 6.24). The overall exergy destruction rate is obtained as a sum of all these sub portions and can be obtained using equation (6.25).

6.3.2.6. Exergy model for unendogenous and mexogenous exergy destruction estimation

It has been stated that the unavoidable portion of destruction in exergy in various units is a major challenge as it is not possible to completely eradicate it even though one uses one of the pre-eminent accessible technologies [8, 9]. Further, it was also stated that in order to obtain the unavoidable portion in a particular unit its necessary to analyze the operation in that unit under the assumptions of maximum efficiency and negligible wastage. These operating conditions were termed unavoidable operations. However, while fixing assumptions the strategists must consider the probable up-gradation likely achievable in the imminent future. To determine the unavoidable portion one can use the relation [8, 9] given in Eq. (6. 26) as:

$$\dot{\psi}_{D,j}^{UEN} = \dot{\psi}_{P,j}^{EN} \times \left(\frac{\dot{\psi}_D}{\dot{\psi}_P}\right)_j^U \qquad (6.26)$$

In Eq. (6. 26), $\dot{\psi}_{D,j}^{UEN}$ is the rate of unavoidable endogenous desolation in exergy in the *j*th unit, $\dot{\psi}_{P,j}^{EN}$ is the endogenous portion of desolation in exergy rate of the product in the *j*th unit. There is, however, another kind of destruction of exergy termed mexogenous that is associated with the exogenous portion affecting the jth unit. It takes into account the destruction in the exogenous portion inside the jth unit and the total rate of exergy destruction considering the total number of units present in the system [14, 22]

$$\dot{\psi}_{D,j}^{EX} = \dot{\psi}_{D,j}^{MEX} + \sum_{\substack{r=1, \\ r\neq j}}^{r=r} \dot{\psi}_{D,r}^{EX,r} \qquad (6.27)$$

The details of the procedure for evaluating the endogenous/exogenous and the avoidable/ unavoidable portions of the desolation of exergy are described in the works of [18,22].

6.3.3. Assumptions for hypothetical, actual and unavoidable operating conditions

The assumptions on the operative hypothetical, actual and unavoidable cases for the various units of the MHD system are exemplified in Table 6.4. Likewise in [10, 14], in the present work, the endogenous and exogenous portions of exergy desolation are examined under the hypothetical situations, and to satisfy the unavoidable situations the avoidable and unavoidable portions of exergy desolation were evaluated. In Table 6.4, the unavoidable portion represents that part of the exergy destruction that cannot be minimized in the near future without further improvement of technology. While the hypothetical values are the theoritical values of the performance parameters which are normally idealised and the actual parameters are those generally observed in the real working environment.

Table 6. 4. Assumptions of hypothetical, actual and unavoidable conditions

Units, j	Theoritical	Actual	Unavoidable
AC	$\eta = 100\%$	$\eta = 86.4\%$	$\eta = 96\%$
CC	$\dot{Q}_L = 0\%$ $EA_H = 2.0$ $\Delta P = 0\ bar$	$\dot{Q}_L = 2\%$ $EA_{ACT} = EA_H$ $\Delta P = 0.10\ bar$	$\dot{Q}_L = 0\%$ $EA_U = 3.5$ $\Delta P = 0.02\ bar$
Nozzle	$\eta = 100\%$	$\eta = 96\%$	$\eta = 100\%$
GEN	$\eta = 100\%$	$\eta = 90\%$	$\eta = 97\%$
APH	$\Delta P = 0\ bar$ $\Delta T_{min} = 0^0C$	$\Delta P = 0.30\ bar$ $\Delta T_{min} = 300^0C$	$\Delta P = 0.09\ bar$ $\Delta T_{min} = 100^0C$
OTSG	$\Delta P = 0\ bar$ $\Delta T_{min} = 0^0C$	$\Delta P = 3\ bar$ $\Delta T_{min} = 30^0C$	$\Delta P = 1\ bar$ $\Delta T_{min} = 5^0C$
SRU	$\Delta P = 0\ bar$	$\Delta P = 0.03\ bar$	$\Delta P = 0.001\ bar$
DSU	$\Delta P = 0\ bar$	$\Delta P = 0.10\ bar$	$\Delta P = 0.03\ bar$
Stack	$\eta = 100\%$	$\eta = 98\%$	$\eta = 100\%$

6. 4 Determination of MHD plant performance parameters

6.4.1. Determination of thermodynamic data, energy and exergy rates of the flow streams

The present work assessed the various units of a standalone MHD power plant to estimate the outcome in terms of the advanced exergy parameters. Initially, the investigation is conducted using the standard energy and exergy approach. The estimated values for the energy and exergy flow rates at the various points of the flow stream have been specified in *Table 6.5* using initial data of Chapter 5 by considering the real working settings of the MHD system. In Table 6.5, the method of determination of the mass flow rate, pressure and temperatures at the state points has been stated in chapter 4 and 5 respectively. Similarly, these values are utilized for the determination of the specific and total molar enthalpies and entropies which in turn are used for the computation of the energy and exergy rates at those state points. The values of the energy and exergy rates again are considered while evaluating the performance parameters of the MHD system under consideration in Fig. 6.1..

Table 6.5. Mass flow rate, state properties, energy and exergy rates at various states of the standalone MHD power generation system

State	$\dot{m}\ (kg/s)$	T (K)	P (bar)	$Energy\ rate, \dot{E}(MW)$	$Exergy\ rate, \dot{\psi}(MW)$
1	73.367	298.15	1.0000	22.631	0.0000
2	73.367	621.00	10.0000	48.970	21.549
3	73.367	1800.00	9.5000	166.949	112.750
4	2.410	298.15	1.0000	81.147	89.134
5	0.758	298.15	20.0000	0.467	6.095
6	76.535	3555.00	12.0000	228.232	205.382
7	76.535	2979.00	1.5655	141.054	105.348
8	76.535	2050.00	1.5342	205.991	132.319
9	76.535	993.30	1.4575	90.016	36.734
10	76.535	550.095	1.4575	45.088	7.042
9′	21.067	360.150	1.0000	7.691	360.559
10′	21.067	759.035	1.0000	72.841	369.637
11	76.535	539.093	1.4298	44.066	6.386
12	75.777	528.311	1.3620	43.1146	4.451
13	75.777	518.167	1.0000	42.321	2.537

6.4.2. Determination of fuel and product exergies, exergy destruction rates, exergetic efficiencies and exergy destruction ratios of the flow streams

The exergy parameters of the individual unit of the MHD system are evaluated and specified in *Table 6.6* part of which are obtained up to the air preheater section using the initial data of Chapter 5. The effectiveness of these parameters was realized while carrying out the process of advanced exergy. From the power generation perspective in the MHD plant, the crucial units are being limited up to the MHD generator including the air preheater, the other downstream units being more concerned with the process utilization and environmental factors. From the standard exergy evaluation, the maximum desolation in exergy rate is found to occur in the CC unit (82.121 MW) with an overall system exergy destruction of 146.903 MW. The overall system efficiency (exergetic) is low at 22.93 % and thus provides a scope of its augmentation through appropriate technical strategies. The exergy destruction ratio reflects a similar trend among all the units of the MHD system as that of the rate of exergy desolation in all these units when evaluated with respect to the fixed overall fuel exergy rate. As seen from Table 6.6, the exergy rates of the fuel and those of the products for each unit of the MHD system are computed to obtain the exergy destruction in that particular component. Knowing the rate of exergies of the fuel and product and the exergy destruction one can compute the exergetic efficiency of the component. On the otherhand the exergy destruction ratio evaluated for each MHD component gives an idea about the fraction of exergy destruction in that component relative to the overall system.

Table 6.6. Results of standard exergy analysis for the units of the MHD system

MHD System unit $'j'$	$\dot{\psi}_{F,j}(MW)$	$\dot{\psi}_{P,j}(MW)$	$\dot{\psi}_{D,j}(MW)$	$\varepsilon_j(\%)$	$\gamma_{D,j}$ (%)
AC	26.339	21.549	4.7903	81.823	1.666
CC	287.503	205.382	82.121	71.436	28.564
Nozzle	100.034	87.178	12.856	87.148	4.472
GEN	105.348	87.468	17.880	83.027	6.219
APH	153.868	149.484	4.391	97.149	1.527
OTSG	397.293	376.933	20.360	94.875	7.082
SRU	7.042	6.386	0.656	90.684	0.228
DSU	6.386	4.451	1.935	69.699	0.673
Stack	4.451	2.537	1.914	56.998	0.666
Overall *MHD* system	287.503	65.919	146.903	22.93	51.097

6.4.3. Estimation of the sub portions of exergy destruction

The various parameters of the advanced exergy method were evaluated for the MHD system considering the assumed hypothetical, actual and the unavoidable working conditions. From Fig.6.3 and Table 6.6 it is seen that the CC unit accounts for the utmost destruction in exergy rate with 82.121 MW and the lowest occurs in the SRU with 0.656 MW. The division of the overall exergy destruction in the MHD system is given in Table 6.7 which makes up for the sum total of either avoidable and unavoidable portions or those for the endogenous and exogenous portions. In Table 6.7, the exergy destruction in the individual components are splitted to obtain the values for its different major sub-portions namely the avoidable, unavoidable, endogenous and exogenous parts following the advanced exergy analysis approach. From the Table, it is seen that the total avoidable portion of exergy destruction rate surpasses the unavoidable portion by 38.7233 MW whereas the total rate of destruction of the endogenous exergy portions surpasses the total exogenous portion by 19.5733 MW. Among the MHD units the maximum avoidable destruction of exergy rate occurs in the CC with 57.386 MW while the least avoidable destruction of 0.1292 MW occurs in the APH. The CC unit also dissolves the maximum unavoidable exergy rate with 24.735 MW while the least unavoidable destruction rate in exergy occurs in the SRU with 0.0674 MW. The division of the overall endogenous exergy destruction among the MHD units estimated in Table 6.7 are arranged in descending order in Fig.6.4 with utmost destruction in the CC unit with 57.512 MW.

Table 6.7. Splitting of exergy destruction in the *j*th unit into its main portions

System unit $'j'$	$\dot{\psi}_D, j\ (MW)$	$\dot{\psi}^A_{D,j}\ (MW)$	$\dot{\psi}^U_{D,j}\ (MW)$	$\dot{\psi}^{EN}_{D,j}\ (MW)$	$\dot{\psi}^{EX}_{D,j}\ (MW)$
AC	4.790	3.892	0.898	3.582	1.208
CC	82.121	57.386	24.735	57.512	24.609
Nozzle	12.856	10.902	1.954	4.001	8.855
GEN	17.880	17.328	0.552	10.535	7.345
APH	4.391	0.129	4.262	2.389	2.002
OTSG	20.360	1.024	19.336	1.883	18.477
SRU	0.656	0.588	0.067	0.304	0.352
DSU	1.935	1.094	0.841	1.296	0.638
Stack	1.914	0.461	1.444	1.736	0.1780
Overall *MHD* plant	146.903	92.813	54.090	83.238	63.665

6.4.4. Determination of mexogenous part of exergy reduction

The contribution of other units (unit ‘r’) of the MHD system to the exogenous part of the exergy destruction rate in the *jth* unit can be known by determining the mexogenous partion of the exergy destruction rate. The mexogenous exergy destruction rate is determined using the standard procedure of the advanced exergy analysis which is defined in the earlier section of this chapter. In Table 6.8, the rate of mexogenous exergy destruction in the *j*th unit of the MHD system due to those of the exogenous exergy destruction rate in the rth units are determined. Here, unit ‘r’ denotes one of the remaining eight units in the overall system except for the *jth* unit for which the mexogenous portion of exergy destruction is considered.

Table 6.8. Mexogenous exergy destruction in the *j*th unit of the MHD system

System unit $'j'$	$\dot{\psi}_{D,j}^{EX}$ (MW)	$\dot{\psi}_{D,j}^{MEX}$ (MW)	$\sum_{r=1, r\neq j}^{r=r} \dot{\psi}_{D,r}^{EX,r}$ (MW)
AC	1.2083	0.242	CC: 0.562, Nozzle:0.029, GEN: 0.077, APH:0.193, OTSG: 0.019, SRU:0.009, DSU: 0.019, Stack:0.038
CC	24.609	8.613	AC: 1.691, Nozzle: 7.084, GEN: 4.987, APH: 0.701, OTSG: 1.478, SRU: 0.0176, DSU: 0.0319, Stack: 0.0089
Nozzle	8.855	1.328	AC: 0.2054, CC: 4.922, GEN: 1.8052, APH: 0.112, OTSG: 0.8314, SRU: 0.007, DSU: 0.009, Stack: 0.002
GEN	7.345	1.542	AC: 0.151, CC: 2.756, Nozzle:1.771, APH:0.300, OTSG: 0.721, SRU: 0.035, DSU: 0.057, Stack: 0.012
APH	2.002	1.201	AC: 0.120, CC: 0.295, Nozzle: 0.088, GEN: 0.184, OTSG: 0.106, SRU: 0.003, DSU: 0.004, Stack: 0.001
OTSG	18.477	11.456	AC: 0.024, CC: 4.911, Nozzle: 0.075, GEN: 0.1.102, APH: 0.700, SRU: 0.123, DSU: 0.076, Stack: 0.010
SRU	0.3521	0.106	AC: 0.015, CC: 0.123, Nozzle: 0.017, GEN: 0.0621, APH: 0.011, OTSG: 0.007, DSU: 0.009, Stack: 0.004
DSU	0.6386	0.319	AC: 0.016, CC: 0.096, Nozzle: 0.008, GEN: 0.0384, APH: 0.013, OTSG: 0.0112, SRU: 0.080, Stack: 0.057
Stack	0.1780	0.036	AC:0.019, CC: 0.033, Nozzle: 0.011,GEN: 0.008, APH: 0.017, OTSG: 0.023, SRU: 0.001, DSU: 0.030

6.4.5. Determination of the mixed values of destruction in exergy rates

The amalgamation of one of the two from the first category (avoidable/unavoidable) of exergy destruction rate with one of the exergy destruction in the second category (endogenous/exogenous) is given in Table 6.9. Further, in Table 6.9 we see that most of the endogenous portion of exergy destruction in the entire MHD system is avoidable in nature (nearly 64.40%) and exceeds the total unavoidable endogenous destruction (nearly 35.59%) by 23.9857 MW. Moreover, in Table 6.9 it is found that nearly 61.57 % of exogenous portion of exergy destruction in the entire MHD system is of avoidable type whereas the rest 38.43 % is unavoidable with a difference of about 14.7376 MW. Further, the CC accounts for the maximum unavoidable and also for the avoidable endogenous exergy destruction rate which indicates a higher opportunity of its enhancement in the near future with appropriate technology and design considerations. A higher avoidable endogenous exergy rate is an opportunity whereas its higher unavoidable part is a concern. The exegoneous avoidable and unavoidable are often not considered to be of much influence as far as the component performance is concerned.

Table 6.9. Classifying exergy destruction in the *j*th unit into the sub-portions

System unit $'j'$	$\dot{\psi}_{D,j}\ (MW)$	$\dot{\psi}_{D,j}^{AEN}\ (MW)$	$\dot{\psi}_{D,j}^{UEN}\ (MW)$	$\dot{\psi}_{D,j}^{AEX}(MW)$	$\dot{\psi}_{D,j}^{UEX}\ (MW)$
AC	4.7903	3.1550	0.4270	0.7367	0.4716
CC	82.121	35.861	21.651	21.525	3.084
Nozzle	12.856	2.289	1.712	8.613	0.242
GEN	17.880	9.994	0.541	7.334	0.011
APH	4.391	0.0702	2.3188	0.059	1.943
OTSG	20.360	0.811	1.072	0.213	18.264
SRU	0.656	0.2727	0.0312	0.3159	0.0362
DSU	1.935	0.7328	0.5636	0.3610	0.2776
Stack	1.914	0.4263	1.3097	0.0437	0.1343
Overall *MHD* plant	146.903	53.612	29.6263	39.2013	24.4637

While evaluating the advanced exergy parameters in Tables (6.7- 6.9), it can be observed that evaluation of the given systems under the given set of conditions is primarily the functions of the real conditions as well as the assumptions made for the unavoidable conditions. The assumptions for the unavoidable conditions rely upon the actual operating conditions of the related units. The unavoidable conditions of operation in the assumptions reflect the comparative unachievable conditions of operation once the actual operating conditions were known or evaluated. The advanced exergy analysis thus takes into account not only the theoretical conditions but also the prevailing real and future conditions of operations that make this analysis differ from the conventional method of exergy analysis [10, 17]. Nonetheless, the decisions of the operational strategist also play a vital role while setting the conditions for the advanced exergy analysis of the system dealt with.

6.5 Advanced exergy analysis of the standalone MHD power plant

6.5.1. Effects of variation of exergy reduction rate of endogenous type

The distribution of the total exergy destruction in the MHD system is represented by Fig.6.3.

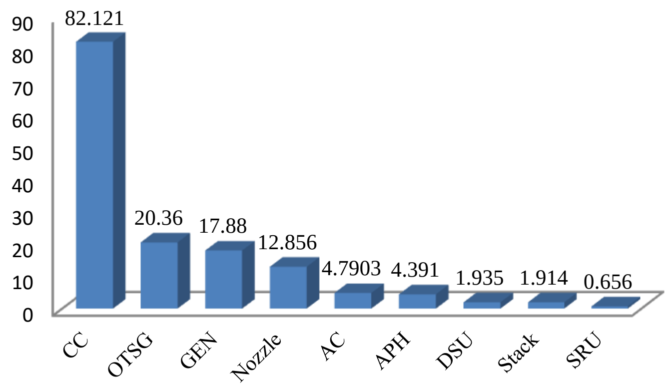

Fig. 6.3. Value of exergy destruction rate in the *j*th unit of the MHD system in *MW*.

As seen from Fig. 6.3, the CC unit of the MHD system accounts for the largest destruction rate out of the overall destruction in rate of exergy in the system whereas the SRU accounts for the least rate of exergy destruction. The OTSG, the MHD generator and the nozzle are the other major components where the exergy destruction rate are of reasonable values and cannot be ignored at once. However, these values cannot ascertain the exact value of the rate of exergy destruction in these components as part of these values are also possible for recovery as observed from the advanced exergy method.

The endogenous exergy destruction distribution among the units of the MHD system is represented in Fig.6.4. Out of the total destruction of exergy (146.903 MW) maximum destruction is of endogenous type with 83.2383 MW (nearly 57%) which suggests that the functional linkages among the units of the MHD system are reasonably on a higher side. Moreover, the CC unit accounted for the highest endogenous exergy reduction rate with 57.512 MW (in Fig. 6.4) or 69.039 % (in Fig.6.5) making it the most influential unit in the overall system.

The endogenous part of exergy destruction rate as discussed tells about the irreversibility within a system unit or a system itself under real operating conditions. Moreover, this irreversibility is not affected by other units of the system as these units are supposed to be operating under theoretical conditions either with maximum or minimum or the best applicable values of the operating variables [14, 16]. Thus, from Fig. 6.4 arrangement of the MHD units for the rate of endogenous exergy destruction the CC and to some extent the GEN has to be prioritized for their enhancement in efficient operation. Unlike Fig 6.3, the component arrangement with respect to the decreasing value in the rate of endogenous rate of exergy destruction is found to be different. It implies that the simple exergy destruction rates and the endogenous exergy destruction rates are two entirely different entities. Moreover, from Fig. 6.4, a clear picture about the unavoidable or avoidable endogenous portion of the exergy rate cannot be drawn which is essential from the point of possible recovery of such exergy destruction in these components.

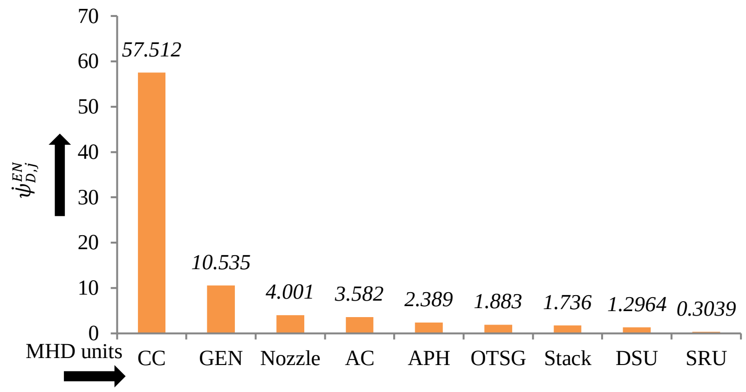

Fig. 6.4. Comparing endogenous exergy destruction rate in the *j*th unit of the MHD system in *MW*.

In Fig. 6.5, a comparison has been made between the MHD system components based on percentage endogenous exergy destruction rate with respect to the overall endogenous exergy destruction rate in the MHD system. Fig. 6.5 is actually another representation form of the Fig. 6.4. With the variations in unavoidable conditions set for the evaluation, ratio of the exergy destruction rate to the product exergy changes and hence the amount of unavoidable part of endogenous exergy destruction also tends to change. Accordingly, changes are also expected in the avoidable endogenous portion. Thus, it is the plant strategist (s) for appropriate selection of the unavoidable conditions based on the real operating conditions.

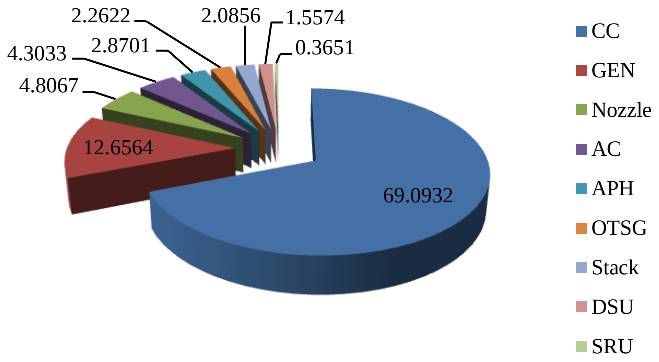

Fig. 6.5. Percentage comparison of the endogenous exergy destruction in the *j*th unit of the MHD system.

6.5.2. Effects of variation of exergy reduction rate of avoidable type

The distribution of the total avoidable rate of exergy destructions into its endogenous and exogenous sub-combinations is shown in Fig. 6.6. The endogenous type of the total avoidable portion of the rate of exergy destruction accounted for 57.763% whereas for the exogenous type of the avoidable exergy destruction rate is 42.267%. Thus, a higher value (%) in the avoidable endogenous exergy destruction rate indicates that there is a better opportunity for enhancing of the individual components. However, the percentage difference between the two avoidable portions is not very high. Hence, the overall enhancement of the MHD system will only be marginal.

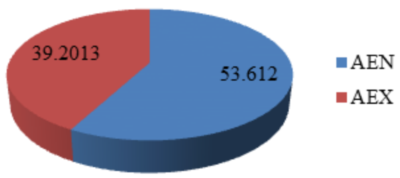

Fig.6.6. Distribution of overall avoidable exergy destruction rate into endogenous and exogenous portions of the MHD system in *MW*.

The avoidable endogenous portion of exergy destruction rate for the MHD system is found to be higher with 53.612 MW as compared to the avoidable exogenous portion which is shown in Fig. 6.6. So, there will be a greater enhancement possibility of the MHD system by overcoming the limitations posed by some of its functional components.

6.5.3. Effects of variation of exergy reduction rate of unavoidable type

The distribution of the total unavoidable portions of the rate of exergy destructions into its sub-combinations is shown in Fig. 6.7. Here, out of the total unavoidable destruction in exergy rate with 54.09 MW, the presence of the endogenous type is about 54.772% whereas the exogenous nature of unavoidable exergy destruction is 45.228%. As can be seen from Fig. 6.6, similar trend is observed from Fig. 6.7 but with respect to the unavoidable portion of the exergy destruction rates. So, in Fig. 6.7, as the percentage difference between the two unavoidable portions is not very high, and also because both are unavoidable in nature, they constitute a deterrent to the enhancement of the overall MHD system. The effects of higher unavoidable endogenous portion are however countered by the higher rate of avoidable endogenous portion of the rate of exergy destruction.

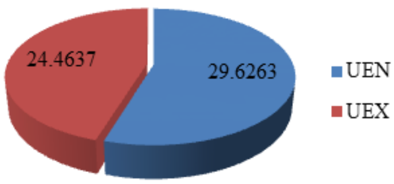

Fig.6.7. Distribution of overall unavoidable exergy destruction rate into endogenous and exogenous portions of the MHD system in *MW*.

The unavoidable endogenous portion of exergy destruction rate is a function of the set parameters that have not been possible to meet yet due to the present technical limitations. The operating personnel and the decisive team of the system's installation needs to roll out the appropriate conditions that can be achieved within a given time duration. In view of the actual conditions and with the assumed unavoidable conditions in the present study, the unavoidable endogenous portion of the exergy destruction rate for the MHD system as shown in Fig. 6.7 indicated the possibility of enhancing the performance of the MHD system.

6.6. Result Validation

The results of the present study are verified by the work presented in [36]. For the purpose of validation, the combustion chamber and the MHD generator having air and fuel input and the power output in [28] were taken into account represented by the states 5, 6, 7, and 8 respectively. In Table 6.10, a comparison between the mass flow rates and the exergy rates of the air, fuel to the CC and the generator is provided obtained from Ref. [36] and those from the approach in the present study.

Table 6.10. Comparison of mass flow rates and exergy rates between Ref [36] and present study

Streams	Ref [48]		Present study	
	$\dot{m}$ $(^{kg}/_{s})$	$\dot{\psi}_j(MW)$	$\dot{m}$ $(^{kg}/_{s})$	$\dot{\psi}_j(MW)$
Air to CC	17.34	7.2955	17.35	7.47001
Fuel input	0.998	51.824	0.996	52.074
Inlet of generator	18.34	46.734	18.30	47.821
Generator exit	18.34	26.073	18.30	24.800

Similarly, in Table 6.11 the exergy rates of the fuel and the products of the CC and the MHD used in Ref. [36] are listed and compared with the values obtained using the present study approach. The fuel and product exergy rates are then used for computing the exergy destruction rates in these two components.

Table 6.11. Results of validation of the present study with that of Ref.[36]

Streams	Ref [36]				Present study			
	$\dot{\psi}_{F,j}(MW)$	$\dot{\psi}_{P,j}(MW)$	$\dot{\psi}_{D,j}(MW)$	$\varepsilon_j(\%)$	$\dot{\psi}_{F,j}(MW)$	$\dot{\psi}_{P,j}(MW)$	$\dot{\psi}_{D,j}(MW)$	$\varepsilon_j(\%)$
CC	59.1195	46.734	12.386	79.05	59.544	47.821	11.723	80.312
MHD Gen	20.661	19.390	1.271	93.85	23.021	19.611	3.41	85.187

Under similar conditions of pressure and temperatures, the enthalpy and entropy of the inlet air to the CC are computed using Peacesoftware.de [37] and hence the exergy of air is estimated. For the fuel exergy, the chemical and physical exergy of methane was considered under the prescribed conditions. For the CC, the fuel and product exergies as well as the exergy desolation and the exergetic efficiency were found to be closer to the values of Ref [36] as given in *Table 6.11*.

However, for the MHD generator, in the present study, the estimated value for the fuel exergy was obtained to be somewhat higher than those given by Ref [36] thereby leading to a rise in exergy desolation in the MHD generator with a reduction in exergetic efficiency. The reason for this variation may be because whereas in Ref [36], the reaction mechanism within the generator has not been elaborately discussed, and also the details on the ionization mechanism were not mentioned.

6.7. Summary

An advanced exergy analysis is performed on a standalone MHD power generation system consisting of 9 units utilizing the results of the standard exergy analysis. First, from the standard or conventional exergy analysis, the unit-wise and overall exergy of the fuel and products, exergetic efficiencies, and the exergy destruction in the MHD system are evaluated. Next, the total destruction in exergy rate in the MHD system is divided into the sub-portions namely the endogenous, avoidable, exogenous, and unavoidable types together with their possible combinations. The results of the analysis indicated that most of the reductions in the exergy rate are avoidable and are mostly of endogenous type indicating that the augmentation of the MHD system is possible through appropriate measures of efficiency improvements in its various units. The information derived from the current advanced analysis for the MHD plant in terms of exergetic parameters is listed in the following:

- Lower rate of non-avoidable destruction in exergy with 54.09 MW (nearly 37%) signifies that there is a reasonably high scope of possibilities for the system's performance upgradation.

- Higher rate of endogenous destruction of exergy with 83.2383 MW (nearly 57%) suggests that the functional linkages among the units of the MHD system are reasonably on a higher side.
- In the MHD system, the CC unit accounts for the highest rate of exergy destruction of the avoidable endogenous type with 35.861 MW (nearly 67%) which is greater than its non-avoidable endogenous counterpart with 21.51 MW (26.01%). For the CC unit, both portions of the exergy desolation exhibit the highest values with respect to the other units of the MHD system. Thus, the chances of upgradation of the CC unit are high together with a strong influence on other units of the system.
- Next to the CC unit, there is also a relatively higher chance for efficiency upgradation of the GEN unit with system advancement as it has high avoidable and avoidable endogenous exergy destruction rates among the other units comparatively. Like the CC, the GEN unit also exhibited a higher influence on other units of the MHD power generation system.
- The OTSG unit shows the least possibility of enhancing its performance when attached to the MHD system due to its very high unavoidable portion of exergy desolation rate. It is also in the category of low interactively influential units due to very high destruction of exogenous exergy rate which is also of unavoidable type.

Thus, from the results of this current analysis, it can be inferred that the MHD system has a reasonably high scope for its further development through appropriate improvements in the performance of the related units.

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