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Performance assessment of a magnetohydrodynamic power generation system: Division of the exergy destruction rate into its sub-portions

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Abstract: Sustainable and environmental friendly energy extraction and utilization is the foremost priority of the energy sector to meet the present and near future energy demands. The need of the day is to have efficient and eco-friendly energy conversion technologies either through the enhancement of the existing technologies or the development of some all-new technology. The present study investigates a standalone open-cycle Magnetohydrodynamic (MHD) power generation system using the advanced exergy analysis analytically. The effects of distributing the exergy destruction into endogenous/exogenous and avoidable/unavoidable on the improvement possibilities and the mutual interlinkages among the different units of the MHD system have been studied. The results showed that the MHD system has a higher possibility of its further development due to low unavoidable (36.82%) and high avoidable (63.18%) exergy desolation rates. The interlinkages among various units of the MHD system were found to be reasonably stronger due to the higher rate of exergy destruction of the endogenous type as compared to the exogenous portion. In the present study, the combustion chamber is found to have the highest possibility of upgradation as it possesses the largest value of avoidable exergy destruction rate together with the maximum rate of avoidable endogenous portion of the exergy destruction.

Keywords: *Avoidable, Endogenous, Exergy analysis, Exogenous, Magnetohydrodynamics, Unavoidable*

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Nomenclature				Greek Letters	
h	specific enthalpy (kJ/kmol)	ch	chemical	ϵ	specific exergy
s	specific entropy (kJ/kmol-K)	ph	physical	ε	exergy efficiency
HHV	higher heating value (MJ/kg)	i	flow state	$\dot{\psi}$	exergy rate
T	temperature (K)	o	degree	χ	mole fraction
$\dot{E}$	energy rate (MW)	A	avoidable	γ	exergy ratio
P	pressure (bar)	l	liquid	Δ	difference or change
Superscripts		U	Unavoidable/non-avoidable	η	efficiency
j	unit of MHD plant	0	standard state		
D	exergy destruction/desolation	EN	endogenous		
F	fuel	EX	exogenous		
P	product	MEX	Mexogenous		
H	hypothetical	r	an MHD sub-unit contributing exogenous portion to the jth unit		
ACT	actual	EA	excess air		
min	Minimum	AC	air compressor		
L	loss	CC	combustion chamber		
tot	total	GEN	generator		
comb	combustion	APH	air preheater		
y	instantaneous	OTSG	once through steam generator		
CV	control volume	SRU	seed recovery unit		
f	formation	DSU	desulphurisation unit		

1. INTRODUCTION

Conventional energy conversion systems are primarily dependent upon non-renewable energy sources. The use of these energy resources, on the one hand, has an adverse impact on the environment due to their pollution causing characteristics while on the other hand, their continuous depletion has posed uncertainty on their long-term availability and pricing. All these have put a challenge among the research communities to look for the development of new and efficient alternate energy conversion systems and technologies apart from making improvements in the existing systems [1].

Among the various non-conventional power generation systems, one of the most promising and potential future energy conversion systems is the MHD power generation system. The MHD power generation utilizes the flow of an ionized, conductive and electrically neutral fluid to generate electricity. In 1832, Michael Faraday with his pioneering discovery demonstrated the possibility of electric power generation due to the interactions between flowing water and the earth's magnetic field. From then onwards, efforts to generate power using MHD technology have passed through a series of developmental stages both in theory and in experimentation. Realizing the potential benefits of MHD power, a number of MHD based National programmes were initiated stage wise globally [2]. The MHD power generation could possibly overcome the problems of maximum material temperature limit, limited service-life, failure due to wear and tear, environmental deterioration and more such issues of present-day technologies of power generation. The MHD energy conversion component (generator) does not possess any rotational parts. It allows direct energy conversion of thermal energy to electricity without going through any intermediate energy transition stages. The resulting advantages are realized in terms of high working temperature, low emission of harmful gases, and higher conversion efficiency [3].

Though the concept of MHD power is not new and is highly advantageous, still its full-scale commercialization is awaited due to certain technological barriers. The choice of seed and the electrode materials are two such limitations even though pilot projects of MHD power have worked successfully to a great extent with the available materials. The operating cycle for the MHD system can be either open or closed. In the open case, the MHD system uses fossil fuel combustion products with the addition of suitable seed material such as potassium salts to achieve desired electrical conductivity at a lower ionization temperature. The closed-cycle operation is achieved by the addition of seed material to a noble gas or liquid metal [4]. A strong magnetic field is applied transversely to the generator flow using super magnets attached to the walls of the generator. Under the influence of the magnetic field, an electric field is induced having its direction perpendicular to the gas flow and the magnetic flux. Electrodes connected at the generator walls collect the generated electric current [5].

The underlying principles governing the interactions of the fluid flow with the applied magnetic field and the induced electric field have been explained elaborately in the work of Ref. [6]. The combustion products are accelerated through a nozzle acquiring high velocity before entering into the generator. Inside the generator, the electromagnetic field regulates the ionic movements to produce the desired power. The generator exhaust gases which are still at a higher temperature but insufficient for MHD power generation can be passed through a suitable heat exchanger for heat recoveries such as the air preheater and some kind of heat recovery steam generators (HRSGs). A standalone MHD plant by itself is less efficient due to the irreversibility present in the system and perform well in combination with other power generating systems [7-8]. Hence, it is extremely necessary to find the real position, causes and amount of irreversibility for the improvement of the MHD system.

Performance evaluation of the conventional and non-conventional energy systems requires the use of suitable methods and approaches to propose improvement measures. In recent times, exergy analysis has evolved as a useful way for predicting the performances of various systems. Such analysis has been able to provide qualitative information about the cause and location of inefficiencies in a thermodynamic system [9]. The exergy method utilizes the first and second law principles of thermodynamics for the purpose of analysis. It thus enables the determination of meaningful efficiencies [10]. Exergy balances can be used to analyse multi-component systems that will indicate the distribution of the entire plant irreversibility indicating the most inefficient component of the overall plant [11]. 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 [12].

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. However, only a portion of the exergy desolation in a component is actually avoidable 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 of the essential information that could not be derived from such analysis [13]. 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 actually 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 [14]. These drawbacks can be suitably eliminated by using the advanced method of splitting the exergy desolations.

The advanced method of exergy analysis splits the total desolation in exergy rates into several 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 irreversibility that occur 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 occurring within other components of the system. Information 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 [15].

The splitting of exergy destruction in energy systems has been a topic of research interest in recent times. Investigation of the improvement potential of thermal systems was one of the primary goals of advanced exergy analysis. Evaluating the sub-portions of the exergy desolation rate, one can reveal important information on the interactions among the components of a system and the possibility of improvement in efficiency by reducing irreversibility in the components or overall system [16].

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 irreversibility [17]. The advantages of the application of advanced exergy analysis over the conventional exergy method were evident from the available literature undertaking investigations on various systems [1, 14-29].

Application of advanced exergy analysis to a coal-fired power plant (supercritical) following the standard exergy analysis helped in the determination of the differences in the percentage contribution of endogenous and exogenous exergy desolations among the subcomponents. Moreover, improvement measures were suggested after consideration of both internal and external irreversibility [18]. Application of advanced exergy analysis to a system that is based on the consideration of real, conceptual, and unavoidable processes reveals the improvement potential and the interactions among the system components [19].

Application of advanced exergy analysis showed high enhancement possibilities for the combustion chamber, high pressure turbine (HPT), and the condenser in a natural gas-driven facility for electrical energy generation [20]. By considering the avoidable and unavoidable parts of exergy desolation together with the endogenous/exogenous parts, the splitting process leads to a better understanding of the interactions among the components and can improve exergy conversion systems [21].

The existence of a large amount of avoidable exergy desolation was observed while analyzing an existing plant for ethane gas recuperation and suggested a high potential for improvement for the units [22]. A determinative method based on the splitting of exergy destructions was proposed to analyze deterioration in performance in thermal power plants [23]. In this method, degradation was quantified by the determination of the endogenous part of exergy destruction. From the analysis, it was found that a major portion of the total exergy destruction is due to the endogenous exergy destruction in most components and suggested the method for potential improvement measures.

Exergy destruction or desolation is a useful parameter in the overall evaluation of any thermal system. However, the advanced exergy analysis proved to be a better approach for obtaining system information and a clear understanding of the enhancement potential for efficient operations [24].

When a real combined cycle power plant (CCPP) with supplementary firing was investigated for varying fuel mass flow rate in a duct burner it was shown that variations in different parts of the exergy destruction or their combinations exist among the system components. The results of the investigation showed that there is a reduction in thermal and exergetic efficiencies under actual, theoretical, and non-avoidable situations [25].

Splitting of the exergy destruction rate into endogenous/exogenous and avoidable and/unavoidable parts showed the existence of a 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. However, the combustion chamber was found to have the maximum possibility of improvement due to its low avoidable exergy destruction rate [26].

Another investigation, that conducted a parametric study of an existing CCPP using the exergy splitting method showed an increase in the thermal and exergetic efficiencies with an increase in turbine inlet temperature (TIT) and pressure ratio. Moreover, it was found that 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 while some other components showed a high decrement in the endogenous exergy desolation. Further, a rise in pressure ratio was found to affect the various components differently in terms of these exergy desolation parts [27].

In some cases, however, an improvement in design can reduce the avoidable portion of exergetic desolation. The advanced exergetic analysis was proved to be advantageous as it can provide an idea of the real range of exergetic efficiency for the overall system [28].

Thus, it can be seen that advanced exergy analysis has certain advantages over conventional exergy analysis. Advanced exergy analysis enables an investigator to be more precise on their prediction on the amount of exergy that has been lost and is possibly recoverable. Moreover, 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.

The thermodynamic evaluation of MHD systems so far was carried out from varied perspectives [4,8,29,30] including component-based analysis [30,31]. All these analyses were carried out with the sole objectives of achieving more efficient MHD operation together with obtaining higher power output and reducing the technical difficulties of the MHD power generation system. Further, in all such previous studies, the research focus was mainly on MHD system design, material development, and integration of MHD system into different combined levels together with conventional thermodynamic analysis from several different perspectives. As such, an MHD power generation system was never analyzed previously for performance evaluation by using advanced exergy analysis through splitting up of the exergy destruction rates into their endogenous and exogenous parts, further with both endogenous and exogenous divided into their avoidable and unavoidable parts. As such, no study on advanced exergy analysis of a standalone MHD power generation system is available in the literature. Therefore, to address this research gap, in this study, a standalone MHD power plant is analyzed by performing an advanced exergy analysis and by splitting the exergy destruction rates into its sub-portions. For the purpose of advanced exergy analysis, the present study considers the initial fuel-oxidant-seed and combustion data of Haloi and Gogoi [32]. 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.

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 once through steam generator (OTSG), a seed recovery unit, one desulphurization unit, and the stack. The arrangement of the overall MHD system is shown in Fig. 1.

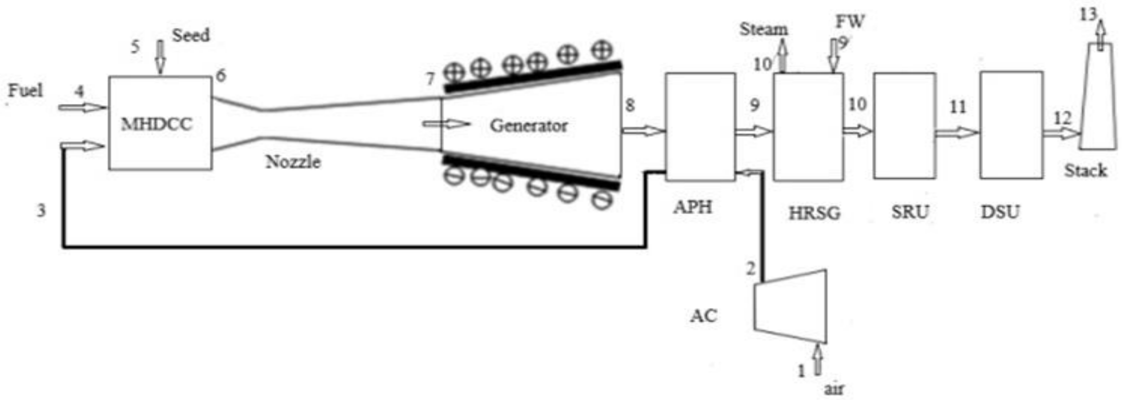

Figure 1. Schematic of the standalone MHD power plant

The system arrangement has been redrawn with component addition (OTSG) using [33]. 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% concerning the molecular species [34,35].

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 [2]. The high-temperature exhaust gas from the MHD generator is utilized in the air-preheater (streams 8-9) and in the single pressure OTSG (streams 9-10) to preheat the compressed gas and for steam generation. Preheating air increases the combustion temperature which assists in the ionization process. Before its release to the atmosphere, the exhaust gases from the OTSG are made to pass through a seed recovery unit for seed regeneration and seed recovery [36,37] and then through a desulphurization unit to control and capture excess sulfur dioxide. The OTSG generates superheated steam for other applications.

3. METHODOLOGY

The method of advanced exergy analysis as discussed previously 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 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.

3.1. Conventional Exergy Analysis

Assuming steady-state steady-flow processes and negligible kinetic and potential energy losses, the mass, energy, and exergy balances for the control volume are given by the Eqs. 1-3 according to the relation of [12,38] as:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q}_{CV} - \dot{W}_{CV} = \sum \dot{m}_{out}\bar{h}_{out} - \sum \dot{m}_{in}\bar{h}_{in} \tag{2}$$

$$\sum_{y}(1-\frac{T_0}{T_y})\dot{Q}_y - \dot{\psi}_W = \sum \dot{m}_{out}\dot{\epsilon}_{out} - \sum \dot{m}_{in}\dot{\epsilon}_{in} + \dot{\psi}_D \tag{3}$$

where $\bar{h}$, $\dot{m}_{in}$ and $\dot{m}_{out}$ are the specific molar enthalpy and mass flow rates 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; $\sum_y(1-\frac{T_0}{T_y})\dot{Q}_y$, $\dot{\psi}_W$ and $\dot{\psi}_D$ are the instantaneous exergy rate due to heat transfer, exergy rate due to work transfer and the exergy desolation rate.

The determination of exergy rates requires the calculation of both thermo-mechanical and chemical exergies of the flow streams [12,38]. The elemental chemical exergies are evaluated using the standard chemical exergy values of [39]. Eqs. 4,5 give the physical and chemical exergy rate of a given fluid stream as:

$$\dot{\psi}^{ph} = \left(\bar{h} - \bar{h}_0\right) - T_0(\bar{s} - \bar{s}_0) \tag{4}$$

$$\dot{\psi}^{ch} = \sum \chi_m \,\bar{\epsilon}_m{}^{ch} + RT_0 \sum \chi_m ln\chi_m \tag{5}$$

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 [40] and this is given by Eq. 6 as:

$$\bar{\epsilon}^{ch}_{ion} = \bar{\epsilon}^{ch}_{elem} + [\Delta \bar{g}^0_{ion} - \Delta_f \bar{g}^0_{elem}] \tag{6}$$

For solid fuel such as coal, the standard molar chemical exergy is calculated using Eq. 7 on a dry and ash-free (DAF) basis and the total molar specific chemical energy is obtained from Eq. 8 on as-received basis taking the moisture and ash content into account [38]:

$$\begin{aligned}\bar{\epsilon}^{ch}_{DAF} = HHV_{DAF} - T_0\left[\bar{s}_{DAF} + \sum \chi_{m,\ air}\,\bar{s}_m - \sum \chi_{m,\ comb}\,\bar{s}_m\right] \\ + \left[\sum \chi_{m,\ comb}\,\bar{\epsilon}^{ch}_m - \sum \chi_{m,\ air}\,\bar{\epsilon}^{ch}_m\right]\end{aligned} \tag{7}$$

$$\bar{\epsilon}^{ch} = 0.93\bar{\epsilon}^{ch(DAF)} + \frac{0.021}{18}\bar{\epsilon}_{H_2O}{}^{ch}(l) \tag{8}$$

where, $\bar{\epsilon}^{ch}_{DAF}$ 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 and HHV_{DAF} is the higher heating value of coal obtained on a dry and ash free basis given by Eiserman et al [41].

The energy and exergy rates for a given stream are determined by computing the specific molar values of enthalpies and entropies given by Eqs. 9-11 as in Ref. [32],

$$\bar{h}_i = x \sum \chi_m \bar{h}_{m,\,ionic} + (1 - x) \sum \chi_m \bar{h}_{m,\,molecular} \tag{9}$$

$$\bar{s}_i = x \sum \chi_m \bar{s}_{m,\ ionic} + (1 - x) \sum \chi_m \bar{s}_{m,\ molecular} \tag{10}$$

$$\bar{s}_{m,\ ionic/molecular} = \bar{s}^0_{m,\ ionic/molecular} - Rln\frac{\chi_m p^i}{p^0} \tag{11}$$

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 χ_m is the mole fraction for the stream constituent m.

Table 1. Percentage composition of the constituents of air (assumed) and combustion products (actual) (Fuel and oxidant constituents from Ref. [42])

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

The mole fractions of the different constituents are presented in *Table 1* having fuel compositions of Assam, India colliery [43].

In MHD power generation system, the high velocity ionized flame with the addition of appropriate fraction of potassium carbonate 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, the movement of these oppositely charged ions creates the potential difference thereby generating current on application of load.

The ionization mechanism at the high combustion temperature is 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 2 and are assumed to be formed in accordance with the stated dissociated mechanism used by Haloi and Gogoi [32]. The high temperature partial ionization forms ionic species due to dissociation of the molecular species. However, the positive ions and electrons play the primary role as these species contribute large entropy to the free energy of uniformly moving products. Moreover, the ionic formation is higher over electrons production [44].

Table 2. Mass fractions of ionic species formed during partial ionization (based on initial reaction data of Haloi & Gogoi [32].)

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 is carried out considering similar operating conditions up to the air preheater as in Ref. [32] while assuming a lower value of the adiabatic flame temperature at the combustor exit.

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 [13]. The exergy losses are associated mainly with the overall system due to mass and energy transfer and are fractions of the overall thermodynamic inefficiencies whereas for the components, the thermodynamic inefficiencies can be measured as exergy destruction provided ambient boundaries are in consideration [9,45].

Thus, for the *j*th component and the overall plant, the exergy balances are given by Eqs. 12,13:

$$\dot{\psi}_{P,\ j} = \dot{\psi}_{F,\ j} - \dot{\psi}_{D,\ j} \tag{12}$$

$$\dot{\psi}_{P,\ tot} = \dot{\psi}_{F,\ tot} - \dot{\psi}_{D,\ tot} - \dot{\psi}_{L,\ tot} \tag{13}$$

In Eq. 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 Eq. 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 determination of the exergetic efficiency and the exergy destruction ratio in the *j*th component together with the rate of exergy desolation whereas for the overall system, the exergetic efficiency, rates of exergy desolation and exergy loss and the exergy loss ratio are evaluated [45]:

$$\varepsilon_j = \frac{\dot{\psi}_{P,\ j}}{\dot{\psi}_{F,\ j}} = \frac{\dot{\psi}_{F,\ j} - \dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ j}} = 1 - \frac{\dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ j}} \tag{14}$$

$$\gamma_{D,j} = \frac{\dot{\psi}_{D,\ j}}{\dot{\psi}_{F,\ tot}} \tag{15}$$

$$\varepsilon_{tot} = \frac{\dot{\psi}_{P,\ tot}}{\dot{\psi}_{F,\ tot}} = \frac{\dot{\psi}_{F,\ tot} - (\dot{\psi}_{D,\ tot} + \dot{\psi}_{L,\ tot})}{\dot{\psi}_{F,\ tot}} = 1 - \frac{(\dot{\psi}_{D,\ tot} + \dot{\psi}_{L,\ tot})}{\dot{\psi}_{F,\ tot}} \tag{16}$$

$$\gamma_{D,tot} = \frac{\dot{\psi}_{D,\ tot}}{\dot{\psi}_{F,\ tot}} = \sum_{j=1}^{j=m} \gamma_{D,\ j} \tag{17}$$

$$\gamma_{L,tot} = \frac{\dot{\psi}_{L,\ tot}}{\dot{\psi}_{F,\ tot}} \tag{18}$$

In the Eqs. 14-18, 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 and $\gamma_{L,tot}$ is the exergy loss ratio in the overall MHD system.

In the MHD system (Fig. 1), the conventional exergy analysis uses the energy and exergy balance equations which are shown in Table 3.

Table 3.Energetic and exergetic balances for the units of the MHD plant.

MHD component	Energetic balance	Exergetic 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	$\dot{E}_{13} = \dot{E}_{12}$	$\dot{\psi}_{12} - \dot{\psi}_{13} = \dot{\psi}_{D,\ Stack}$

3.2. Division of the Exergy Desolation Rates into Sub-Portions (Advanced Exergetic Evaluation)

The advanced study of exergy deals with division of the entire exergetic desolations in the system's *j*th unit or component into portions that are 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 [15,21]. Accordingly, the divisions of exergy desolation inside the jth unit is illustrated in Fig. 2.

$$\dot{\psi}_{D,j} = \dot{\psi}^{A}_{D,j} + \dot{\psi}^{U}_{D,j} \quad (19)$$

$$\dot{\psi}_{D,j} = \dot{\psi}^{EN}_{D,j} + \dot{\psi}^{EX}_{D,j} \quad (20)$$

$$\dot{\psi}^{EN}_{D,j} = \dot{\psi}^{AEN}_{D,j} + \dot{\psi}^{UEN}_{D,j} \quad (21)$$

$$\dot{\psi}^{EX}_{D,j} = \dot{\psi}^{AEX}_{D,j} + \dot{\psi}^{UEX}_{D,j} \quad (22)$$

The avoidable and non-avoidable portions of exergy desolation are further arranged as expressed in Eqs. 23,24 as follows:

$$\dot{\psi}^{A}_{D,j} = \dot{\psi}^{AEN}_{D,j} + \dot{\psi}^{AEX}_{D,j} \quad (23)$$

$$\dot{\psi}^{U}_{D,j} = \dot{\psi}^{UEN}_{D,j} + \dot{\psi}^{UEX}_{D,j} \quad (24)$$

Thus, from Eqs. 19-24, it is seen that the different portions of exergy destruction can be combined in a number of ways [13,21].

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

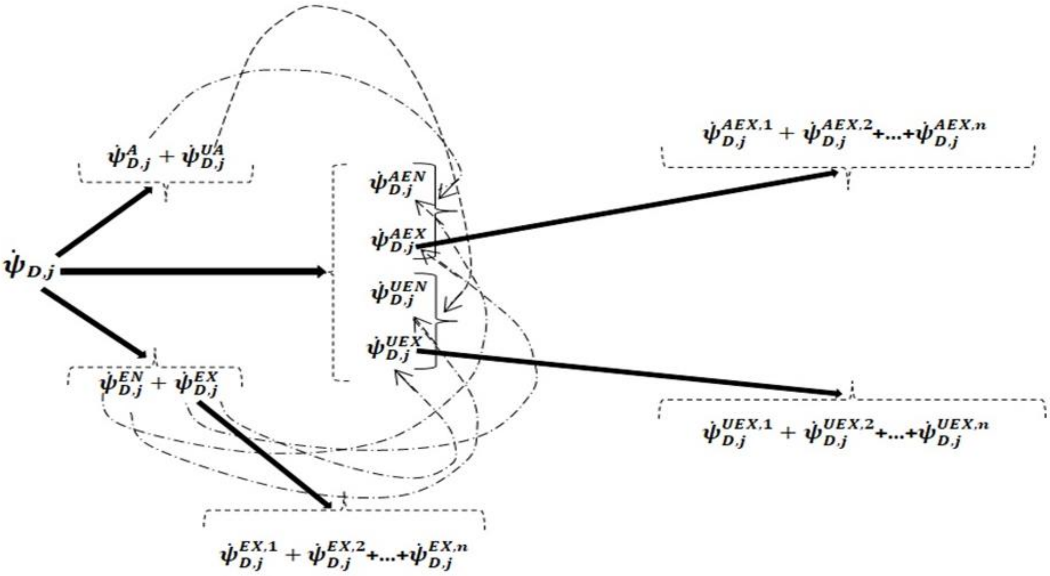

Figure 2. Division of exergy destructions inside the jth unit of the system [26].

It has been stated that the unavoidable portion of exergy destruction 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 [13,14]. Further, to obtain the unavoidable portion in a particular unit, it is necessary to analyse the operation in that unit under the assumptions of maximum efficiency and negligible wastage. These operating conditions were termed as unavoidable operation. However, while fixing assumptions the strategists must consider the probable upgradation likely achievable in the imminent future. To determine the unavoidable portion, one can use the relation [13,14] given in Eq. 25 as:

$$\dot{\psi}^{UEN}_{D,j} = \dot{\psi}^{EN}_{P,j} \times (\frac{\dot{\psi}_D}{\dot{\psi}_P})^{U}_{j} \quad (25)$$

In Eq. 25, $\dot{\psi}_{D,j}^{UEN}$ is the rate of unavoidable endogenous desolation in exergy in the *j*th unit, $\dot{\psi}_{P,j}^{EN}$is the endogenous portion of exergy desolation rate of the product in the *j*th unit.

There is however, another kind of exergy destruction termed mexogenous that is associated with the exogenous portion affecting the *j*th unit. It takes into account the destruction in exogenous portion inside the *j*th unit and the total rate of exergy destruction considering the total number of units present in the system [19,26]:

$$\dot{\psi}_{D,j}^{EX} = \dot{\psi}_{D,j}^{MEX} + \sum_{\substack{r=1,\\ r\neq j}}^{r=r} \dot{\psi}_{D,r}^{EX,r} \tag{26}$$

The detailed procedure for evaluating the endogenous/exogenous and the avoidable/ unavoidable portions of exergy desolation are described in the works of [15,19]. The assumptions on the operative hypothetical, actual and unavoidable cases for the various units of the MHD system are exemplified in Table 4. 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 are evaluated.

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

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

4. RESULTS AND DISCUSSION

The present work considers 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 5* using initial data of [32] by considering the real working settings of the MHD system.

The exergy parameters of the individual units of the MHD system are evaluated and specified in Table 6, part of which is obtained till the air preheater section using the initial data of [32]. The effectiveness of these parameters was realized during the process of advanced exergy analysis.

From the power generation perspective in the MHD plant, the crucial units are being limited up to the MHD generator including 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.

Table 5. Mass flow rate, state properties, energetic and exergetic rates at various state points of the standalone MHD power generation system (tabulated values up to state 9 are obtained based on initial data of Haloi and Gogoi [32]).

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

The division of the overall endogenous exergy desolation among the MHD units estimated in Table 6 are arranged in descending order in Fig.4 with utmost destruction in the CC unit with 57.512 MW. The percentage distribution of the endogenous portion of exergy destruction rate of the various MHD units is shown in Fig. 5.

Table 6. Exergy rates corresponding to fuel, product, desolation and exergy efficiency and exergy destruction ratio of the units of the MHD system (up to APH, the values are based on initial data of Haloi and Gogoi [32]).

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

The results of the present study are verified with the work presented in [46]. For the purpose of validation, the combustion chamber and the MHD generator, having air and fuel input and the power output in Ref. [46] are taken into account. The comparison between the results of present study and that of [46] are shown in Tables 7 and 8, respectively.

Table 7. Comparison of mass flow rates and exergy rates between Ref. [46] and present study.

Streams	Ref [46]		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

Table 8. Results of validation of the present study with that of Ref. [46].

Streams	Ref [46]				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	20.661	19.390	1.271	93.85	23.021	19.611	3.41	85.187

Under similar conditions of pressure and temperature, the enthalpy and entropy of the inlet air to the CC is computed using Peacesoftware.de and accordingly, the exergy of air is estimated. For the fuel exergy, the chemical and physical exergy of methane are considered under the prescribed conditions. As can be seen, for the CC, the fuel and product exergies as well as the exergy desolation and the exergetic efficiency was found to be closer to the values of Ref. [46] as given in Table 8. However, for the MHD generator, the estimated value for the fuel exergy is somewhat higher than that given in Ref. [46] and thus, it causes a rise in the exergy desolation in the MHD generator with a reduction in exergetic efficiency. The reason for this variation could be due to the fact that the reaction mechanism within the generator with the full details of the ionization mechanism was not considered in Ref. [46].

As discussed in the previous section above, the parameters of the advanced exergy method were evaluated for the MHD system considering the assumed hypothetical, actual and unavoidable working conditions. The division of the overall exergy destruction rate in the MHD system is given in Table 9 which shows the sum total of either avoidable or non-avoidable portions or those for the endogenous and exogenous portions. Allocation of exergy desolation rate (MW) in different units of the MHD system is shown in Fig. 3. From Fig. 3 and Table 9, it is seen that the CC unit accounts for the utmost degradation in exergy rate with 82.121 MW and the lowest occurs in the SRU with 0.656 MW.

In Table 9, it was seen that the total avoidable portion of exergy desolation rate surpasses the unavoidable portion by 38.7233 MW whereas the total rate of desolation of the endogenous exergy portions surpasses the total exogenous portion by 19.5733 MW. Among the MHD units, 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 shows the maximum desolation in non-avoidable exergy rate with 24.735 MW while the least non-avoidable destruction rate in exergy occurs in the SRU with 0.0674 MW.

Table 9. Unit-wise division of exergy destruction rate of the system units into avoidable, unavoidable, endogenous and exogenous portions (total exergy destruction rates ($\dot{\psi}_D$, j) up to APH are based on initial data of Ref. [32]).

System unit *j*	$\dot{\psi}_D, j\ (MW)$	$\dot{\psi}_{D,j}^{A}\ (MW)$	$\dot{\psi}_{D,j}^{U}\ (MW)$	$\dot{\psi}_{D,j}^{EN}\ (MW)$	$\dot{\psi}_{D,j}^{EX}\ (MW)$
AC	4.7903	3.8917	0.8986	3.5820	1.2083
CC	82.121	57.3860	24.7350	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	0.1292	4.2618	2.3890	2.002
OTSG	20.360	1.024	19.336	1.883	18.477
SRU	0.656	0.5886	0.0674	0.3039	0.3521
DSU	1.935	1.0938	0.8412	1.2964	0.6386
Stack	1.914	0.4699	1.4440	1.736	0.1780
Overall *MHD* plant	146.903	92.8133	54.09	83.2383	63.665

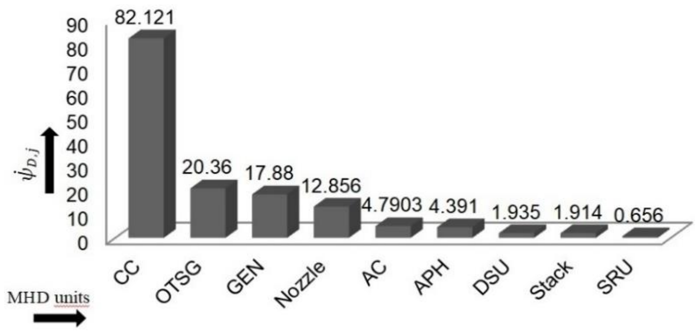

Figure 3. Allocation of exergy desolation rate (MW) in different units of the MHD system.

The contribution of other units (unit *r*) of the MHD system to the exogenous part of exergy desolation rate in the *j*th unit is given in Table 10. Here, unit *r* denotes one of the remaining eight units in the overall system except the *j*th unit for which the mexogenous portion of exergy destruction is considered.

Table 10. Mexogenous exergy destruction rate in various units of the MHD system.

System unit *j*	$\dot{\psi}_{D,j}^{EX}$ (MW)	$\dot{\psi}_{D,j}^{MEX}$ (MW)	$\sum_{r=1}^{r=r} \dot{\psi}_{D,r}^{EX,r}$ (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

The amalgamation of one of the exergy desolation rates of a given category (avoidable/unavoidable) with that of the exergy desolation rate of the other category (endogenous/exogenous) is given in Table 11. Here, we see that major part of the endogenous portion of exergy desolation 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 11 it is seen that nearly 61.57 % of exogenous portion of exergy desolation in the entire MHD system is of avoidable type whereas the rest 38.43 % is non-avoidable with a difference of about 14.7376 MW.

Table 11. Unit-wise distribution of exergy desolation rates into different sub-portions (avoidable/ unavoidable endogenous and exogenous 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 9,10 and 11, it can be seen 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 non-avoidable 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 [15]. Nonetheless, the decisions of the operational strategist also play a vital role while setting the conditions for the advanced exergetic method of analysis of the system dealt with.

In the present application, the evaluation is carried out under the assumptions laid in Table 4.

The distribution of the total avoidable and unavoidable portions of the rate of exergy desolations into its sub-combinations are given in Figs. 6 and 7, respectively. The results of the exergy desolation rate of the MHD units obtained from the standard exergy analysis are compared in Fig. 3. But, prioritizing the units for improvement that have been based on Fig. 3 may not be good choice as it fails to reflect the true scenario of exergy utilization by the respective units.

The cause of irreversibities whether self-generated or due to the influence of external units cannot be predicted from the conventional exergy method [20,21,26]. In addition, no idea can be derived regarding the conditions of operation of these units under conventional exergy analysis. Thus, it sought a more realistic approach such as the analysis by splitting of exergy desolation for better result outcome.

The endogenous part of exergy desolation rate as discussed tells about the irreversibility within a system unit or a system itself under real operating conditions. Moreover, other units of the system do not affect this irreversibility as these units are supposed to be operating under theoretical conditions with either maximum or minimum or the best applicable values of the operating variables [19,21]. Thus, from Fig.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.

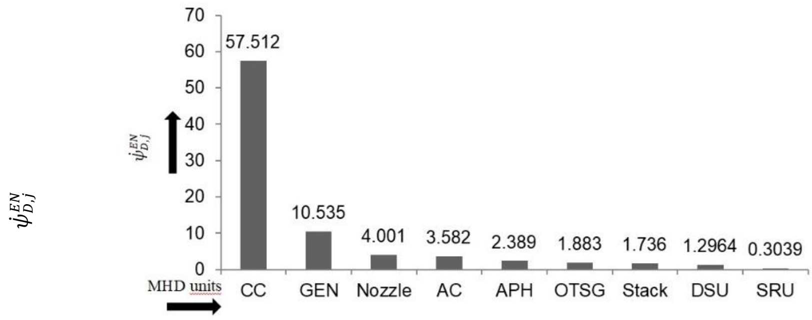

Figure 4. Comparing endogenous exergy desolation rate in the jth unit of the MHD system in MW.

A similar comparison has been made based on percentage endogenous exergy desolation rate as shown in Fig. 5. 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 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.

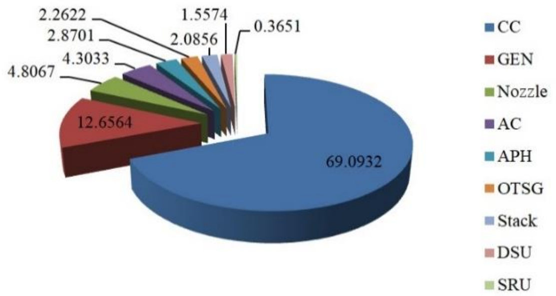

Figure 5. Percentage comparison of the endogenous exergy desolation in the jth unit of the MHD system.

The avoidable endogenous portion of exergy desolation rate for the MHD system is found to be higher with 53.612 MW as compared to the avoidable exogenous portion as shown in Fig.6. This indicated a greater enhancement possibility of the MHD system by overcoming the limitations posed by some of its functional components.

Figure 6. Distribution of overall avoidable exergy desolation rate into endogenous and exogenous portions of the MHD system in MW.

The unavoidable endogenous portion of exergy desolation 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 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. 7 indicated the possibility of enhancing the performance of the MHD system.

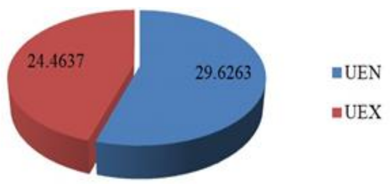

Figure 7. Distribution of overall unavoidable exergy desolation rate into endogenous and exogenous portions of the MHD system in MW.

5. CONCLUSION

The present study investigated a standalone MHD power plant having nine units by employing the advanced approach of splitting of the exergy destruction rates. First, the standard exergy analysis is performed to evaluate the unit-wise and overall exergy of the fuel and products, exergetic efficiencies and the exergy desolation in the MHD system. Next, the results of the standard exergy analysis are utilized in the evaluation of the different divisions of the exergy reduction rates. As such, the endogenous, avoidable, exogenous, non-avoidable and their amalgamated forms of exergy destructions are assessed. The information derived from the current advanced analysis for the MHD plant in terms of exergetic parameters are listed in the following:

Lower rate of non-avoidable destruction in exergy with 54.09 MW (nearly 37%) signifies that there is reasonably high scope of possibilities for 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 portion of the exergy desolation exhibits 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 in 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

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

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