CHAPTER 2

Literature Review

2.1. Introduction

In Magnetohydrodynamics one deals with the mutual interactions between an applied magnetic field and a fast-moving fluid that is also electrically conducting. Magnetohydrodynamics applies the conservation laws and is described by the governing equations of electrodynamics, fluid mechanics, and magnetism [1].

The enormous potential of MHD systems to generate electrical power in the near future has gained worldwide attention. Due to this, various MHD-based programs were initiated internationally for enhancing the technology and cooperation in MHD research and development [2].

Reviews of MHD power technology have been presented to discuss its developments so far and its admissibility for commercialization in India [3, 4] as well as in other parts of the world [5]. It also discusses the developments of various MHD-related components and their issues.

The commercialization of the MHD system to generate electricity has been prioritized time and again with further research and developments in several relevant areas that posed difficulties in its realization. These areas include but are not limited to improvements in MHD components, use of superconducting magnets, direct to alternate current conversion system, plasma formation and its characteristics in the MHD generator, material testing for improved performance, and so on [6].

2.2. MHD systems

Analysis of the MHD system, and its advantages have been discussed from time to time, along with its types and the use of different generators [7]. The basic theory of MHD, its fundamental governing equations, the equilibrium states, and its applications have been described, and flow analysis in the generator channel was conducted to explain the MHD system operation [8]. The flow of plasma in MHD is characterized by the conservation laws and its interactions with the electromagnetic field can be expressed by Maxwell's equations together with Ohm's law [9, 10, 71]. The MHD approximations, its physical effects, flow stabilities, and its turbulent behaviour have been discussed in the literature [11].

The performance of the power-producing generator in MHD relies mostly on the conditions of the plasma employed. It was observed that for higher power generation and to reduce the plasma instability, an optimal electron temperature accompanied by a low fraction of seed material would be required [12]. The MHD interactions thus require the study of the process of ionization and the various aspects of ions in the gas phase. The use of a mass spectrometer to study the ionization energy, affinity of the protons, and the basicity in the gas phase has been emphasized [13]. Therefore, an increase in the rate of ionization and in free-electron concentrations is desired for MHD performance improvement. These can be attained using properly selected seed materials and through improvements in the combustion methods [14]. So, the generation of ionized gases or plasma is one of the major objectives for the successful operation of the MHD electrical energy generation system. To deal with MHD system operation a thorough analysis of the plasma kinetics, the plasma thermodynamics, and its electrodynamics is required to be performed [15]. Although a number of methods exist for ionization such as electron beams, alpha particles, and high-voltage repetitive pulses, the injection of keV-class electron beams along a magnetic field was proved to be the most efficient. The electron beams were able to produce stable plasmas with better control allowing the enhanced performance of the MHD generator [16].

The various thermal and electrical properties of the combustion gas, plasma as well as the seed material are crucial and understanding their impacts on the overall performance of a system, especially the MHD system is necessary. Research studies are performed to evaluate the impact of properties on system performance. These studies also include the study of the impact of the fuel and oxidizer concentrations in different proportions and those affecting power output and dissociations due to variation in pressure and temperature [17].

There is scope to study the dependency of enthalpy, entropy, and the degree of ionization on temperature can be studied using different model diagrams while considering thermodynamic equilibrium conditions for the plasma flow [18].

The use of seed in MHD to increase the electrical conductivity of the fluid is an expensive process. Thus methods to recover and regenerate the spent seed were developed namely the modified Tampella and the PERC processes among others and also methods such as the Claus and Stretford that recover sulphur to protect atmospheric degradation [19].

The feasibility of continuous power generation from the MHD system in a steady manner sought relaxation of the restraints imposed by non-equilibrium plasma. These limitations include a large eddy current, a weaker magnetic field, the resistance between electrode and discharge, and smaller flow velocities [20].

Further investigations are sought for better thermo-chemical conversion in MHD generators along with upgradation of electrical conductivity of the ionized gas and mitigation of slag formation in coal-fired MHD plants because MHD systems are capable of operating at high temperature with more efficiency and can also recover much of the CO_2 [21]. MHD power generation also requires a high flame temperature that could be achieved by preheating the air to a sufficient temperature. But, the preheaters are often subjected to a corrosive environment of seed deposition, thereby it affects the heat transfer process [22].

Irreversible losses in the form of exergy destruction during combustion can be reduced by employing preheating of the combustion reactants. Thus, preheating of oxidant increases the exergy of the combustion gases and also helps in fuel-saving by increasing the fraction of oxidant instead of fuel [23].

The use of supersonic inlets for the MHD system was found to have the advantage of not having any abrupt variation in pressure and velocity at the outlet plane but shows significant variation in maximum power output with an increase in Mach number [24]. Investigations of open-cycle MHD plants having different schemes showed that the use of coal gasified syngas improves the efficiency of the MHD system than those operated with direct combustion of coal. This was due to enhanced recirculation of heat to the combustion chamber and the use of heat recovery at an enhanced temperature [25].

The use of different fuels in MHD needs determination by their heating values. Correlations were developed for the calculation of the higher and lower heating values of fuels of different forms [26-27, 50, 53]. The exergy analysis of coal-fired open-cycle MHD systems requires the evaluation of coal properties. There are methods developed that could predict the thermodynamic properties of coal like the specific heat, enthalpy, and entropy as a function of temperature and material constituents [27].

The properties of coal irrespective of the type widely vary with its geographical distribution or locations. The constituents of coal found in different locations vary in their percentage compositions. The presence of sulphur has been considered a major deterrent in the efficient use of these coals. The advancement in sulphur removal and recovery from coal has been described for its better and more efficient utilization [28]. The fuel combustion and its thermochemistry provided details on the first and second law use on the control volume, chemical equilibrium, and reaction stoichiometry. It also included ways for the determination of the adiabatic flame temperature essential for the combustion of MHD [29].

The selection of coal in combustion MHD is important because that relies mostly on the coal structure, its types, composition, heating values, preparation steps and cost involved, and the products formed. In other words, understanding the technology of coal combustion and its conversion is necessary for efficient coal-fired MHD operation [30]. However, the use of coal creates the problem of slagging and environmental degradation of the coal-fired open-cycle MHD system. Such problems can be resolved by employing a sulfur removal process from the mixture of seed and slag to form hydrogen sulfide [31]. Techniques to reduce carbon dioxide emission considered the use of oxygen and coal combustion and recovery of CO_2 by liquefaction or by using carbon as fuel obtained from the production of methanol followed by liquefaction [32].

The closed-cycle MHD plant having a disk generator has superior transient stability due to the diminishing effect on the swing of the synchronous generator’s transient rotor angle. This effect was observed when a commercial-sized MHD generator was connected to the power grid and a synchronous generator while operating the MHD system with helium working fluid in an ionized state and using cesium as seed material [33].

The potential of closed-cycle liquid metal MHD was realized and steps to evaluate such systems were undertaken. The liquid metal has been preferred as an electrodynamic fluid due to its high conductivity and ability to attain high power density at lower operating temperatures [34].

The liquid metal MHD was developed to a sufficient extent due to its advantages over coal-fired MHD systems, and activities related to the development of MHD and thermodynamic fluids were initiated [35].

2.3. Thermodynamic performance analysis of MHD system

The MHD system that operates either in open or closed-cycle have been investigated to study its performance under different working conditions. The performance of MHD may also deteriorate due to oxidation of electrodes resulting in decrease in current output. When the permanent magnet is used with the MHD channel, the gas flow parameters were to be measured using indirect method of testing because of the low strength of the magnetic field [36].

Performance analysis of MHD cycle for power generation showed that the thermal efficiency computed at maximum power density gives a higher value when compared to that obtained using maximum power for all temperature ratios. In both cases the compressor and generator irreversibilities were assumed constant [37]. The performance of an MHD power plant was analyzed thermodynamically based on the power and efficiency characteristics. It was found that the design optimization of the MHD plant requires the determination of the optimal pressure ratios for the highest values of power and efficiency [38].

Using a thermodynamic model, it was observed that the MHD cycle performance decreases when the flow Mach number is increased whereas by keeping the velocity unaltered the entropy generation in the generator can be reduced [39].

The MHD generator irrespective of its configuration is designed so as to have a uniform distribution of the electrical conductivity of the plasma and decrease the axial current [40]. The design optimization of the shapes and size of a Faraday segmented MHD generator channel from its segmentation distance can be possible using a quasi-one-dimensional model correctly in place of the existing two or three-dimensional electrodynamic models [41].

MHD generator performance can be optimized when the rate of entropy generation is taken into account along with the various generator irreversibilities in the determination of second law efficiency. Further, it was found that there exists another criterion for maximizing the MHD performance, which can be achieved through maximization of the isotropic electrical efficiency by optimal control of the flow Hartmann number, electrical load, and the oscillation frequency conditions [42].

The MHD power system was also investigated in combined cycle configurations with MHD as the topping cycle. Combined cycles based on MHD as the topping cycle has been analyzed and compared using preheated enriched oxygen as in (Fig.2.1.), air, or pure oxygen as the oxidant. From the analyses, it was observed that the highest efficiency that could be achieved among the different combined configurations was the MHD topping combined cycle that used pure oxygen and a heat recovery system with tail gasification [43].

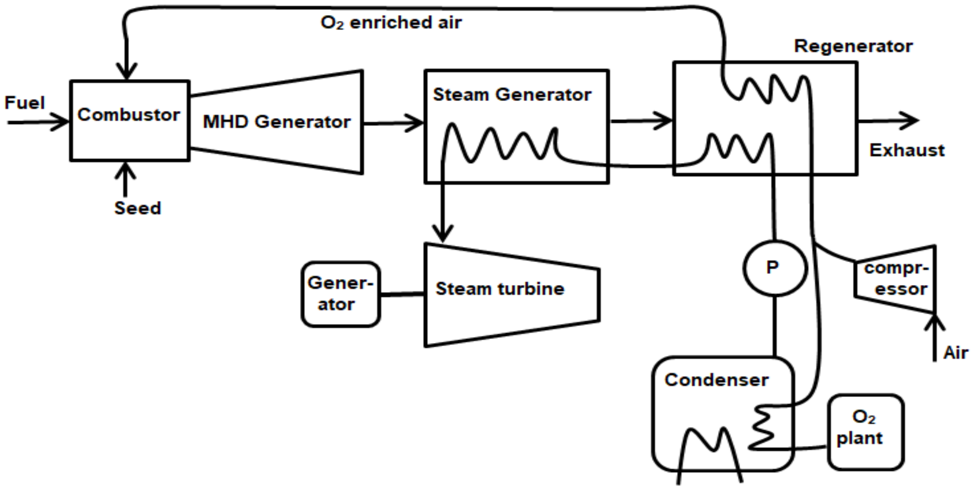

Fig. 2.1. Coal-fired MHD-steam turbine combined cycle with O_2 enrichment of MHD air [43]

Studies showed that a three-level combined MHD power system was more advantageous in both open and closed-cycle configurations (Figs.2.2. and 2.3.) when compared to those of the two-level types. The added advantages of the three-level are more heat recovery, fuel savings, and thus a significant reduction in energy losses can be achieved. However, the closed-cycle type was economically more beneficial than the open cycle type because of the incorporation of heat exchangers and low-temperature air expansion devices [44].

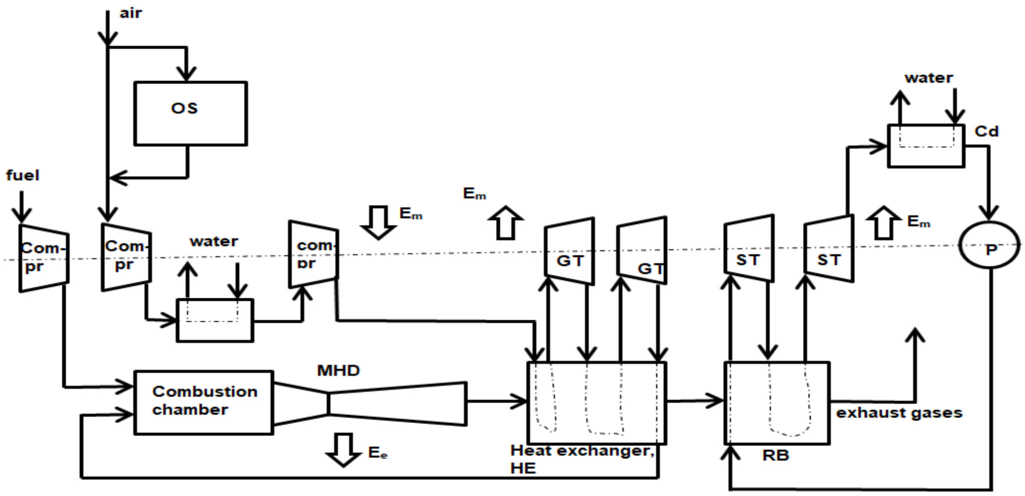

Fig.2.2. Three-level open-cycle MHD combined system [44]

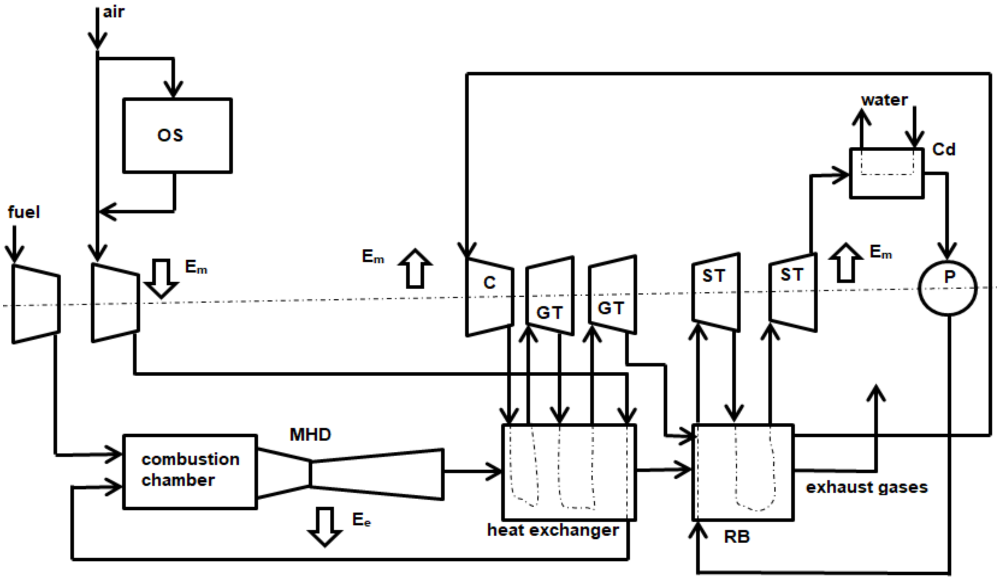

Fig. 2.3. Three-level closed-cycle MHD combined system [44]

The MHD topping gas turbine-steam turbine combined cycle plant was found to generate more electricity. Theoretical study on retrofitting South African power stations with an MHD system has shown to improve the total output capacity [45]. Analysis of combined MHD and steam turbine plants using tail gasification (Fig.2.4.) has shown to operate with higher efficiency than those without tail gasification [43, 46].

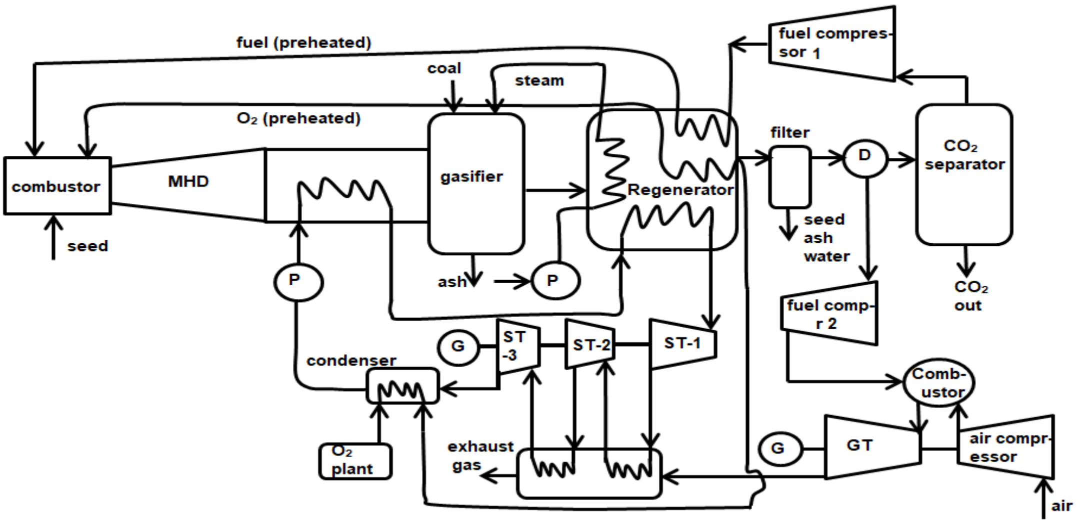

Fig. 2.4. MHD-GT-ST combined cycle with tail gasification [43]

Combined cycle in the form of closed-loop MHD generator using disk accelerator with a nuclear plant has been found useful for high velocity acceleration of plasma [47].

Integration of MHD generator with combined cycles provided a higher operational temperature, and thermodynamic analysis showed that such cycles with MHD as topping plant has the benefits of low emission, improved efficiency, and could reduce the price of exergy destruction [48]. Moreover, the efficiency of the MHD –steam turbine combined cycle plant also improves by using oxygen during combustion of coal [49].

2.4. Energy and exergy analyses of thermal energy systems

Available literature on the historical developments of the MHD electrical power generation systems shows a wide range of studies covering different aspects of plasma formation, material improvements, electromagnetic effects, heat transfer, and fluid interactions, and the performance of open and closed-cycles thermodynamically, and so on. However, the study of MHD systems based on thermodynamics energy and exergy analysis has not been performed. Such analysis will provide a deeper insight not only into the overall performance of the MHD plant but can also highlight the deficiencies of the attached components.

The basics of exergy analysis and minimizing entropy generation can be well understood through proper analysis of the ideas of irreversibility, the concept of the destruction in exergy, and entropy generation [50]. Exergy which is actually a hypothetical concept gives a quantitative measure of the useful work that can be extracted out of a system by taking it to an overall equilibrium condition with its surroundings. The amount of deviation in a system’s state from its immediate surroundings can be quantified in terms of exergy. The concept of exergy is defined by the second law of thermodynamics. Accordingly, the exergy does not follow the law of conservation as it gets destroyed always unlike energy which can be transformed or transferred and is therefore conserved.

The exergy quantity destroyed can be viewed in terms of entropy generation, thus reducing the efficiency of a system below the theoretical value. The total exergy is viewed as the sum of its major constituents namely the physical, chemical, kinetic, and potential exergy. While evaluating the exergy rate at a given state of a system, it is assumed that other effects such as any electrical, magnetic, nuclear, and such others are of the negligible count.

The concept of the ability to do useful work or energy is based on the first law of thermodynamics.

The forms of energy can exist as microscopic or macroscopic depending on whether the external reference frame is an exception or not. However, it does not convey any information about the direction of the spontaneity of a thermodynamic process. Also, the explanation of the conversion of heat into work completely cannot be ascertained using the thermodynamics first law [51]. In such situation, it is the second law of thermodynamics that assisted in explaining the energy availability and the spontaneity of thermodynamic processes.

Another parameter given by the second law is the exergy efficiency that can explain the performance of a system better than that given by the energy efficiency. Both energy and exergy efficiencies are basically meant for the efficiency enhancement and hence the system's performance, however in evaluating energy efficiency the priority is to decrease emissions in energy whereas the evaluation of exergy efficiency takes consideration of all types of irreversibilities be it internal or external [51].

Exergy analysis of different systems served as an important tool in improving knowledge of the operation of those systems and taking appropriate corrective measures in areas for enhanced performance.

The exergy method uses the conservation principles as well as the second law of thermodynamics to improve energy usage more efficiently. It thus attempt to enhance performance of energy systems through identification of the areas of energy wastages quantitatively [52].

The exergy method provides a measure of the energy quality with respect to its surroundings and speaks about the quantity of useful energy used up by a process out of the total exergy input to the system. The overall irreversibility of a plant can be computed by knowing how the deficiencies in the various system components are distributed in order to determine the efficiency of the overall plant system [53].

Exergy method of analysis is an effective way to measure the potential extent of a system to cause environmental degradation [54]. Exergy tool can assist in evaluating the efficiencies of electrical power generation systems by identifying the locations of deficiencies and improve the ability to take precautionary measures to reduce thermodynamic losses [55]. The exergy method can predict the way how the energy in a system is utilized [56].

Exergy method has been applied beneficially to different combined and power cycles where the performance of these systems were evaluated by determining the exergy efficiency by appropriately calculating the component exergies, fuel exergy with required combustion calculations [57].

Another novel way that has been developed for performing exergy analysis is to apply an advanced method where the actual potential of component and overall system improvement as well as the existing interrelations among the components can be evaluated. The advanced exergy analysis takes forward the results obtained from conventional exergy analysis for applying the splitting method [58].

Results of advanced exergy analysis was found to differ from those of the conventional analysis of exergy in the way that conventional exergy analysis can neither predict precisely the components having the most potential for its improvement nor has the ability to show the existence of the influence of different components among themselves [59, 60].

Advanced exergy analysis has been applied to find the sources that may cause anomalies in a system quickly and with minimum errors by the introduction of a kind of internal exergy parameter [61].

The advanced exergy method has been used as a new form of exergy analysis and has been successfully applied in the study of maximizing the power of a regenerative Brayton cycle of closed type [62].

The advanced exergy analysis was applied to power plants working in combined cycles to determine the various irreversibilities in the form of avoidable and unavoidable losses and also their endogenous and exogenous parts. The application was able to enhance such systems in their operational and design considerations [63].

Through the splitting of exergy destruction, it is possible to determine whether the interactions among the system components are weak or strong based on the endogenous exergy rates and their ratio with respect to the other parts of exergy destruction rate [64].

In advanced exergy analysis, the nature of the maximum irreversibilities of different components may be different depending upon the system to which the splitting method is applied and also on the conditions of operation. As such, maximum losses in a component can be of the avoidable or unavoidable type and of endogenous or exogenous nature [65].

In advanced exergy analysis since the mutual interactions among the components are considered which may contribute to developing a better procedure for exergy analysis. Also, the enhancement in performances of energy systems in thermodynamic terms can be judged most conveniently by evaluating the endogenous and exogenous types of exergy destruction rates of the avoidable nature [66].

Like the conventional exergy analysis, in the advanced exergy method too the variation in the mass flow rate of fuel was found to affect the exergy destruction rate but here the effects were observed on the avoidable and unavoidable parts of the exergy destruction rates that may be of endogenous or exogenous types [67].

Advanced exergy analysis showed the actual possibility of enhancement while considering the operation of a steam boiler that can ultimately help in the improvement of different systems operating with a variety of fuels [68]. The endogenous part of the exergy destruction rate counts only for the irreversibilities occurring within a component whereas the exogenous part takes into account both internal and external irreversibilities [69].

The decrease in the endogenous part of exergy destruction rate showed improvement of a component and also the system together with a reduction in the exogenous part. However, the advanced exergy analysis can be applied to energy conversion systems using different approaches depending upon the suitability of the system to these approaches viz. analysis using thermodynamic cycles if such cycle can be defined for the system, splitting into endogenous and exogenous fractions if the exergetic performance can be evaluated through sensitivity analysis, balancing of the exergy input and exit streams or by assuming another component for a given analyzed component.

Improvement in thermodynamic efficiencies of the system component requires an actual measurement of such potential which can be known through evaluation of the avoidable exergy destruction rate [70]. Moreover, it has been found that the interactions among different components of a system not only reduce the thermodynamic efficiency but also add costs to the operation. Apart from the studies on MHD power generation system, a number of relevant studies have also been made in the field of fluid flow associated with MHD effects [72, 73].

2.5. Review Summary

From the literature survey, it has been found that numerous technical works had been performed on the development of MHD power technology for its realization and its commercialization. Efforts to design and develop efficient MHD components have been a continuous process to obtain MHD power to serve society. MHD systems both as a standalone cycle and in integrated configurations have been studied keeping different aspects of analysis to meet the challenges. A number of analyses have been performed for effective operations of MHD power technology theoretically and in the form of experimental tests. The experimental testing of the system sought long-duration runs and on a larger scale that restricted its continuous testing looking at the financial constraints. However, the testing of the system continues on the laboratory scale to reach its technological feasibility through the use of newly developed materials and more efficient components. As mentioned in Chapter 1, previous studies on MHD power generation system emphasized mostly on the system design, material development, and integration of MHD system into different ways together with thermodynamic analysis from different perspectives. The present research work is differentiated from the previous studies by focussing on the thermodynamic performance of the MHD power generation system from certain new aspects such as effects of variation in the nozzle area ratio, analyses through the application of energy and exergy tools and also using the method of advanced exergy for a more in-depth understanding of the component's energy losses which are yet to be sufficiently covered in available literature.

In this study, the MHD power plant and its combined variant with a gas turbine power plant have been analyzed for the evaluation of its performance from a thermodynamic aspect and the point of energy and exergy analysis. Further, the MHD power generation system has been analysed using the advanced method of exergy analysis to get a better way to identify the components that requires upgradation to minimize their losses.

2.6. Scope of the present work

In the present study, first, an MHD power plant configuration is chosen for analysis to evaluate its performance based on the variation of nozzle exit to throat area ratio from a thermodynamics point of view. The effects of the changes in area ratio on the various parameters that may influence the MHD performance are then evaluated. The values of the parameters at the nozzle exit, the adiabatic flame temperature of coal combustion, and the performance parameters of the MHD generator are determined using the nozzles separately. The area ratios are first varied so as to obtain the nozzle exit Mach number using thermodynamic relations which are then used to obtain the nozzle exit temperatures and velocities. A parametric analysis is performed to observe the effect of these variations on the maximum voltage, current, power, and efficiency.

Next, the performance of a coal-fired MHD power generation plant is studied using the energy and exergy analyses tool. The combustion of the fuel, preheated air with the addition of the calculated amount of seed produces the gaseous combustion products. The first and second laws of thermodynamics are applied to determine the energy and exergy rates and the energy loss and exergy destruction rates of the individual components. The maximum energy losses and the exergy destruction are evaluated for the components and analyzed with respect to their energy and exergetic efficiencies. The overall power output and the net power output are then determined. The energy loss and the exergy destruction rates of the various components are then compared.

Third, the exergy analysis of an MHD-gas turbine combined power plant is performed to study the effects of ionized combustion products of MHD on the exergetic performance of the system. The thermodynamic properties of the partially ionized species and the un-dissociated products in molecular forms are determined for the MHD plant. For the MHD an exergetic performance comparison is made between the effects of ionized species and the purely molecular species.

In one more attempt, an advanced method of exergy analysis is performed on a standalone MHD power generation system with OTSG incorporation utilizing the results of the standard exergy analysis. Using 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. Then, 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 are analyzed to obtain information about the type of exergy destruction that accounted for most of the reductions in the exergy rate and to know the possibility of augmentation of the MHD system through appropriate measures of efficiency improvements of its various units.

2.7. **Limitation of the present study**

The following are certain limitations of the present study.

- The present study is based on analysis done from a thermodynamics point of view, and as such the flow behavior and heat transfer aspect was not considered in the study. Flow and heat transfer analysis of the MHD components could be interesting considering the presence of ionized species in the flow field.
- The influence of the magnetic field strength on the induced electric field and MHD performance is not considered for investigation in this study and this is beyond the scope of the present work.
- The present study is based on the use of segmented Faraday type generator and hence, the influence of other types of generators on MHD performance is not known from the outcome of the present study. Lack of generator sizing with respect to power desired is also another limitation of the present work.
- Another weakness is the selection of the ionized proportion of species for which no real data is available and this is based only on available theoretical studies.
- The present study also suffers from lack of experimental data, and hence validation with experimental results is not a part of this study.

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