CHAPTER 1

Introduction

1.1. Magnetohydrodynamics (MHD): A prospective power generation system

Power generation, its supply and the ever growing demand are the important pillars of the economic status of any nation. The economy of a nation can be measured in terms of the volume of power usage of that particular country. To fulfill the energy demand there is also a parallel need for setting up an increased number of power generation stations which are based on both conventional and non-conventional methods of generation. The contribution of fossils fuels towards the development of modern society though unmatchable but still it comes with its own list of demerits.

The continuous usage of fossil fuels through decades has resulted in unfavourable consequences leading to environmental degradation and warming of our earth. According to Smil [1], by 2019, the worldwide usage of different types of fossil fuels as energy sources has been estimated to be in multi terra-watt-hour (TWh) and thus, we can realize the detrimental impacts globally in the present as well as in the following decades to come. It has been realized that a gradual transition to nuclear and other non-conventional energy sources with low or limited carbon emission is necessitated [2]. But even the use of nuclear power as a peaceful alternate energy source comes with its own disadvantages. The use of nuclear energy is not a proper fit to grid, it incurs costly installation, there are phase out difficulties, problems in disposing off the nuclear waste, chances of nuclear accidents that may hinder its safe operations etc. [3]. Other renewable sources include but are not limited to solar energy, use of biomass, wind energy, wave and tidal, hydroelectric, thermionic, geothermal energy. Solar energy is one of the cheapest form of renewables with zero carbon emission which however is somewhat unreliable due to its dependency on weather, high initial cost, large space requirement and environmental degradation due to use of poisonous system materials [4]. Biomass can be considered as zero carbon renewables as far as vegetation sources are concerned which is also cheap but is less efficient than its contemporary sources [5]. Wind energy is a free and clean form of naturally occurring renewable energy source but also adds to noise pollution, poses danger while being off-shore and also to the flying objects [6]. The hydroelectric power technology comes with a number of variations. Its use has been the maximum out of all renewable energy sources being one of the clean with no toxic release, high flexibility in operation, low operating and maintenance cost etc. The installation of hydroelectric power stations has high risk potential causing degradation to the ecosystems, alternate flood like situation and droughts, risk of failure are some of its disadvantages [7]. Geothermal energy sources are reliable and efficient renewable energy sources with low cost of maintenance [8]. But such sources are rare and restricted to certain geographic location and require high investment pricing. Thermionic energy conversion has the advantages of non-presence of movable parts like the Magnetogydrodynamics (MHD) power generation system but is less efficient with high material cost [9]. Thus, it is seen that each type of renewables are accompanied with its own advantages and disadvantages while one is dominating over the other. Among the non-conventional energy sources, the use of MHD power generation as an energy conversion system promises to be one of the potential candidate to meet the future energy demands.

The generation of power using MHD technology has been a topic of research and development since few decades. Continuous efforts have been made to realize MHD power extraction on a commercial front. MHD technology of power generation is based on the interaction between a strong applied magnetic field and the flow of a fluid which is a good conductor of electricity. This phenomenon was stated by the famous electromagnetic induction law of Faraday that showed the production of electromotive forces on a conductor under the influence of a magnetic field whose direction is obtained using Lenz law. The emf or electromotive force thus can be expressed as the time rate of deviation in magnetic flux ($\emptyset_B$) as given below:

$$F_{EM} = -\frac{d\emptyset_B}{dt} \tag{1.1}$$

The power generation in MHD relies on the movement of the electrically conducting fluid through the applied strong magnetic field where the particles possessing charge (q) moving with velocity v experience the Lorentz force (F_L) that counts the effect of magnetic as well as induced electric field (vB) and the electric field E_F due to the electrodes potential difference.

$$F_L = q(E_F + vB) \tag{1.2}$$

The induced field (vB) gives rise to an electric current in a direction normal to that of v and B. Electrodes that are attached to the generator walls and exposed to the moving conducting fluid are attached to loads in an external circuit and the generated current is thus transferred to these electrodes.

The Ohm’s law thus in general defines the current density $\boldsymbol{\rho}_I$, for the gas through the generator as:

$$\boldsymbol{\rho}_I = \sigma\ (E_F + vB) \tag{1.3}$$

Where σ, is the electrical conductivity of the moving fluid.

The phenomena of electrodynamics and magnetism in MHD concerning the motion of the ionized fluid or plasma can be best described by the coupled mass, energy and momentum equations and the Maxwell’s equations [10]. The Maxwell’s equations applicable to MHD can be expressed by the following governing equations [11].

$$\nabla \times B = \mu \boldsymbol{\rho}_I \ , \qquad \nabla . \boldsymbol{\rho}_I = 0 \tag{1.4}$$

$$\nabla \times E_F = -\frac{\partial B}{\partial t}, \qquad \nabla . B = 0 \tag{1.5}$$

For normal loading, a loading parameter L is considered that defines the relation between the two electric fields with respect to the current density (ρ_I). In MHD power technology, the current density plays an important role while defining the power extraction capacity from the MHD generator. The current density thus is a function of the loading parameter and the induced electric field (vB) while the electric field E_F, due to the potential difference depends both on the loading parameter and the induced electric field.

$$\rho_I = -(1 - L) \times \sigma v B \tag{1.6}$$

$$E_F = L \times vB \tag{1.7}$$

As such, the power that can be extracted at the electrodes (P_{EX}), can be expressed as

$$P_{EX} = -\rho_I \times E_F \tag{1.8}$$

$$\text{Or,} \qquad P_{EX} = L(1 - L)\sigma v^2 B^2 \tag{1.9}$$

The MHD generator efficiency can be defined as the ratio of the power extracted at the electrodes to that of the rate of obtaining energy out of the moving gases through the generator. In either case, the power has been obtained with respect to the volumetric consideration of the generator.

The MHD power can be realized from the MHD generator that can operate at a very high temperature due to the absence of moving parts unlike the conventional turbines of steam and gas turbine power plants.

In MHD power generation there is direct conversion of energy inherent in fuel to electricity. The advantages of MHD power have been seen as a promising alternative to augment the power requirement in the near future. MHD power generation was found to be of high overall efficiency with lower harmful emissions. Therefore, many countries in the world have carried out MHD related programmes to realize its commercialization [12, 44]. The various developmental stages marked for the realization of MHD power commercially have been described in the work of Malghan [12]. These developments could be seen as a series of research and experiments carried out at different times and starting of pilot projects and plans for setting up of plants for MHD electrical power viability. Keeping aside the advantages, however, there are certain limitations as imposed by high capital cost, design of high temperature resistant and efficient electrode materials, seed regeneration technology, insufficient experimental outcome, lack of strong interactions between the applied magnetic field and the ionized working fluid are some of the areas which are sought to be further developed for optimal MHD power output. MHD power generation systems under different conditions of component geometry, configurations as well as material considerations have been studied and analyzed for evaluating the performance, enhancement and optimization of efficiency and power output [13-22]. MHD combined plants were also investigated to evaluate their performance with MHD as a topping cycle [23, 24]. Study on decreasing carbon-dioxide emissions in MHD plant have also been undertaken [25]. The effect of Lorentz force on the static pressure variation and the supersonic flow deceleration was found to be mainly due to MHD interactions [48].

The above studies have contributed much towards understanding the complexities associated with the operation of MHD power plants and its subsequent improvements.

1.2. MHD power cycles

The MHD power generation is achieved by the flow of ionized gases or plasma through the MHD generator to which a strong magnetic field is applied where the moving charged particles are affected by an induced force called the Lorentz force [26]. The conversion of thermal to electrical energy in the MHD generator could be realized using either of the two primary cycles applicable in MHD energy conversion systems. These cycles basically differ on account of the type of ionized gases, type of seed materials employed and the type of recirculation loop followed for the working fluids [27]. These cycles are therefore termed as an open-cycle or a closed-cycle. From a thermodynamic point of view, the open-cycle MHD resembles the Brayton cycle while in the closed-cycle, it is either the Brayton or Rankine cycle depending upon whether the working fluid used is an inert gas or a two-phase liquid metal [28]. A brief account of the two MHD cycles is described below:

1.2.1. **Open-cycle MHD**

The MHD open-cycle system uses ionized gases which are products of combustion of certain fossil fuels. In open-cycle MHD system, fossil fuel such as coal is allowed to burn at a very high temperature in an environment of preheated and excess oxygen which is then seeded with some kind of alkali compounds like the potassium carbonate. The high temperature combustion thus results in the formation of gases having charged particles. The added seed material helps in the enhancement of electrical conductivity of the ionized gas and in the lowering of ionization temperature to some extent. The ionized gases are then made to acquire sufficient velocity by passing them through a high velocity nozzle before they enters the generator of the MHD system.

In the MHD generator the high temperature and high velocity gas interacts with the applied strong magnetic field under the influence of the Lorentz force. These interactions lead to the accumulation of the oppositely charged ions on the opposite electrodes of the generator. Thus, there exists a potential difference across the electrodes producing electricity across the terminals of an external load connected to the electrodes.

In the open-cycle system, the collision frequency between the molecules of combustion ionized gases and that of the electrons are found to be high in order to maintain the conditions of thermal equilibrium. However, it was found to suffer from drawbacks such as the low electrical conductivity of the product gases and a slagging atmosphere [26].

1.2.2. **Closed-cycle MHD**

The closed-cycle MHD system utilizes an inert gas or a liquid metal as the working fluid which is circulated in a closed loop [27]. It uses a heat transfer device to heat the working fluid to a high temperature with the addition of suitable seed material such a vapours of Cesium for electrical conductivity enhancement [26]. In the closed-cycle operation using inert gases, the collision frequency between the gaseous molecules and the electrons was found to be low requiring Ohmic heating to maintain the electrical conductivity and the non-equilibrium conditions with lower gaseous and higher electron temperature [26].

The liquid-metal based closed-cycle MHD (LMMHD) system was found to exhibit a better power density than those of the open-cycle using ionized combustion products [28] at comparative low temperature ranges. In the LMMHD, the working fluid constitutes a two phase mixture of a electrodynamic and a thermodynamic fluid. The thermodynamic fluid acts as the driver for the electrodynamic fluid in the MHD generator. From the earlier investigations of Rand (DOE) and works at Argonne National Laboratory (ANL) and Jet Propulsion Laboratory (JPL), it was found that the maximum efficiency obtained from the LMMHD approximated to that of the Ericsson cycle.

1.3. **Magnetohydrodynamic power technology components description**

The MHD system performance depends upon the proper working of all the related components and associated materials. For open-cycle gas or coal-fired systems which usually operates under a very high temperature environment, the choice of suitable materials for the various components has been a continuous challenge. In case of the open-cycle MHD system various components function in coordination for the final output. Normally, the combustion chamber, a supersonic nozzle, compressor, air preheater, seed regeneration system, MHD generator, inverter system and the stack constitutes the major components of an open-cycle MHD system together with a fuel preparation system in case if solid fuel (coal) is used. Likewise, in the closed-cycle depending upon whether it uses an inert gas or a liquid-metal as the working fluid, the components requirement vary. Apart from the above, suitable materials are to be considered for the electrodes and the MHD generator. The various components of the open-cycle MHD power generation system are briefed in the following:

1.3.1. **MHD Combustor**

The combustion section of the MHD power generation system is a crucial part in the overall performance of the plant. In the open-cycle MHD using coal suffers from the problem of slagging which has been largely reduced through stage combustion. In the initial stage, the fuel (coal) is partially combusted with preheated air which is further preheated at this stage [26] with the removal of slag. The next stage of the combustion process involves feeding of seed material and the sufficient supply of oxygen for the attainment of the required fuel-air ratio. The process thus is able to attain a reasonable value of conductivity of the combustion ionized gases [29-31].

1.3.2. **Nozzle**

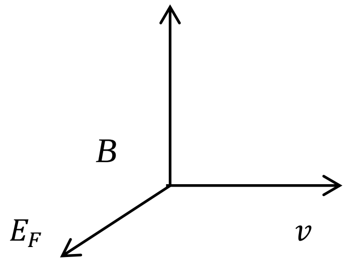
The nozzle in MHD system is used to accelerate the ionized gases to a very high velocity and direct it to the inlet of the MHD generator. The plasma flow through the supersonic nozzle ensures required flow Mach number at the MHD generator inlet for power output. The flow through the nozzle is considered reversible adiabatic for simplified fluid flow evaluations. In MHD power technology, the Joule heating in the region between the generator inlet and the nozzle exit was found to be low leading to a lower total pressure drop [32]. It was observed that the use of supersonic flow at the MHD generator inlet do not affect the pressure and velocity sharply and neither there is any abrupt drop in terminal voltage [15].

1.3.3. **MHD generator**

The generator of the MHD system is devoid of any rotational parts enabling its operation without any temperature restraints to a much higher value. Unlike conventional turbines that are in use for obtaining mechanical power output, the MHD generator produces power in the form of electrical energy. The MHD generator can be of different configurations namely the linear Faraday, segmented Faraday type, diagonal type, Hall generator, and the disk type [26, 33] depending upon the electrodes arrangement. The linear and the segmented types are shown in Fig.1.1. and Fig.1.2. respectively. In diagonal type generators (Fig.1.3.), an internal electric field downstream as the electrodes are which are in the environment of ionised gas flow thereby increasing the potential difference. In MHD generators, an undesirable phenomenon called the Hall Effect leads to a decrease in the current density and the power output. In ideal MHD operation, the directions of the electric field, magnetic field and that of the plasma flow maintains perpendicularity among themselves. Due to the Hall effect, the current flow is initiated in the gas flow direction inducing an emf called the Hall emf, E_{Hall} . Hall emf needs to be handled by the induced electric field (vB) along with the electric field (E_F) due to potential difference between the electrodes. Accordingly, the MHD generator should have the ability to maintain the plasma conductivity uniformly and also to reduce the effects of Hall current. Measures suggested by Rosa et al. [33] to overcome the detrimental effects include electrode segmentation with connection of separate loads between the opposed pairs of segmented electrodes as well as provision of some kind of barrier to axial electric field. The Hall type generator (Fig.1.4.), shortens the axially induced electric field between the downstream and the upstream electrodes in an external or internal circuit and was found to be more efficient compared to the segmented Faraday type.

The disk type generator (Fig.1.5.), does not have segmented electrodes, is with circular movement of the current while delivering power by means of the Hall current and field.

.



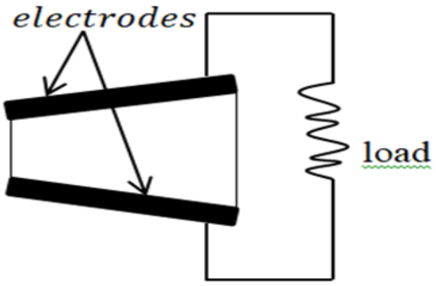


Fig.1.1. Linear (continuous) Faraday generator [44]

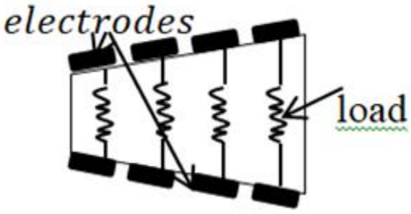


Fig.1.2. Segmented Faraday generator [44]

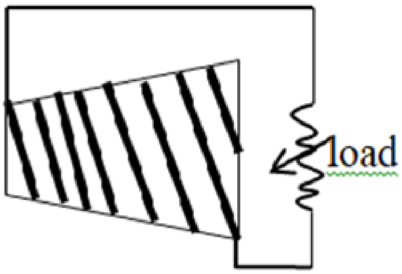


Fig.1.3. Diagonal type MHD generator [44]

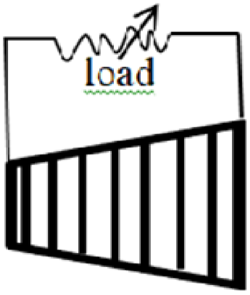


Fig.1.4. Hall type MHD generator [44]

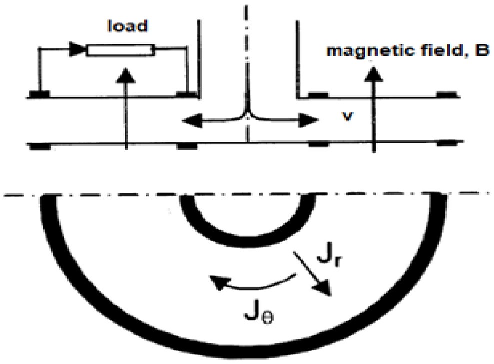


Fig.1.5. Disk type MHD generator [21]

1.4. MHD Materials

The efficient operation of the MHD power plant largely depends on the effective functioning and choice of appropriate materials. The primary materials include those used for the plasma seeding, magnets and the electrodes. These materials have been briefly described below:

1.4.1. **Seeding material**

In the open-cycle MHD, the combustion products are seeded with compounds of potassium or cesium vapours which dissociate at the plasma formation temperature to atoms and ions. The overall effect due to the decomposed seed, its evaporation and also the ionization resulted in imparting and enhancing the electrical conductivity of the ionized gases [34]. The seed materials especially when the solid fossil fuel such as coal is used have been beneficial in the removal of sulphur due to their attraction towards it. The seed materials being costly also need to be regenerated. The sulphur removal processes helps in the separation of the seed element. The injected seed materials in the combustion process forms sulphur compounds which are then subjected to seed regeneration by a number of available processes. Separation of sulphur from the seed metals is made possible using processes such as the Pittsburgh Energy Research Center (PERC), Aqueous

Carbonate, Markant, Formate, Engel-Precht, Double-alkali and the Tampella process out of which the PERC and modified Tampella were found to be more suitable following an elimination rule [35]. In the same report [35], it was asserted that for the sulphur recovery, the Claus process and Stretford process can be used though from the point of seed regeneration the Stretford process was found to be a better choice.

1.4.2. **Electrodes**

In open-cycle coal-fired generators, the electrode typically consists of a base material copper using non-corrosive elements like platinum, stainless steel or a mix of copper and tungsten as capping materials for anode and cathode [26]. A proper choice of electrode materials determines not only the longetivity of such substances but also control the voltage drops and power density. The electrodes are to be of high temperature materials. The electrodes being subjected to erosion and also due to their possible failure can be made of zirconium dioxide and chromites based graphite and ceramic materials to reduce such undesirable incidents [37]. The electrode erosion and reduction in voltage tends to affect the generator [38]. The electrode material to be used has to be stable with temperature, vaporization, oxidation and sulphidation. Among the electrode material, sole use of zirconia was reported to be unfavorable due to its low conductivity, problems of electrochemical oxidation at the anode, unstable at high current densities. Zirconia was unsuitable considering thermal gradient across the electrode and was highly temperature relied and has high resistivity. Later, zirconia was stabilized with yttria, calcia or magnesia were tested. It was found that the addition of yttrium to zirconia doped with cerium was highly effective with increase in ionic conductivity [36]. Moreover, at high voltages zirconium dioxide decompose forming zirconium metal and zirconium oxide Zr_2O_3. On the other way it also has high melting point and low vaporization rate. However, zirconia dioxide has to be stabilized by doping with yttria, calcia or magnesia as its volume and phase tends to change at higher temperature.

Other materials such as UO_2 with low base radioactivity were a candidate due to low vaporization, resistant to decomposition by oxidation, resistant to oxidation and sulphidation. Similarly, different doping materials like titanium, neodymium were also tested [36] where the effectiveness of neodymium was found to be equivalent to cerium.

1.4.3. **Magnets**

The extraction of power using MHD system is based on the interaction of the moving and electrically conducting ionized fluid and the applied magnetic field. So the generation of current is based on the application and strength of the magnetic field that may induce the required electric field.

As seen from eqn. (1.9), the power density in the MHD generator is proportional to square of applied magnetic field. The MHD generator uses superconducting type of magnet which serves the benefit of low or negligible ohmic losses [44] while its performance in MHD power extraction is desired to be stable and steady. In Faraday generators of linear design, the magnetic field is applied using saddle type magnets while in the disk generators; it’s a solenoidal coil [44]. The conversion efficiency in MHD generator can be improved through changes in the magnetic field geometry [45]. Design considerations for superconducting magnets have been discussed and emphasis has been made for improvement in conductor and other electrical and mechanical failure causing elements [46].

1.5. Plasma in MHD

1.5.1. Ionization and plasma formation

The power generation in the generator of MHD is very much affected by the ionization of the working fluid which is very crucial in the operation of MHD power generation system. In plasma or ionized gases, the gaseous molecules and atoms are in the form of ions. The plasma consists of a large number of charged particles and is usually neutral. Plasma can be either natural or man-made. The particles in plasma may or may not be all in the ionized state. As such the plasma can be one of completely, weakly or partially ionized forms and are depended on the degree of ionization.

The temperature attained by the plasma is a function of the mean energy possessed by its particles and the number of degrees of freedom. The particles in plasma may exist at different temperatures and as such the plasma is said to be a non-equilibrium or non-thermal plasma where the temperature of the electrons play a dominant role in directing either the process of ionization or other chemically reactive processes. When the plasma particles cannot be distinguished in terms of temperature then such kind of plasma is said to exist in thermal equilibrium and such plasmas are called thermal plasma. In MHD power systems, the high velocity and highly densed plasma intercepted by a strong magnetic field induces the electric field for the generation of electric current. An extensive elaboration of the plasma formation, its types, chemical behavior and thermodynamics and other characteristics including those described above can be read from [39]. Details of the dissociation of ions and ion formation could also be found in the work of Gross [40]. In MHD generators, the plasma of the combustion products is in thermodynamic equilibrium while non-equilibrium plasma rules in the inert gas plasma [33]. The non-equilibrium plasma is formed due to low-pressure discharges with the heating of electrons namely the Joule heating under the effect of induced emf [41]. In inert gas MHD, the plasma becomes non-uniform because of increased discharge at the generator inlet causing the ionization to become unstable thereby reducing the performance of the MHD system [42]. Such effects are caused by the gas or seed ionization as the Hall coefficient become larger than its critical value.

1.5.2. **Plasma conductivity**

When no magnetic field is applied, the current produced in the generator of MHD is a result of electron movement relative to the plasma flow. The ratio of current density ($\rho_{I,e}$) to the generated electric field (E_F) gives a measure of the electrical conductivity (σ), as given in eqn. (10).

$$\sigma = \frac{\rho_{I,e}}{E_F} \tag{1.10}$$

When the plasma flow is subjected to a magnetic field at right angles in the MHD generator, an electric field gets induced that induces a force on the electrons normal to that of the plasma flow and the applied magnetic field. In this scenario, the current density deviates from being parallel to the magnetic field.

The electrical conductivity of the working fluid in MHD is in fact dependent upon the electron characteristics such as the charge (q_e), density ($\rho_{n,e}$) and the mobility ($\mathcal{M}_e$) of electrons [33].

$$\sigma = q_e \times \rho_{n,e} \times \mathcal{M}_e \tag{1.11}$$

The electron density can be determined using Saha equation [eqn. (12)] for both equilibrium and non-equilibrium plasma by considering the electron temperature in inert gas plasma.

$$\frac{\rho_{n,e}\times\rho_{n,i}}{\rho_{n,a}} = \frac{w_{s,e}\times w_{s,i}}{w_{s,a}}\left(\frac{2\pi m_e kT}{h^2}\right)^{\frac{3}{2}} e^{-\frac{I_p}{T}} \tag{1.12}$$

here $\rho_{n,i}$ and $\rho_{n,a}$ are the ion and atom number densities; $w_{s,e}$, $w_{s,i}$ and $w_{s,a}$ are the statistical weights of the electron, ion and the atoms; m_e is the electron mass; I_p is the ionization potential; k, h and T are the Boltzmann constant, Plank' constant and the temperature respectively.

Considering the total collision-frequency between the electrons and the neutrals or heavy particles, the electrical conductivity can be expressed [33. 39] as:

$$\sigma = \frac{\rho_{n,e}\, q_e^2}{m_e v_{e\mathcal{H}}} \tag{1.13}$$

here, $v_{e\mathcal{H}}$ is the electron-heavy particle collision-frequency.

The collision frequency between the electrons and the neutral particles with respect to pressure has been numerically computed [39] and the power density due to the electric field on the electrons of the moving plasma can be found as follows.

$$\wp = \sigma E_F^2 = \frac{\rho_{n,e}\, q_e^2 E_F^2}{m_e v_{e\mathcal{H}}} \tag{1.14}$$

The collision frequency is affected by the average speed of the electrons $(\bar{S}_e)$, density of the neutrals $(\rho_{n,\mathcal{H}})$ and the mean cross-section $(\bar{A}_{e\mathcal{H}})$ for collision momentum transfer [33] and is expressed as

$$v_{e\mathcal{H}} = \bar{S}_e \sum(\rho_{n,\mathcal{H}} \times \bar{A}_{e\mathcal{H}}) \tag{1.15}$$

The coal-fired and the gas-fired combustion plasmas suffer from low electrical conductivity owing to improper mix of the combustion and seed materials [43]. The electrical conductivity is limited by minimum temperature limit which depends on the level of oxygen enrichment [26]. This adds to increased stresses on materials and also harmful emissions.

1.5.3. Mobility of electrons and ions in plasma

The movement of electrons in plasma is quite complex owing to the difficulties in understanding of the collision cross-sections and its decelerations [33]. The mobility of electrons is seen to be influenced by their drift velocities and the electric field [39]. The electron mobility is also affected due to the interactions with the charged particles. Thus, the electron mobility can be expressed as:

$$\mathcal{M}_e = \frac{v_{drift}}{E_F} = \frac{\sigma}{q_e \times \rho_{n,e}} = \frac{q_e}{m_e v_{e\mathcal{H}}} \tag{1.16}$$

Likewise, the mobility of ions in plasma can vary depending on the strength of the electric fields, the collision frequency of the ions with the heavier particles $v_{i\mathcal{H}}$ and their masses [39].

$$\mathcal{M}_{ion} = \frac{v_{drift}}{E_F} = \frac{q_e}{v_{i\mathcal{H}} \times (\frac{m_e m_{ion}}{m_e + m_{ion}})} \tag{1.17}$$

1.6. Motivation and Research Objectives

The performance of the MHD power generation systems was analyzed for both open and closed-cycle versions in some previous studies [16, 26, 44, 46]. Advantages of high operating efficiency, absence of moving parts in generator, and lower emissions have placed MHD systems in the category of most promising alternative source of electricity generation. There has been phase-wise testing of MHD systems for their commercialization possibilities [47] with the setting of pilot facilities to study the technical viability and cost of acquiring such systems. The interactions of magnetic field and the conductive fluid flow have been studied widely in the context of MHD power production. Several theoretical and laboratory-based experimental studies have been performed for a better understanding of this system [22-26, 32-36, 38, 43, 46]. The MHD systems were evaluated thermodynamically from varied perspectives [13, 15, 17, 24] including component-based analysis [14-15, 38]. 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.

The motivation and novelty of the current research are summarized as follows. First, the growth in MHD power technology since its inception has been a continuous process to date. Secondly, in previous studies, there has been significant emphasis on MHD system design, material development, and integration of MHD system into different combined levels together with thermodynamic analysis from many different perspectives. The present research work can be differentiated from the previous studies by concentrating on the thermodynamic performance analysis of the MHD power generation system from a new aspect through variation in the nozzle area ratio and application of the first and second laws of thermodynamics.

As to the authors' best knowledge, the study of MHD power plants based on energy and exergy analysis is not sufficient in the 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 understanding of the actual loss components and their future upgradation requirements. The specific objectives of this research are stated below:

- Development of a thermodynamic model for an MHD power plant and conduction of thermodynamic performance analysis of the MHD plant with the variation in nozzle area ratio.
- Development of a thermodynamic model and conduction of energy and exergy based performance analysis of a coal-fired MHD power plant.

- Development of a thermodynamic model and conduction of exergy analysis on a combined MHD-gas turbine (GT) configuration with dual preheaters for performance prediction.
- Conduction of advanced exergy analysis of a standalone coal-fired MHD power plant for assessment of unit-wise divisions of total exergy degradation and to predict the possibilities of system upgradation.

1.7. Chapter-wise thesis organization

The thesis consists of seven chapters. The present chapter provides an introduction to the field of the research and highlights the motivation and objectives of the current research towards the end. The remaining chapters are organized as follows:

- Chapter 2 presents a detailed review of the studies that were carried previously on the different aspects of Magnetohydrodynamics (MHD) power technology development and the performance analyses of MHD and MHD integrated combined power plants. The scope of the present research work is highlighted at the end.
- Chapter 3 presents the performance analysis of the MHD power plant using the variation in nozzle throat to exit area ratio. In this chapter, a parametric analysis was performed to observe the resulting effect of these variations on the maximum voltage, current, power and efficiency.
- In Chapter 4, an exergy analysis is performed on a MHD power generation system. In this chapter component-wise energy and exergy rates, the energy loss and the exergy destruction rates are determined and compared. The maximum energy losses and the exergy destruction rates are evaluated for the components and analyzed with respect to their energy and exergetic efficiencies. The overall power output and the net power output is then determined.

- In Chapter 5, an exergy based parametric analysis is carried out to evaluate the exergetic performance of a MHD-gas turbine combined power plant. The thermodynamic properties of the partially ionised species and the un-dissociated products in molecular forms are determined. Further, the effects of partial ionization and un-dissociated combustion products on the exergetic performance of the combined system is evaluated and compared.
- Chapter 6 describes the exergetic performance of a standalone MHD power generation system with the use of an OTSG. In this advanced exergy analysis, the total exergy destruction 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 splitting of the total exergy destruction rate into various sub-portions is done after performing the standard or conventional exergy analysis. Further, the results are analysed in order to obtain information about the type of exergy destruction that accounts for most of the reductions in the exergy rate and to ascertain the possibility of augmentation of the MHD system through appropriate measures of efficiency improvements of its various units.
- Chapter 7 provides the summary of the important observations and conclusions made in this research work. The possible scope of future research in the field of Magnetohydrodynamics power generation technology is highlighted at the end of this chapter.

Bibliography

[1] Smil, V. *Global Fossil Fuel Consumption*. Retrieved on 23 Dec. 2021 from https://www.ourworldindata.org/fossil-fuels

[2] Ritchie, H. and Roser, M. *Fossil Fuels*. Retrieved on 23 Dec. 2021 from https://www.ourworldindata.org/fossil-fuels

[3] Good Energy. *8 Disadvantages of Nuclear Energy*. Retrieved on 23 Dec. 2021 from https:// https://www.goodenergy.co.uk/8-reasons-good-energy-doesnt-want-nuclear-power-as-part-of-the-uks-energy-mix/, 2016.

[4] Vourvoulias, A. *Pros and Cons of Solar Energy*. Retrieved on 23 Dec. 2021 from https://www.greenmatch.co.uk/blog/2014/08/5-advantages-and-5-disadvantages-of-solar-energy, 2021.

[5] MCFARLAND, K. *Biomass Advantages and Disadvantages*. Retrieved on 23 Dec. 2021 from https://www.syntechbioenergy.com/blog/biomass-advantages-disadvantages

[6] Lloyd, D. *Wind Energy: Advantages and Disadvantages*. Retrieved on 23 Dec. 2021 from http://large.stanford.edu/courses/2014/ph240/lloyd2/ , 2014.

[7] NS Energy Staff Writer. Profiling the Top Pros and Cons of Hydroecectric Power Generation. Retrieved on 23 Dec. 2021 from https://www.nsenergybusiness.com/features/newsmajor-pros-and-cons-of-hydroelectric-power-5915836/ **, 2021.**

[8] Greenmatch. *Advantages and Disadvantages of Geothermal Energy-The Source of Renewable Heat*. Retrieved on 23 Dec. 2021 from https://www.greenmatch.co.uk/blog/2014/04/advantages-and-

[9] Swifter, S. *Thermionic Energy Generation as a Source of Clean Energy*. Retrieved on 23 Dec. 2021 from http://large.stanford.edu/courses/2018/ph240/swifter2/,2018.

[10] Munz, C.D. and Sonnendrucker, E. Chapter 14-Maxwell and Magnetohydrodynamic Equations. *Handbook of Numerical Analysis*, 18: 385-401, 2017.

[11] Lenz, M. Introduction to Magnetohydrodynamics. Retrieved on 24 Dec. 2021 from https://www.numa.uni-linz.ac.at/Teaching/Bachelor/schafelner-bakk.pdf , 2016.

[12] Malghan, V. R. History of MHD power plant development. *Energy Conversion and Management*, 37 (5): 569-590, 1996.

[13] Assad, M. El. H. Thermodynamic analysis of an irreversible MHD power plant. International Journal of Energy Research, 24: 865-875, 2000.

[14] Ibanez, G., Cueves, S., Lopez de Haro, M. Optimization analysis of an alternate magnetohydrodynamic generator. *Energy Conversion and Management*, 43: 1757-1771, 2002.

[15] Aithal, S. M. Characteristics of optimum power extraction in a MHD generator with subsonic and supersonic inlets. *Energy Conversion and Management,* 50: 765-771, 2009.

[16] Yiwen, Li., Yinghong, Li., Haoyu, Lu., Tao, Z., Bailing, Z. Feng, C., and Xiaohu, Z. Preliminary Experimental Investigation on MHD Power Generation Using Seeded Supersonic Argon Flow as Working Fluid. *Chinese Journal of Aeronautics*, 24: 701-708, 2011.

[17] Cicconardi, P. S. and Perna, A. Performance analysis of integrated systems based on MHD generators. *Energy Procedia,* 45: 1305-1314, 2014.

[18] Pengyu, Y., Bailing, Z., Yiwen, Li., Yutian, W., Chengduo, D., Hao, F., and Ling, G. Investigation of MHD power generation with supersonic non-equilibrium RF discharge. *Chinese Journal of Aeronautics,* 29(4): 855–862, 2016.

[19] Poonthamil, R., Prakash, S., and Varma, A. K. Enhancement of power generation in thermal power plant using MHD system. *IOSR Journal of Mechanical and Civil Engineering,* 13: 142-146, 2016.

[20] Sahin, B., Ali, K., and Hasbi, Y. A performance analysis for MHD power cycles operating at maximum power density. *Journal of Physics D. Applied Physics*, 29: 1473-1475, 1996.

[21] Chernyshev, V. International co-operation in MHD electrical power generation. *IAEA Bulletin,* 20: 42-53, 1978.

[22] Murakami, T., Nakata, Y., Okuno, Y., and Yamasaki, H. An analytical study of the plasma conditions and performance of an MHD generator. *Electrical Engineering in Japan,* 144: 9-15, 2003.

[23] Kayukawa, N. Comparisons of MHD topping combined power generation systems. *Energy Conversion and Management,* 41: 1953-

1974, 2000.

[24] Ayeleso, A. O and Kahn, Md. T. E. Modelling of a combustible ionised gas in thermal power plants using MHD conversion system in South Africa. *Journal of King Saud University-Science,* 30: 367-374, 2018.

[25] Ishikawa, M. and Steinberg, M. MHD power systems for reduction of CO_2 emissions. *Energy Conversion and Management,* 39 (5/6): 529-539, 1998.

[26] Kayukawa, N. Open-cycle magnetohydrodynamic electrical power generation: a review and future perspectives. *Progress in Energy and Combustion Science*, 30: 33-60, 2004.

[27] Electrical 4U. *MHD Generation or Magneto Hydro Dynamic Generation*. Retrieved on 25 Dec. 2021 from https://www.electrical4u.com/mhd-generation-or-magneto-hydro-dynamic-power-generation/ , 2020.

[28] Pei, R.Y. and Hess, R.W. The liquid-metal closed-cycle system of magnetohydrodynmic power generation. Technical Report No.R-2343-DOE, The Rand Corporation, Santa Monica, CA,

[29] Bauer, M., Albright, J., Braswell R., Grove, A., Koyama, T., Myrick, S., Pote B., and Thom, H. Demonstrated performance of the TRW pressurized slagging coal combustor during the MHD POC program. In Proceedings of the 32nd SEAM, N. p, Pittsburgh, USA, 1994. https://www.osti.gov/search/semantic:Demonstrated%20performance%20of%20the%20TRW%20pressurized%20slagging%20coal%20combustor%20during%20the%20MHD%20POC%20program

[30] Listvinsky, G., Eglitis, A., Grove, A., Hession, B., Motchell, P., and Myrick, S. Combustor design status. In Proceedings of the 28th SEAM, N. p, Chicago, USA, 1990.

[31] Braswell, R., Koyama, T., McAllister, M., Myrick, S. and Pote, B. 50 MWt prototypical combustor performance. In Proceedings of the 31st SEAM, N. p, Whitefish, 1993.

[32] Sakamoto, Y., Sasaki, R., and Fujino, T. Numerical Study of Plasma Characteristics in Supersonic Nozzle of Nonequilibrium Magnetohydrodynamic Generator. In AIAA Propulsion and Energy Forum, pages 1-16, 2020. https://doi.org/10.2514/6.2020-3655

[33] Rosa, R. J., Krueger, C. H., and Susumi, S. Plasmas in MHD power generation. *IEEE Transactions on Plasma Science*, 19 (6): 1180-1190, 1991.

[34] Feldmann, H.F., Simons, W. H., Gallagher, J. J., and Bienstock, D. Kinetics of recovering sulfur from the spent seed in a magnetohydrodynamic (MHD) power plant. *Environmental Science*

[35] Sheth, A. C., and Johnson, T. R. Evaluation of available MHD seed-regeneration processes on the basis of energy considerations. Technical Report No. ANL/MHD-78-4 TRN: 79-007777,

[36] Rudins, G. U.S and USSR electrode materials development. Technical Report No. R-1656-ARPA, 6L10 Technology Assessment Office, Rand Corporation, Santa Monica, CA, U.S, 1974.

[37] Kirillin, V. A. and Sheyndlin, A. E. MHD energy conversion: Physiotechnical problems. American Institute of Aeronautics and Astronautics, U.S., 1986. https://doi.org/10.2514/4.865756

[38] Adams, R.C. and Robinson, E. Electrode processes in MHD generators. In Proceedings of the IEEE, volume 56(9), pages 1519-1535, 1968. doi: 10.1109/PROC.1968.6640

[39] Fridman, A. *Plasma Chemistry*. Cambridge University Press, New York, 1st edition, 2008.

[40] Gross, J. *Mass Spectrometry.* Springer-Verlag, Berlin Heidelberg, 2nd edition, 2011. DOI 10.1007/978-3-642-10711-5_2

[41] Kerrebrock, J. L. and M. A. Hoffman, M. A. Non-equilibrium ionization due to electron heating. *AIAA Journal*, 2 (6): 1072-1086, 1964.

[42] Velikhov, E.P. and Dykne, A. M. Plasma turbulence due to the ionization instability in a strong magnetic field. In *Sixth International Conference on Ionization Phenomena in Gases***,** pages 511-512, 1963.

[43] Daniel V.W. Performance analysis of the 1A4 generator tests at the CDIF. In Proceedings of the 32nd SEAM, Session 3 Pittsburgh, USA, 1994.

[44] Rohatgi, V. K. and Venkatramani, N. Recent advances in open cycle MHD power generation. Sadhana, 7 (1): 1-72, 1984.

[45] Ozawa, Y. and Kayukawa, N. MHD electrical power generation. In Seventh International Conerence, volume 2, page 516, MIT, Cambridge, USA, 1980.

[46] Petrick, M. and Shumyatsky, B. Ya. Open Cycle Magnetohydrodynamic Electrical Power Generation. Argonne National Laboratory, USA, 1st edition, 1978.

[47] General, C. Magnetohydrodynamics: A promising technology for efficienctly generating electricity from coal. Technical Report No. EMD-80-14, Washington D.C., 1980.

[48] Nishihara, M., William, R. J., Lempert, W. R., Adamovich, I.V., and Gogineni, S. Low-temperature M=3 flow deceleration by Lorentz force. Physics of Fluids, **18**: 086101-1-086101-11, 2006.