Performance Prediction of Proposed Indian MHD Retrofit Channel

A. Chandra and B. S. Bhadoria

Abstract—A mathematical model for the channel analysis of MHD generators based on nonlinear fluid dynamics and Maxwell's equations has been presented. The fluid properties of the seeded combustion products of coal burnt with oxygen enriched/preheated air, needed for the present analysis, have been obtained by using a computer program based on the principle of minimization of Gibbs's free energy (NASA-SP-273). This has been used to study the variation of different flow parameters inside the MHD channel. Thus, the power generated by the Indian MHD retrofit channel (having segmented geometry) has been estimated under different operating conditions. The limitation imposed due to electrical stress on the insulating walls and due to slagging have also been considered for limitation of power output from the channel.

I. INTRODUCTION

An alternative methodology that is gaining momentum nowadays in several countries is the concept of retrofit. In India a coal-fired MHD retrofit plant is being set up at Ennore Thermal power station, Madras, Tamilnadu, and is referred to as Ennore plant [1]. The Ennore thermal power station has a 60 MW<sub>e</sub> capacity burning sulfur-free coal (Neyveli Lignite) found in Bihar and Andhra Pradesh. The retrofitting is expected to increase overall efficiency of the plant beside providing useful experimental data.

In the present communication we have optimized power output with respect to electrode arrangements, loading and input gas parameters (pressure and temperature) of the channel. The electrical stresses developed in the insulating walls and leakage through slag limit the power output from each pair of electrodes this effect has also been considered while predicting the power output from the channel. The output from the channel is modest and hence no effort is made to take up the economic viability of the retrofit systems. For making economic viable system channel with much larger power output (e.g., > 200 MW<sub>e</sub>) are needed.

II. ANALYSIS

The plant uses the combustion products of Neyveli Lignite coal as a working fluid, which is characterized by high ash contents. The analysis has been carried out in two stages (i) calculation of combustion gas properties and (ii) solution of MHD flow equations to get the power output from the channel using the gas properties.

The chemical composition of the coal, oxidant, seeding used in the present analysis are as:

<table>
<thead>
<tr>
<th>Composition of Coal</th>
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<tbody>
<tr>
<td>Proximate Analysis</td>
</tr>
<tr>
<td>(percent)</td>
</tr>
<tr>
<td>Moisture = 2.00</td>
</tr>
<tr>
<td>Ash = 47.0</td>
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<tr>
<td>Volatile Matter = 0.00</td>
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<tr>
<td>Fixed Carbon = 51.90</td>
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Chemical formula without ash:

C<sub>4.156H<sub>2.18N<sub>0.029S<sub>0.00031O<sub>0.0325</sub>

Composition of the oxidant is pure air (i.e., N<sub>2</sub>/O<sub>2</sub> = 3.76) and seeding is one percent by weight of potassium (K).

A. Combustion Gas Properties

In order to determine the detailed combustion gas properties, it is necessary to calculate the composition of the coal combustion products (burnt with preheated air/oxygen) which is a complicated task due to the simultaneous presence of ash, liquid and solid particles within the gas combustion products. The composition is determined by using NASA-SP-273 computer code which has been modified for microcomputers (PC-XT, Fortran-77) language [2] at operating parameters of pressure and temperature. Based on the composition of the fuel system, the various thermodynamic properties like density, enthalpy, entropy, molecular weight and sonic velocity of the combustion products have been calculated.

The combustion gases have been made electrically conducting by introducing potassium salts. The above computer code is further developed to calculate necessary electrical properties (viz., electron density, mobility, electron-neutral particle collision frequency, electrical conductivity, and Hall parameter) and transport properties (i.e., thermal conductivity and viscosity) [3]. Based on these values simple polynomials, power law relations have been derived for the range of operating parameters corresponding to the proposed channel (Appendix I).
The calculations show that the most favorable condition is to keep stoichiometric parameter = 0.9 at which adiabatic temperatures of combustion products ranges from 2760 K to 3250 K as the oxygen contents of air is increased from 23% to 60% (rest being nitrogen and other gases found in atmosphere air) in the pressure range (1-5 atmospheric). With low oxygen contents (23, and 40%) in oxidant air the temperature of the system can be increased by preheating the oxidant up to 1500 K. Thus the flame temperature can be obtained in the range of (2950-3150 K). The electrical conductivity for the range of temperatures (2300-2600 K) and pressure (3.1-1.05 atm.) used in calculation varies from (0.44-25.2) fT^-m^-1. These values are sufficient to have useful interaction for power extraction.

### B. MHD Fluid Equations

The MHD process for generating power is inherently three dimensional. However, the quasi-one-dimensional approximations permit the reduction of three-dimensional MHD equations to a simpler system of first order ordinary differential equations for the ease of numerical solutions [4], [5] without sacrificing much accuracy. Neglecting the transverse variations compared to axial variations in flow direction. In order to simplify the discussion of flow in terms of mass, momentum and energy conservation equations for quasi-one-dimensional flow equation may be rearranged and combined in vector notation to form a single vector equation. The vector functions \( U(x, t) \), \( F(U) \), \( H(U, x) \), \( S(U, x, t) \), and \( D(U, x, t) \) are defined as:

\[
U(x, t) = \begin{bmatrix} \rho \\ m \\ \varepsilon \end{bmatrix} \quad (1)
\]

\[
\overline{H}(U) = \begin{bmatrix} \frac{m^2}{\rho} + P \\ (\varepsilon + P)m/\rho \end{bmatrix} \quad (2)
\]

\[
\mathcal{S}(U, x, t) = \begin{bmatrix} 0 \\ (J \times B)_x \\ (J \cdot E)_x \end{bmatrix} \quad (3)
\]

\[
\mathcal{D}(U, x, t) = \begin{bmatrix} 0 \\ 4\rho_0/\rho \frac{D_H}{4q_0/\rho} \end{bmatrix} \quad (4)
\]

where \( p \) is the density of mass flow; \( m \) is the mass flow density \((m = \rho u)\) and the total energy density \( \varepsilon = p\varepsilon + u^2/2 \) and \( u \) is the velocity in \( x \) direction; \( \varepsilon \) is the internal energy; \( A \) is cross section area; \( I \) is the current density; \( J \) is the velocity in \( x \) direction; and \( E \) is the electric field. \( Ft \) and \( QT \) are given in terms of the wall shear stress and heat flux respectively.

\[
F_t = AT \frac{dD_H}{dx} \quad (5)
\]

\[
QT = 4q_0/\rho \frac{D_H}{4q_0/\rho} \quad (6)
\]

where \( D_H \) is the hydraulic diameter of the duct and \( T_W \) and \( q_0 \) are functions of the flow variables, \( u \) and \( \varepsilon \) and are given in Appendix II. The equation of states are formally obtained in the form of

\[
P = P(p, \varepsilon) \quad \text{and} \quad T = T(p, \varepsilon) \quad (8)
\]

where

\[
\varepsilon = (e, m^2/2p) (u/p)
\]

Equations (1)-(5) can be combined to form one single vector equation representing fluid state at any time \( t \) and position

\[
\frac{dU}{dx} = -\frac{\partial F(U)}{\partial x} + \mathcal{C}(U, x, t) \quad (9)
\]

or

\[
\frac{dU(x, t)}{dx} = -\frac{\partial F(U)}{\partial x} + \mathcal{C}(U, x, t) \quad (10)
\]

where undifferentiated are given by

\[
\mathcal{C}(U, x, t) = -\mathcal{H}(U, x) - \mathcal{S}(U, x, t) - D(U, x, t)
\]

Thus (10) defines the fluid state \( U \) in terms of vector \( F \) describing the mass, momentum and energy fluxes of fluid, \( H \) contains the area variation effect, the vector \( S \) illustrates the Lorentz forces, power and other losses due to voltage drop near electrodes while the vector \( D \) contains the losses due to wall shear stress (depends upon the smoothness of the wall) and heat fluxes which include the convective and radiative losses.

### III. MODEL OF MHD GENERATOR

Although steady state model could be enough to solve magnetohydrodynamic and other equations representing the flow conditions inside the MHD channel. But, due to non-linearity arises from, the transition response of the generator to changes in load conditions, start and shut down, coupled unsteady interactions of the generator to faults such as electrode breakdown or sudden deposition of a short along the insulator wall, we are using unsteady model.

The above set of equations has been solved as have followed by Oliver [6] using finite difference technique incorporating the modifications due to Mac Cormack [7]. In this method the nonlinear partial differential operator in (9) is replaced by a non-linear finite difference operator. The state \( U \) at time \( t \) and location \( x \) is then represented as \( U(x, t) = U^n \). The finite difference form of (10) is then \( U^{n+1} = LU^n \). Where \( L \) is an appropriate finite difference operator for (10). An operator \( L \) with attractive accuracy and computational economy is the two step operator in which \( L \) is formed by first step involves the evaluation of an intermediate step \( U^n_* \) where

\[
U^n_* = U^n + \Delta t \left[ -\frac{S}{\partial x} F(U^n) + \mathcal{D}(U^n, x, t) \right]
\]

The second and final state is then determined by:

\[
U^{n+1} = \frac{1}{2} \left[ U^n_* + U^n + \frac{\Delta t}{\partial x} (F(U^n)) \right]
\]

where
where \(i\) and \(n\) are the space and time integers given by
\[
x = iS_x, \quad t = nSt.
\]

Thus, if an initial fluid state \(U_f\) is given, the subsequent fluid states may be computed forward in time through the full subsonic, transonic and supersonic ranges. The numerical stability of the relations (12) and (13) at each point where the fluid state is evaluated, is ensured by satisfying the Courant condition that is
\[
\frac{\delta t}{\delta x} \leq \frac{\delta x}{\bar{U} + C}
\]
where, \(C = \) Courant number and \(\bar{U} = \) local fluid velocity.

A computer program has been developed incorporating the above set of nonlinear coupled differential equations along with the relations given in Appendix I to evaluate the electrical characteristics of the MHD channel at given parameters of loading, magnetic field, and different electric configurations of channel i.e., Faraday geometry.

IV. PERFORMANCE CHARACTERISTICS OF INDIAN MHD CHANNEL

The proposed MHD retrofit channel contains copper electrodes and magnesium oxide (MgO)/alumina (Al2O3) as insulating walls. The copper electrodes have been filled with Zirconia oxide (ZrO2) blocks to keep the surface temperature high in order to reduce the heat losses from the electrodes. A superconducting magnet (field strength \(> 6 \text{T}\)) is proposed to be coupled with the channel. The magnetic field is supposed to have maintained uniform throughout along the length of 7.0 m with 140 electrodes pairs. Some of the useful parameters and relevant data are given in Appendix II.

Gas dynamics and electrodynamics characteristics have been studied for the segmented mode of electrode configuration maintaining constant velocity of the gas throughout the channel. The values of load factor are varied from 0.85 to 0.7 because of electrical stress developed in insulating walls as explained in the following section.

V. GAS DYNAMICS OF THE CHANNEL

Fig. 1 shows the final variation the temperature and pressure of the seeded combustion products along the length of the channel for two different loadings (0.7 and 0.85). The outlet duct pressure and temperature can be selected by choosing proper load. There is higher temperature and pressure drop for lower loading factors which indicates higher power output from the channel. The mach number is found to increase with the increase of channel length for both loadings for a constant velocity channel and is found subsonic \((M < 1)\).

The variation of height (or width) and cross section area along the length of the channel is illustrated in Fig. 2 for the loadings of 0.7 and 0.85. The cross section area and hence the height of the channel depend upon the loadings and are found to increase with the decrease of load along the length of channel.

The gas dynamics characteristics are useful for the overall dimension of the channel once the power output and loading are decided as per requirements.

VI. ELECTRODYNAMICS OF THE CHANNEL

The currents and voltages developed across the direction of flow for respective number of electrodes inside the channel have been plotted for the two loadings of 0.7 and 0.85 in Fig. 3. The voltage developed is found to increase along the length of channel because of larger distance between the electrodes in the channel for both loadings. However, the current collected by each electrodes decreases along the direction of flow as the length increases. It happens despite the fact that the collecting electrodes areas increases along the outlet of the channel for both loadings.
The voltage current characteristics of the channel for two loadings are shown in Fig. 4, while the Hall voltage and Hall parameters for the channel along the direction of flow are shown in Fig. 5.

Electrical stresses and dielectric strength of the insulated materials (e.g., alumina and magnesia) used for making duct wall play important role in the design and power output from the channel. The energy stored in insulating dielectric walls across the flow decide the maximum faraday current density \(J_y\) and hence power delivered by each electrode to the load (and hence the load factor). Similarly along the direction of flow the hall current \(J_x\) and the Hall voltage \(E_x\) is determined with the help of dielectric strength of insulator between the adjacent electrodes and energy stored by them for each electrode. Some useful data in the analysis is given in Appendix II.

Fig. 6 shows the power delivered by each pair of electrodes along the channel length for different loading. The internal resistance of the channel is effected by the loading because the local gas temperature depends on the power taken out by each electrode pair to the load. The maximum power by each electrode pair for different thickness of insulating wall (MgO) is also shown. One can see from the figure that the thickness of the wall (across the direction of the flow) plays an important role. With the decrease of the wall thickness the maximum sustainable power by the wall between the pairs of electrode increases because of high sustainable potential of the walls. Similar behavior is also obtained for alumina (Al2O3) insulating walls. For getting the desired power from the electrode pairs the thickness and the material of the wall can be chosen. For a given thermal input to the channel of 270 MW\(_{th}\) the electrical output varies from 8.0 MW\(_e\) to 16.0 MW\(_e\) the wall thickness of alumina varies from 0.068 to 0.039 mm and for magnesia varies from 1.34 to 0.78 mm. The corresponding load factor for these power levels are 0.85 and 0.7, respectively. Higher power can be obtained from the channel for the load factor varying between 0.7 to 0.5. However the sustainable limits of the walls should far exceed. Lower thickness may have practical problems of fabrication. At these level \((K = 0.7)\) the following are the parameters for magnesia: \(J_y = 0.55 \, \text{A/m}^2, E_x = 0.65 \, \text{kV/m}, E_y = 2.8 \, \text{kV/m}\). These values are well under the limit [11].

The above results are valid if no slag deposition is assumed on the electrodes. The slag conductivity is calculated for Indian slag having 10% potassium [12]. The performance is affected drastically by taking the effect of the current leakage through the slag deposited between the consecutive electrode along the direction of flow. Table I shows that at higher magnetic field the affect is most pronounced because of large Hall field. It may lead to the breakdown between the downstream electrodes of the channel and thereby reducing the effective length for the power generation. At lower magnetic field, however, leakage is less pronounced and utilization length of channel increases. Thus power up to 6.0 MW can be obtained under slagging condition for a channel of 7.0 M long at 4.0 T magnetic field. In order to get higher power output the slag should be removed before entering the channel and by working at higher wall temperatures (> 1700 K).

VII. CONCLUSION

One may conclude that the total power output from the channel is critically dependent on loading conditions. For getting the optimum power (≈ 16 MW\(_e\)) the loading should be around 0.7 from a channel of 7.0 m length. Power output reduces drastically under slagging conditions at higher magnetic fields.
the present working range of pressure (P), temperature (T), Mobility (m) and Thermal conductivity (κ) used for combustion products for MHD channel operating parameters: 

\[ T_{in} = 2600 \text{ K} \]

\[ P_{in} = 3.01 \text{ atm} \]

\[ \text{Tin} \] and \( \text{P}_{in} \) are the temperature and pressure of the seeded combustion products at the duct inlet.

\[ a = \text{constant wall (insulator) temperature} \]

The values of \( K \) and \( a \) can be calculated for different wall (insulator) temperature \( T \) (1300-1600 K) and partial pressure of oxygen (PPO)\(^{[10]}\).

\[
K(\text{Al}_{2}O_{3}) = 30.99 + 0.09441XT - 7.444 \times 10^{-2}XT^2 \\
+ 1.849 \times 10^{-8}XT^3
\]

\[
K(\text{MgO}) = 102.9 - 1.833 \times 10^{-2}XT - 0.8579XT^2 \\
+ 2.28 \times 10^{-4}XT^3
\]

\[
\text{cr}(\text{Al}_{2}O_{3}) = 5.445 \times 10^{-10} \exp(0.002607T) \\
- 1.544 \times 10^{-8}
\]

\[
\text{cr}(\text{MgO}) = 8.988 \times 10^{-12} \exp(0.020T) - 1.427 \times 10^{-6}
\]

\[
\text{cr}(\text{Slag}) = 1.04 + 6.663 \times 10^{-4}XT + 2.722 \times 10^{-9}XT^2 \\
+ 2.28 \times 10^{-6}X\text{PPO} + 1.089 \times 10^{-10}X\text{PPO}^2
\]

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**REFERENCES**

A. Chandra received the M.Sc., M.Phil., and Ph.D. degrees from Aligarh Muslim University, Aligarh, India. Thereafter, he joined the Physics Department at the Indian Institute of Technology, (IIT) Delhi, India. Since then he has set up experiments related with seeded combustion flame, electrode, and wall plasma interactions and has made extensive studies in these areas. In addition to these fields at present, he is engaged in channel design for retrofit MHD plants. He was with the Electrical Eng. Dept. of the University of Sydney, Australia on a Price Fellowship during 1980-1981. Since then, he has been working as an Assistant Professor at the Centre for Energy Studies, IIT. He is providing consultancy services to Bharat Heavy Electricals Ltd. at Tiruchirapalli for MHD channel design.

He has published and presented more than 60 papers on the above areas. Dr. Chandra was a member of the National Technical Committee for 10th International Conference on MHD Power Generation.

B. S. Bhadoria received the M.Sc. degree from Jiwaji University, Gwalior, India, in 1988. Currently, he is working with Dr. A. Chandra towards the Ph.D. degree on the topic "Performance of Retrofit MHD Channel" at the Centre for Energy Studies, Indian Institute of Technology, Delhi, India. He joined as a Research Assistant in 1988 on the channel for MHD retrofit on the existing thermal plant project under Dr. A. Chandra.