Investigation Of MHD Power Fluctuations

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Session Name: Generators, Part B

SEAM: 23 (1985)

SEAM EDX URL: https://edx.netl.doe.gov/dataset/seam-23

EDX Paper ID: 1110

INVESTIGATION OF MHD POWER FLUCTUATIONS

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ABSTRACT:

Electrical power output from an MHD generator depends critically on the combustion plasma parameters. Fluctuations in plasma pressure, temperature and velocity result in the fluctuations of MHD power output. From the consideration of grid stability and generator performance, it is necessary to control the power fluctuations from MHD generators. The sources of MHD power fluctuations can be identified as pressure and temperature fluctuations in feed lines of oxidiser, fuel, and seed to MHD combustor, and fluctuations in combustor proper. The operating parameters and the channel inlet and outlet conditions determine the actual contribution of these source fluctuations to MHD power fluctuations. In an earlier work of the author[1], the dependence of MHD power fluctuations on combustor temperature, pressure and mass flow fluctuations were considered. In the present work, MHD power fluctuations are investigated in a more detailed way taking into account the fluctuations in feed line, combustor proper and channel operating parameters. By choosing proper operating conditions, it may be possible to suppress the effect of feed line and combustor fluctuations. It is shown how by proper selection of operating parameters it is possible to contain the MHD power fluctuations within bounds for sonic condition at the channel inlet.

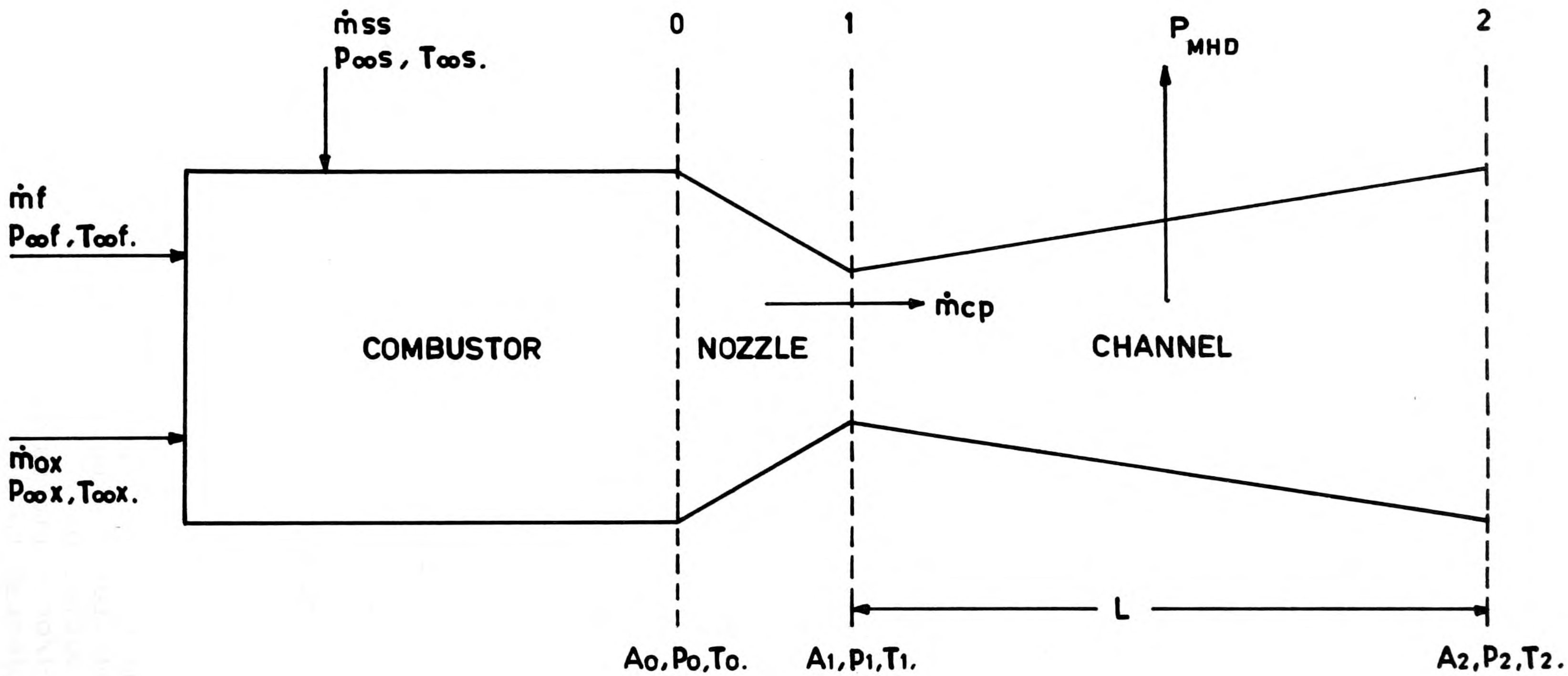
INTRODUCTION:

In MHD power plant operation, it is essential to maintain the fluctuations in MHD power output at a minimum level if not completely eliminated. MHD power fluctuations could result due to various factors like non-uniform combustion, plasma instability, magneto acoustic instabilities, fluctuations in fuel, oxidiser and seed lines etc. In an earlier work of the author[1], dependence of MHD power fluctuations on combustion plasma parameters were investigated. Fluctuations in fuel, oxidiser and seed line and channel outlet conditions were not taken into account.

In the present paper, MHD power fluctuations have been investigated in a more detailed way taking into account the fluctuations in feed line, combustor proper and channel operating parameters. Considering the MHD power output from the channel, a relationship has been derived relating MHD power fluctuations to the above mentioned source fluctuations. The results are analysed and nature of fluctuations are investigated.

ANALYSIS:

Schematic of MHD combustor nozzle and channel system is shown in Fig. 1. Combustor receives fuel, oxidiser, and seed through respective feed lines. The upstream conditions of feed line are indicated by subscript ∞. The conditions in combustion chamber are indicated by subscript 0, and channel inlet and outlet by 1 and 2 respectively. The fuel with oxidiser (preheated and/or enriched with oxygen) is burnt in the combustion chamber and seed is injected to obtain the combustion plasma. The combustion plasma after accelerating through the nozzle interacts with magnetic field in the channel and delivers MHD power P_{MHD}.



$$\dot{m}_{cp} = \dot{m}_{ox} + \dot{m}_f + \dot{m}_{ss}$$

FIG: 1 SCHEMATIC OF MHD COMBUSTOR NOZZLE CHANNEL SYSTEM

For a given MHD system, the upstream pressure and temperature in feed line, and combustion chamber pressure and temperature can be considered as independent variables. The channel inlet and outlet conditions can be expressed in terms of these variables and operating parameters. The operating parameters include magnetic field, channel loading factor $K = E/UB$; Mach number at the channel inlet; excess oxidizer coefficient in combustor, percentage of seed solution. The fluctuations in MHD power - dP_{MHD}/P_{MHD} can be expressed in terms of fluctuations of upstream conditions in feed line - dp_∞/p_∞ and dT_∞/T_∞ , and fluctuations in combustor - dp_o/p_o , dT_o/T_o along with the dependence on independent variables and operating parameters.

MHD POWER EQUATION:

Considering one dimensional MHD flow, the power output from an MHD generator may be expressed as[2] :

$$P_{MHD} = \int_0^L \sigma u^2 B^2 K(1-K) A \cdot dx$$
$$= [A_1 L K(1-K) B^2][\sigma_1 u_1^2][\beta] \quad \cdots (1)$$

$$\text{where, } \beta = \int_0^L (\sigma/\sigma_1)(u/u_1)^2 (A/A_1) \cdot dx/L \quad \cdots (2)$$

Evaluation of β requires the knowledge of the variation of σ, u, A along the channel length. For general case, it is difficult to get an analytical solution for the variation of σ and u . However, the trend and parametric dependence can be obtained by considering a simplified approach. In this simplified approach, the channel can be treated as (a) constant velocity channel, (b) constant Mach number channel, or (c) constant temperature channel. Many of the practical channels have been designed as constant velocity channels. Hence, only constant velocity channel is considered here.

Electrical conductivity σ is a strong function of temperature. For combustion plasma of interest, following Ref. (2), it can be represented as :

$$\sigma = \sigma_0 (T)^{n_1} \cdot (p)^{-1/2} \quad \cdots (3)$$

For MHD combustion plasma, the temperature index n_1 varies from 10 to 14.

With the above relation for σ and for constant magnetic field B and load factor K ; temperature, pressure and area variation along the channel may be obtained as below[2] :

$$(T/T_1) = (1 + \alpha x/x^*)^{-1/\alpha} \quad \cdots (4)$$

$$(p/p_1) = (T/T_1)^{r/[K(r-1)]} \quad \cdots (5)$$

$$(A/A_1) = (T/T_1)^{[1 - r/K(r-1)]} \quad \cdots (6)$$

Where:

$$\left.\begin{aligned} x^* &= r p_1 / [(r-1) K(1-K) \sigma_1 U_1 B^2] \\ \alpha &= [n_1 - (\tfrac{r}{r-1}) \cdot \tfrac{3}{2} K] \\ K &= E/U_1 B \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots (7)$$

For constant velocity channel $U/U_1 = 1$.

Substituting for (σ/σ_1) and (A/A_1) from equations (6) to (7) in equation (2) and integrating, β can be evaluated as :

$$\beta = \left(\frac{x^*}{L}\right)\left[1 - \left(1 + \frac{\alpha L}{x^*}\right)^{-1/\alpha}\right] \quad \ldots\ldots\ldots\ldots (8)$$

It may be noted that $(1+\alpha L/x^*)^{-1/\alpha}$ in the above equation represents (T_2/T_1) which is less than 1 for power generation mode. Hence, for MHD power generation β is always positive.

With equation (8) and expressing the combustion product mass flow rate as $\dot{m}_{cp} = \rho_1 U_1 A_1$, equation (1) may be rewritten as :

$$P_{MHD} = \left[\left(\frac{r}{r-1}\right) \dot{m}_{cp} R T_0\right]\left[\frac{T_1}{T_0}\right]\left[1 - \left(1 + \frac{\alpha L}{x^*}\right)^{-1/\alpha}\right] \quad \ldots\ldots\ldots (9)$$

For isentropic flow through the nozzle, temperature and pressure ratios can be represented by :

$$[T_1/T_0] = [1/X] \quad \ldots\ldots\ldots\ldots (10)$$

$$[p_1/p_0] = [1/X^{r/r-1}] \quad \ldots\ldots\ldots\ldots (11)$$

Where: $$X = 1 + \frac{r-1}{2} M_1^2 \quad \ldots\ldots\ldots\ldots (12)$$

Using the above equations, MHD power output from a constant velocity channel connected to an isentropic nozzle can be expressed as :

$$P_{MHD} = \left[\left(\frac{rR}{r-1}\right)\right] \cdot \left[\dot{m}_{cp} \cdot T_0 \cdot \frac{1}{X}\right][F] \quad \ldots\ldots\ldots (13)$$

Where: $$F = \left[1 - \left(1 + \frac{\alpha L}{x^*}\right)^{-1/\alpha}\right] \quad \ldots\ldots\ldots (14)$$

MHD POWER FLUCTUATIONS:

Using equation (13), MHD power fluctuation can be expressed as :

$$\frac{dP_{MHD}}{P_{MHD}} = \frac{d\dot{m}_{cp}}{\dot{m}_{cp}} + \frac{dT_o}{T_o} - \frac{dx}{x} + \frac{dF}{F} \quad \ldots \quad \ldots \quad \ldots \quad (15)$$

Combustion product mass flow rate $\dot{m}_{cp}$ is given by :

$$\dot{m}_{cp} = \dot{m}_{ox} + \dot{m}_f + \dot{m}_{ss} \quad \ldots \quad \ldots \quad \ldots \quad (16)$$

Considering the flow through individual feed lines, $\dot{m}_{ox}$, $\dot{m}_f$ and $\dot{m}_{ss}$ can be expressed in the following form :

$$\dot{m}_{ox} \sim \left[p_{\infty x} (p_{\infty x} - p_o) / T_{\infty x} \right]^{1/2} \quad \ldots \quad \ldots \quad \ldots \quad (17)$$

$$\dot{m}_{cp} \sim \left[p_{\infty f} (p_{\infty f} - p_o) / T_{\infty f} \right]^{1/2} \quad \ldots \quad \ldots \quad \ldots \quad (18)$$

$$\dot{m}_{ss} \sim \left[p_{\infty s} - p_o \right]^{1/2} \quad \ldots \quad \ldots \quad \ldots \quad (19)$$

For isentropic flow through nozzle dx/x is given by :

$$\frac{dx}{x} = \frac{M_1^2 (\gamma - 1)}{(1 - M_1^2)} \left[\frac{d\dot{m}_{cp}}{\dot{m}_{cp}} + \frac{1}{2}\frac{dT_o}{T_o} - \frac{dp_o}{p_o} \right] \quad \ldots \quad \ldots \quad \ldots \quad (20)$$

Further, the expression for dF/F is obtained as :

$$\frac{dF}{F} = (b_1) \left[2.5 \frac{dp_o}{p_o} - \frac{d\dot{m}_{cp}}{\dot{m}_{cp}} - (n_1 + 1) \frac{dT_o}{T_o} + n_4 \frac{dx}{x} \right] \quad \ldots \quad \ldots \quad (21)$$

Where:

$$b_1 = - \left[(L/x^*) (1 + \alpha L/x^*)^{-(1+\alpha)/\alpha} \right] \quad \ldots \quad \ldots \quad (22)$$

$$n_4 = \left[(n_1 + 1) - 2.5 (\gamma / n_1) \right] \quad \ldots \quad \ldots \quad \ldots \quad (23)$$

Using equations (17) to (23) in equation (15) and rearranging the terms, MHD power fluctuation equation in the final form is given by :

$$\frac{dP_{MHD}}{P_{MHD}} = F_0\left(\frac{dS}{S}\right) + F_1\left(\frac{dT_0}{T_0}\right) + F_2\left(\frac{dp_0}{p_0}\right) \quad .. \quad .. \quad ..(24)$$

where:

dS/S = Feed line fluctuations

$$= \left[a_1\, dp_{\infty x}/p_{\infty x} + a_2\, dp_{\infty f}/p_{\infty f} + a_3\, dp_{\infty s}/p_{\infty s} - a_4\, dT_{\infty x}/T_{\infty x} - a_5\, dT_{\infty f}/T_{\infty f}\right]$$

$$F_0 = [(1-b_1) + n_6]$$

$$F_1 = [1 - b_1(1+n_1) + 0.5 n_6]$$

$$F_2 = \{(2.5 b_1 - n_6) - [(1-b_1)+n_6]\, a_6\}$$

$$a_1 = a_4\,[1 + p_{\infty x}/(p_{\infty x} - p_0)]$$

$$a_2 = a_5\,[1 + p_{\infty f}/(p_{\infty f} - p_0)]$$

$$a_3 = 0.5\,[\dot{m}_{ss}/\dot{m}_{cp}]\,[p_{\infty s}/(p_{\infty s} - p_0)]$$

$$a_4 = 0.5\,[\dot{m}_{ox}/\dot{m}_{cp}]$$

$$a_5 = 0.5\,[\dot{m}_f/\dot{m}_{cp}]$$

$$a_6 = a_4\,(p_0/p_{\infty x} - p_0) + a_5\,(p_0/p_{\infty f} - p_0) + a_3\,(p_0/p_{\infty s})$$

$$n_6 = [(b_1 n_4 - 1)\, M_1^2\, (\gamma - 1)/(1 - M_1^2)]$$

$$n_4 = [(n_1 + 1) - 2.5\,\gamma/(\gamma - 1)]$$

$$b_1 = -\left[(L/x^*)\left(1 + \frac{\alpha L}{x^*}\right)^{-\frac{(1+\alpha)}{\alpha}}\right] \Big/ \left[1 - \left(1 + \frac{\alpha L}{x^*}\right)^{-1/\alpha}\right]$$

$$\alpha = [n_1 - (\gamma/\gamma - 1)\cdot \tfrac{3}{2} K]$$

$$x^* = \left[\left(\frac{\gamma}{\gamma - 1}\right)\frac{1}{K(1-K)}\cdot\frac{A_1}{B^2 C_0 R}\right]\left[\frac{p_0^{2.5}}{\dot{m}_{cp}\cdot T_0^{n_1+1}}\right]\left[\left(1 + \frac{\gamma - 1}{2} M_1^2\right)^{n_4}\right]$$

Equation (24) relates the MHD power fluctuation to feed line fluctuations : dS/S ; combustor temperature and pressure : dT_o/T_o , and dP_o/P_o fluctuations. The coefficients F_o , F_1 and F_2 depend on the operating parameters.

OPERATION NEAR SONIC VELOCITY:

Each of the functions F_o , F_1 and F_2 contain the term :

$$n_6 = (b_1 n_4 - 1)(\gamma - 1) M_1^2/(1 - M_1^2).$$

As $M_1 \rightarrow 1$, $n_6 \rightarrow \infty$. Hence the MHD power fluctuations can grow very fast as $M_1 \rightarrow 1$. However, it may be possible to make n_6 finite by choosing operating conditions so that $(b_1 n_4 - 1) \rightarrow 0$ as $M_1 \rightarrow 1$. For $(b_1 n_4 - 1)$ to be zero, n_4 should be negative as b_1 is always negative. The condition of n_4 negative requires the following inequality to be satisfied :

$$n_1 < \left[2.5\left(\frac{\gamma}{\gamma - 1}\right) - 1 \right] \quad \cdots \quad (25)$$

For combustion plasma γ varies between 1.10 to 1.25 and n_1 from 10 to 14. Fig. 2 shows the plot of γ vs. $n_1^* = [2.5 (\gamma/(\gamma-1)) - 1]$ In this figure, the area of MHD operation is also shown. It is clear that in the region of MHD operation, it is possible to limit the fluctuations within bounds for operation near sonic velocity.

OPTIMUM SELECTION OF PARAMETERS:

Evaluation of magnitude and phase of pressure and temperature fluctuations in combustor and feed line is difficult. In MHD application, the low frequency instabilities are predominant[1]. These generally result due to instabilities in feed line. It may be impossible to eliminate completely the feed line and combustor fluctuations; however, by choosing proper operating parameters it may be possible to suppress their effect on the MHD power fluctuations. From equation (24), it is clear that the effect of feed line fluctuations, combustor temperature and pressure fluctuations can be suppressed if for certain operating conditions F_o , F_1 and F_2 can be made zero respectively. The conditions required may be expressed as :

$$b_1 = [1 + n_6] \quad \text{FOR } F_0 \equiv 0 \quad \cdots \quad (26)$$

$$b_1 = [(1 + 0.5 n_6)/(1 + n_1)] \quad \text{FOR } F_1 \equiv 0 \quad \cdots \quad (27)$$

$$b_1 = \left[\frac{a_6 + n_6(1 + a_6)}{(1 + n_1)}\right] \quad \text{FOR } F_2 \equiv 0 \quad \cdots \quad (28)$$

The sign of b_1 is always negative and of a_6 and n_1 always positive. The sign of n_6 can be positive or negative. Equations (26) to (28) can be satisfied only if n_6 is negative. If n_6 is positive or zero, it will not be possible to make F_o , F_1 or $F_2 = 0$.

From these consideration, it is clear that it is useful to operate with $n_6 = 0$ when operating near sonic velocity. For subsonic or supersonic operation, it is useful to choose the operating condition such that at least one of the coefficients F_o , F_1 or F_2 become identically zero.

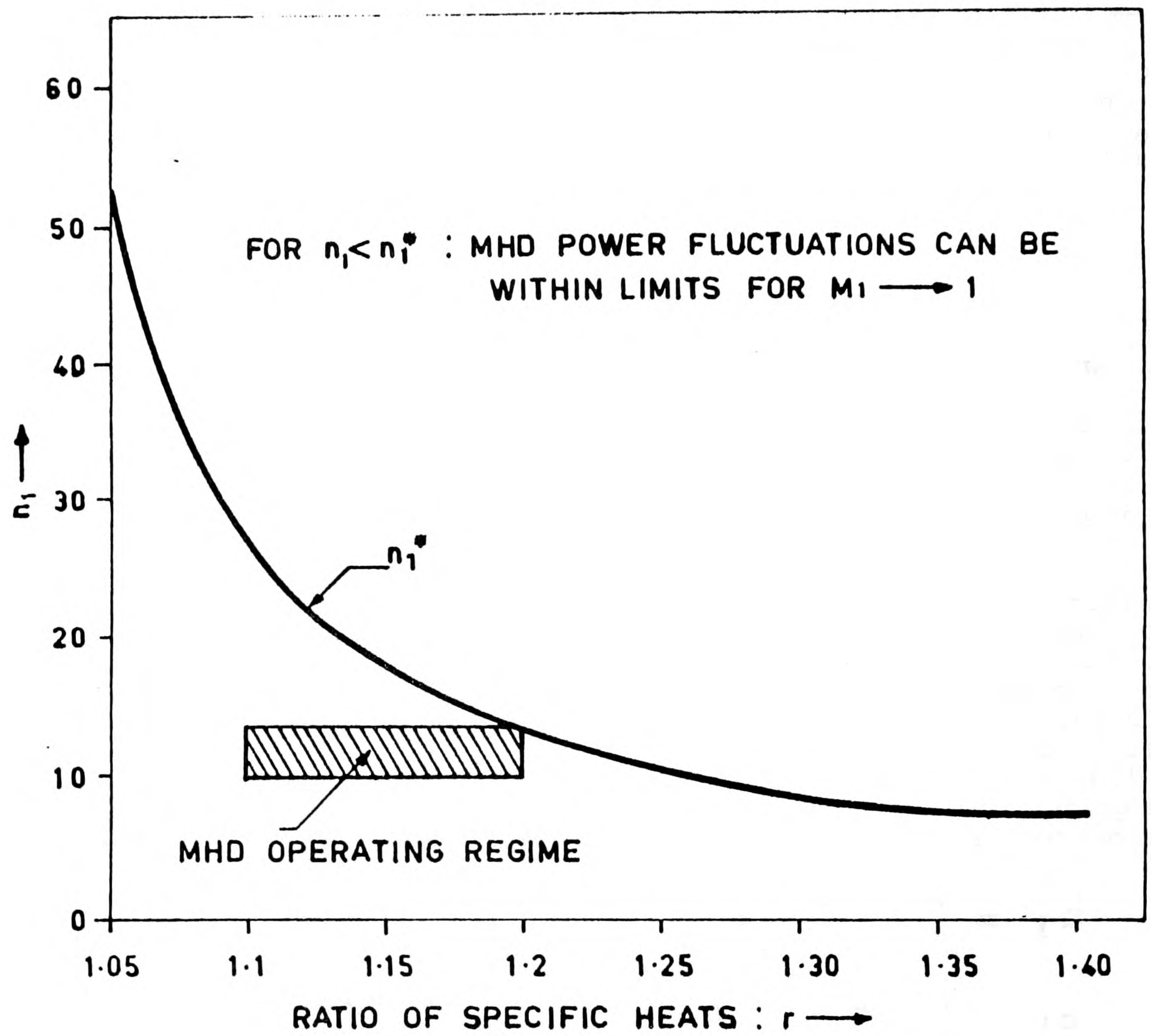


FIG : 2 REGION OF BOUND FLUCTUATION FOR $M_1 \to 1$

INDIAN PILOT PLANT PARAMETERS:

Indian MHD pilot plant has been designed for 5 MW thermal input. For a typical operating conditions, the functions F_o, F_1 and F_2 are evaluated. The values are : $F_o = 4.58$; $F_1 = 16.93$; $F_2 = -7.49$. As can be seen, the F_1 is large and shows the importance of controlling temperature fluctuation.

CONCLUSIONS:

Dependence of MHD power fluctuations on the feed line fluctuation and combustor temperature and pressure fluctuation has been derived. For certain range of operating condition, it may be possible to suppress the effect of feed line and combustor fluctuations. Generally, the combustor temperature fluctuations become very important. The feed line fluctuations also become important due to low frequency oscillations.

ACKNOWLEDGEMENTS:

Thanks are due to colleagues in the MHD Project for many useful discussions. The author is thankful to the management of Bharat Heavy Electricals Limited for giving permission to present this paper. This work was carried out under the project sponsored by the Department of Non-conventional Energy Sources, Government of India.

NOMENCLATURE:

A	:	Cross sectional area
$a_1, a_2, a_3, a_4, a_5, a_6$	:	Functions defined in the text
B	:	Magnetic field
C_o	:	Constant in σ expression Eq.(3)
E	:	Electric field
F, F_o, F_1, F_2	:	Functions defined in the text
K	:	Channel load factor = E/UB
L	:	Length of the channel
M	:	Mach number
$\dot{m}_{cp}$	:	Combustion product mass flow rate
$\dot{m}_{ox}$	:	Oxidizer mass flow rate
$\dot{m}_f$	:	Fuel mass flow rate
$\dot{m}_{ss}$	:	Seed solution mass flow rate
n_1	:	Temperature index of σ
n_1^*	:	Defined in the text
n_4, n_6	:	Defined in the text
P_{MHD}	:	MHD power output

p	:	Pressure
$p_{\infty f}$	:	Fuel line upstream pressure
$p_{\infty s}$	:	Seed line upstream pressure
$p_{\infty x}$	:	Oxidizer line upstream pressure
R	:	Gas constant
$\frac{dS}{S}$	:	Feed line fluctuations defined in the text
T	:	Temperature
$T_{\infty f}$	:	Fuel line upstream temperature
$T_{\infty x}$	:	Oxidizer line upstream temperature
U	:	Velocity
X	:	Defined in the text
x^*	:	Defined in the text
α	:	Defined in the text
β	:	Defined in the text
γ	:	Ratio of specific heats
σ	:	Electrical conductivity

Subscripts:

0	:	In the combustor
1	:	At the entrance to channel
2	:	At the exit of the channel

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