Effects of Presence of Impurities on Non-Equilibrium MHD Power Generation Incorporating Fossil Fuel-Fired Heat Exchanger

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A theoretical analysis has been conducted to gain an insight into the effects brought on the non-equilibrium MHD gas properties and on the performance characteristics of a non-equilibrium MHD generator by the presence of impurities introduced into the potassium-seeded argon working gas from the fossil-fuel-fired heat exchanger adopted for heating the gas. Propane is envisaged as fuel, and as typical operating condition, the working gas is assumed to have a stagnation temperature of 2,000 K, stagnation pressure of 5 atm, Mach number of unity, and seed fraction of \(10^{-3}\). The gas enters a Faraday-type MHD generator with infinitely finely segmented electrodes operating at a loading factor of 0.75 in a magnetic field of 5 T subject to ionization instability. The results of computation reveal that the presence of impurities below certain limits in a range of roughly 10 to 100 ppm at the entrance of the generator (exact limit depending on the operation condition) will not prevent the MHD generator from operating at practically useful levels of power and current densities, and that the power level will not be unduly disturbed by fluctuations in the impurity concentrations if they are below the limits referred to above. The pumping work required for evacuation is found to be less than 1% of the total output power of a dual-cycle plant.

**KEYWORDS:** non-equilibrium MHD power generation, heat sources, fossil fuel-fired heat exchanger, propane, combustion gases, impurity mixing, concentration of impurities, potassium-seeded argon, ionization instability, pumping work

I. INTRODUCTION

The extensive studies performed in the past in non-equilibrium MHD power generation, aimed at deriving higher energy conversion efficiencies and power densities, have contributed significantly to elucidating the complex physical phenomena inherent to non-equilibrium MHD generation, and, particularly, in respect of ionization instability.

A most essential and important problem, however, has remained unsettled, i.e., that of a suitable heat source. The high-temperature gas-cooled reactor (HTGR) was once regarded promising as source of high temperature inert gas adequate for non-equilibrium MHD power generation, but this expectation has been belied with the finding that the current technology is not capable of offering an HTGR that can furnish gas at the temperatures necessary for MHD power generation. An alternate possible heat source is fossil fuel: A fossil-fuel-fired heat exchanger was proposed quite long ago\(^{1}\), followed much later by a preliminary feasibility study by GE, with positive results\(^{2}\). More recently a 5 MWt blowdown experimental facility based on this concept has been constructed at the Eindhoven University of

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Technology, which is expected to begin operating quite soon (3).

The practice in such fired heat exchangers is to let the combustion gas directly heat alumina balls, or other suitable ceramic material, which leaves the possibility of residual combustion gas remaining to some extent in the heat exchanger even after evacuation of the gas. This calls for consideration of possible involvement of undesirable mass transfer (contamination) in addition to the expected heat transfer affecting the inert working gas, particularly, in the initial stage of its heating. The combustion components present large momentum transfer cross sections for collision with electrons and/or large collision energy loss factors, so that even a small immixture of the combustion components can considerably affect the non-equilibrium MHD gas properties, to impair the performance characteristics of the non-equilibrium MHD generator. The theoretical (4)~(7) and experimental (8)~(10) studies so far reported on such effects of impurities have not completely clarified the picture, in that, particularly in respect of the theoretical aspect, only several kinds of impurities at most, have been considered, and chemical reactions have not been taken into account. The present paper covers a study in which both chemical equilibrium reaction and ionization instability are given consideration, through which practical limits are derived for the concentration of impurities present in the heat exchanger, i.e., for the evacuation pressures to be attained prior to the introduction of the inert gas, in order to ensure freedom from appreciable impairment of the initial performance characteristics of the MHD generator. The criteria adopted for determining the limits for sound operation are: (i) whether sufficient non-equilibrium ionization can be realized in the MHD generator; (ii) whether power and current densities will attain practically operable levels; (iii) whether the properties of the gas and the performance characteristics of the MHD generator can be made relatively immune to fluctuations in impurity concentrations in the vicinity of the operating point, (iv) whether the pumping work required for evacuating the combustion gas remaining in the free volume of the heat exchanger can be held within a reasonable range compared with the total output energy generated by a dual cycle plant (MHD + conventional) (11).

II. THEORY

1. Assumptions

In this study, the following assumptions are adopted:

(1) The regenerative heat exchanger has a considerably large heat capacity in reference to the heat transferred to the inert gas, so as to ensure an almost constant stagnation temperature $T_s$.

(2) The first passage of working gas amounting to 1 free volume of the heat exchanger entrains all the impurities remaining in this space: This will give a conservative estimation of the MHD performance characteristics. Condensation and adsorption of the combustion gases on the ceramic surfaces of the heat-exchanger are not considered.

(3) Chemical reactions are always in thermal equilibrium.

(4) Thermal non-equilibrium between electrons and other componts is treated by two-temperature model. The vibrational and rotational energy levels of heavy particles and the excited levels of seed atoms are neglected, as is also the loss due to radiation from seed-atoms.

(5) Ionization instability is taken into account.

(6) A value of 1.67 is taken for the ratio $\gamma$ of specific heats, the inert gas being the major component of the working gas.
(7) A Faraday-type MHD generator with infinitely finely segmented electrodes is used; and there is no Hall current short-circuiting.

One difficulty encountered in carrying out the calculations is the unavailability of certain data concerning the physical properties of impurities, i.e. their momentum transfer cross section, and for some of the impurities, their collision loss factors. While it is true that the major components of the impurities have their data given in literature from theoretical and experimental studies (13) - (15), there are certain exceptions, and for such components, their values have been fairly roughly presumed as listed in Table 1, in order to proceed with the calculations. These values are therefore subject to correction or refinement; they represent the "pessimistic" limits of estimation. The opposite "optimistic" limits are given by letting these presumed values equal zero. The true values should lie somewhere roughly between these two extremes.

2. Basic Equations

Adopting the assumptions set forth above, the basic equations are derived in what follows.

We take up propane \((\text{C}_3\text{H}_8)\) as fuel, which is assumed to be burned with preheated air of 50% relative humidity at room temperature under the condition of equivalence ratio of unity. The resulting fuel-air mixture before introduction of the inert gas is considered to comprise the 18 components of \(\text{CO}_2\), \(\text{CO}\), \(\text{HCO}\), \(\text{H}_2\text{O}\), \(\text{H}\), \(\text{H}_2\), \(\text{O}\), \(\text{O}_2\), \(\text{OH}\), \(\text{NO}\), \(\text{NO}_2\), \(\text{N}\), \(\text{N}_2\), \(\text{NH}\), \(\text{NH}_2\), \(\text{NH}_3\), \(\text{HNO}\) and \(\text{Ar}\), which are taken into account in the chemical equilibrium equations.

(1) MHD Gas Flow

After evacuating the heat exchanger to pressure \(p^*\), potassium-seeded argon gas of seed fraction \(\varepsilon\) is introduced, during which the temperature of the heat exchanger is kept constant. Then, the inert working gas flows out of the heat exchanger into the MHD generator, attaining on the way a Mach number \(M\).

The static temperature \(T_s\), the static pressure \(p_s\) and the velocity \(u\), of the working gas are expressed in terms of the stagnation temperature \(T_s\), the stagnation pressure \(p_s\), the Mach number \(M\) and the ratio \(\gamma\) between the specific heats of the working gas, and the gas constant \(R\) :

\[
T_s = T_s/\left(1 + \frac{\gamma - 1}{2} M^2\right),
\]

Table 1 Cross sections and collision loss factors of various species

<table>
<thead>
<tr>
<th>Species</th>
<th>(Q_j(10^{-11}\ \text{cm}^2))</th>
<th>(\delta_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>Ref. [13]</td>
<td>1</td>
</tr>
<tr>
<td>K</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>(N_2)</td>
<td></td>
<td>Ref. [16]</td>
</tr>
<tr>
<td>(\text{H}_2\text{O})</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>(\text{CO}_2)</td>
<td></td>
<td>&quot;</td>
</tr>
<tr>
<td>(\text{KOH})</td>
<td>250&quot;</td>
<td>1,000&quot;</td>
</tr>
<tr>
<td>(\text{K}^+)</td>
<td>250&quot;</td>
<td>20&quot;</td>
</tr>
</tbody>
</table>

(Above this line: Major components)

\(\dagger\) Presumed values.
Upon seeding with potassium, 15 more components —K, K₂, KO, KOH, (KOH)₂, K₂CO₃, KH, K⁺, O⁻, O₂⁻, OH⁻, CO₂⁻, NO₃⁻ and electrons— are added to the working gas. Also taken into account is Ar⁺, when the seed fraction ε is relatively small and the electron temperature relatively high. The number density (or mole fraction) of each component is calculated from the chemical equilibrium equations. The chemical reactions involving electrons are calculated on the basis of the electron temperature, and those concerning other components on the gas temperature.

(3) Electron Temperature

The electron temperature is obtained from the electron energy equation

\[ j^2/\sigma_{\text{eff}} = 3/2 \cdot k(T_e - T_\gamma)n_e \sum_j \nu_{ej}\delta_j(2m_e/m_j) , \]

in which the radiant energy loss is neglected, and where \( j \) represents the current density, \( \sigma_{\text{eff}} \) the effective electrical conductivity, \( k \) the Boltzmann constant, \( T_e \) the electron temperature, \( \nu_{ej} \) the collision frequency of electrons with the \( j \)-th species, \( \delta_j \) the collision loss factor of electrons with the \( j \)-th species, \( m_e \) the mass of an electron, \( m_j \) the mass of the \( j \)-th species and \( n_e \) the number density of electrons.

For a Faraday-type MHD generator with infinitely finely segmented electrodes, the current density

\[ j = \sigma_{\text{eff}} u B (1 - K) , \]

where \( B \) is the applied magnetic field, and \( K \) the loading factor.

In the evaluation of \( \sigma_{\text{eff}} \), it is assumed that

\[ \sigma_{\text{eff}} = \begin{cases} \sigma & \text{for } \beta \leq \beta_{\text{cr}} , \\ \sigma(\beta_{\text{cr}}/\beta) & \text{for } \beta \geq \beta_{\text{cr}} . \end{cases} \]

where \( \sigma \) is the electrical conductivity and \( \beta \) the Hall parameter, both expressed in terms of the electron mobility \( \mu_e \):

\[ \mu_e = \frac{e}{m_e \sum_j \nu_{ej}} , \quad \sigma = n_e \epsilon \mu_e , \quad \beta = \mu_e B , \]

and the critical Hall parameter

\[ \beta_{\text{cr}} = \sqrt{A_T^2 - \sigma_T^2/n_T} , \]

where \( A_T = d \ln A/d \ln T_e , \quad \sigma_T = d \ln \sigma/d \ln T_e , \quad n_T = d \ln n_e/d T_e \), and \( A \) is the right-hand side of Eq. (4).

The collision frequency of electrons with the \( j \)-th species is calculated by

\[ \nu_{ej} = \sqrt{8kT_e/m_e \cdot n_jQ_j} , \]

where \( n_j \) is the number density of the \( j \)-th species and \( Q_j \) the momentum transfer cross section of electrons with the \( j \)-th species. The Newton-Raphson method is applied in the calculations of the chemical reactions.
III. RESULTS AND DISCUSSIONS

In the present calculations, the typical values chosen to represent the gas properties were:

\[ T_s = 2000 \text{ K}, \quad P_s = 5 \text{ atm}, \quad M = 1, \]
\[ B = 5 \text{ T}, \quad \varepsilon = 10^{-3}, \quad K = 0.75. \]

The static temperature and pressure, and the gas velocity calculated from Eqs. (1)~(3) were 1,500 K, 2.44 atm and 721 m/s, respectively. The current density \( j \) and the power density \( P_e \) are expressed in terms of the effective electrical conductivity \( \sigma_{\text{eff}} \) (S/m):

\[ j = \sigma_{\text{eff}} u B (1 - K) = 9.01 \times 10^{-4} \sigma_{\text{eff}} \quad (\text{A/cm}^2), \quad (10) \]
\[ P_e = j u B K = 2.44 \sigma_{\text{eff}} \quad (\text{MW/m}^3). \quad (11) \]

For \( \sigma_{\text{eff}} = 11.1 \text{ S/m} \) for example, the current density obtained is 1 A/cm\(^2\), which can be considered quite typical for a practical generator, the corresponding power density being 27.1 MW/m\(^3\).

1. Properties of MHD Working Gas

Figure 1 shows the electron temperature as a function of the total impurity concentration \( f \), defined by \( f = b'/b_s \). The two curves represent the calculations based on the “pessimistic” and “optimistic” assumptions, the other conditions assumed being those prescribed above as typical. When the value of \( f \) is relatively high, the impurities come to constitute for the electrons collision loss factors of value such as to dominate their energy loss, which results in no appreciable increase of electron temperature. With decreasing \( f \), the contribution of impurities to the electron energy loss diminishes to a level comparable with that of Ar, K and K\(^+\), which are components not considered to be impurities, and this leads to sharp changes of electron temperature; below about \( f = 2 \times 10^{-6} \) (\( b'/b_s = 10^{-6} \text{ atm} \)), the electron temperature approaches the ideal value (the case of no impurities). The band between the solid (“pessimistic” assumption) and dotted (“optimistic” assumption) lines in Fig. 1 presents a width corresponding to a range of 270 K in terms of electron temperature, in the region of \( f = 10^{-4} \sim 10^{-6} \). In what follows, we shall base all calculations on the “pessimistic” assumption, unless otherwise indicated.

In Fig. 2, the partial pressure ratios of the major components are shown as function of \( f \) (argon partial pressure is virtually constant and is hence omitted). With decreasing \( f \), the partial pressures of the different impurities decrease at varying rates. Conversely, K\(^+\) and electrons increase their partial pressure ratios with lowering \( f \), until they tend to saturate below \( f = 10^{-6} \) with approach to the ideal values (\( f = 0 \)). It is to be noted that the partial pressure of electrons can exceed that of potassium ions while maintaining charge neutrality on account of their non-equilibrium thermal states.
The minor components may be thought to have no direct influence on the chemical equilibrium, especially, in the region of present interest, but numerical calculations have proved that they actually influence quite appreciably the partial pressures of the major components through chemical reactions, despite the small presumed values of the cross sections and collision loss factors. Thus, the effects brought by the presence of these minor components cannot be ignored in chemical calculations.

The collision frequencies of components with electrons are shown in Fig. 3 as a function of $f$. It is seen that the collision frequency of K is almost constant over a wide range of $f$, and that the same applies also to Ar except for the temperature region where the Ramsauer effect is predominant. Thus, in so far as concerns collision frequency, potassium ions and impurities would appeal to play an important role in determining the non-equilibrium MHD gas properties. With decreasing $f$, the total collision frequency first shows a tendency to fall, due mainly to the declining number densities of impurities, following which the rapid increase of $K^+$ number density reverses the trend, and the consequent enhancement of collision frequency is progressively accentuated with the accompanying rapid rise of electron temperature. For efficient non-equilibrium MHD generation (to be discussed later), the collision frequency of the impurities should be held to a fraction that is below $10^{-4}$ of the total collision frequency.

In determining the electron temperature of the conducting gas, it is seen from Eq. \(4\) that the term $n_{e} \delta_{j} (2m_{e}/m_{j})$ plays an important role, and its relation to $f$ is presented.
in Fig. 4 for the various components. It is seen that major contributions are provided by \( \text{H}_2\text{O}, \text{CO}_2, \text{KOH} \) and \( \text{K}_2\text{O} \), whereas \( \text{N}_2 \) and \( \text{CO} \)—which are the major components in terms of partial pressure ratio—have relatively little influence on electron temperature. The values of \( \nu_e \beta / (2m_e/m_i) \) of the components not considered to be impurities are overtaken by those of the impurities around a position of \( f \) slightly below \( 10^{-5} \), beyond which the MHD gas is known to change its properties abruptly as a general rule.

The Hall parameter \( \beta \) and critical Hall parameter \( \beta_{cr} \)—physical properties of equal importance—are taken up in Fig. 5. Between \( f=10^{-4} \) and \( 10^{-5} \), \( \beta \)—which is inversely proportional to the collision frequency—and \( \beta_{cr} \) both undergo a sharp change, but in opposite directions. This particular relation existing between \( \beta \) and \( \beta_{cr} \) indicates that the conditions currently adopted in MHD generation are inherently liable to ionization instability.

2. Effects of Variations in Parameters Brought on Generator Performance Characteristics

Figure 6 plots the power density against current densities with the intensity \( B \) of magnetic field as parameter, and \( f \) as secondary parameter. Numerical calculations indicate that, with \( B=5 \, \text{T} \), the power density becomes relatively stable to fluctuations in impurity concentrations around \( f=2 \times 10^{-6} (p^* = 10^{-4} \, \text{atm}) \), when the corresponding current and power densities are \( 2.9 \, \text{A/cm}^2 \) and \( 77 \, \text{MW/m}^3 \) respectively. With \( B=3 \, \text{T} \), the values of \( f \) should require to be much smaller. For practical purposes, however, the power densities corresponding to \( B=3 \, \text{T} \) (about \( 17 \, \text{MW/m}^3 \) ), should be found rather too small and the current densities corresponding to \( B=7 \, \text{T} \) (about \( 5.5 \, \text{A/cm}^2 \) ) too high for convenient manipulation. Hence, if the conditions of \( T=2,000 \, \text{K} \) and \( p_s=5 \, \text{atm} \) are to be maintained, some modification will be required of the Mach number and the loading factor for \( B=3 \, \text{T} \) and \( =7 \, \text{T} \) to meet practical requirements at the entrance of the MHD generator.

The stagnation temperature \( T_s \) is taken up as parameter in Fig. 7 to examine its influence on power density, which can be expected to be quite strong, since it is directly related to the gas enthalpy. The curves reveal that a lower stagnation temperature requires a smaller value of \( f \) for realizing efficient non-equilibrium thermal state: Taking \( 2,000 \, \text{K} \) as typical value of \( T_s \) in the region of efficient non-equilibrium state, an increase of \( T_s \) by \( 200 \, \text{K} \) to \( 2,200 \, \text{K} \) produces an enhancement of power density amounting to \( 60\% \) and a
converse decrease to 1,800 K a corresponding reduction of 40%.

The next parameter, taken up in Fig. 8, is the stagnation pressure, the lowering of which would reduce the number density of impurities present, and open the way to higher power densities, which otherwise would be prohibited by the high impurity concentrations that would be induced. Reduction of $p_s$ from 5 to 3 atm yields a rise of approximately 35% in power density, and conversely, an increase from 5 to 7 atm lowers the power density by about 30%. Operation with lower stagnation pressures, on the other hand, calls for larger volume flow rates, and hence larger generator cross sections for extracting a given power (about 40% larger volume flow rate required for $p_s=3$ atm than for $p_s=5$ atm). The value of stagnation pressure thus needs to be determined with consideration given to overall economy.

The Mach number $M$ is the parameter adopted in Fig. 9, which indicates that, in the region around $f=10^{-4}$ a larger Mach number allows larger values of $f$ at evacuation for deriving a given power density, while below $f=10^{-5}$, larger $M$ provides higher power densities to be derived with given $f$. In this region of $f$, a small increase of $M$ from 1.0 to 1.3 multiplies the power density by a factor of 2.4, and if further enhanced to $M=2.0$ the impurities become permissible to amounts exceeding 100 ppm. This evidences the advantage of operating under supersonic condition in realizing fully non-equilibrium thermal states. The power density appears to be improved particularly effectively when the Mach number is raised in the downstream portion of the MHD channel.

The final parameter taken up—in Fig. 10—is the
seed fraction \( \varepsilon \). It is seen that in the region of relatively small \( f \), of present interest, a larger power density is derivable with smaller \( f \), and with smaller \( \varepsilon \) in so far as it remains in the range between \( 10^{-3} \) and \( 10^{-4} \)—which is that subject to ionization instability. When \( \varepsilon \) reaches \( 10^{-4} \), however, the power density shows the opposite tendency with change in \( f \), and further, at a point around \( f=10^{-4} \), where the seed atoms become almost fully ionized while ionization has not yet started on the Ar atoms, there occurs a discontinuity in power density resulting in disappearance of ionization instability. The inverse tendency shown against diminishing \( f \) below \( 10^{-4} \) is due to the critical Hall parameter lowering again below the Hall parameter in the region of \( f=10^{-6} \sim 10^{-8} \), with accompanying reinitement of ionization instability, although with an effect far milder than noted in the region above \( f=10^{-4} \). These observations would indicate that the presence of impurities within certain limits should even serve usefully in inhibiting ionization instability that is due to the retarded onset of Ar atom ionization, and could thus offer a means of increasing the effective electrical conductivity, and, eventually, power density. The foregoing example of numerical results consequently merits follow-up with further detailed studies.

3. Evaluation of Pumping Work

For examining the evacuation of impurities in the free volume of the heat exchanger, it is recalled that, in the foregoing calculations we have assumed that all the impurities remaining in the heat exchanger are entrained by the initial flow of one-free volume. In practice, however, the impurities flow out continuously\(^{(2)} \), so that the actual evacuation pressure could validly be allowed to be increased above the values calculated on the above assumption. In a commercial system such as proposed by GE\(^{(18)} \), where several heat-exchangers are to be used cyclically, the concept of the evacuation pressure \( p^* \) is no longer meaningful, since the impurity concentration in the system will be diluted by the mixture of working gases supplied by the several heat-exchangers operating in different phases. Be that as it may, the present results will still validly apply if \( f \) is considered to represent the impurity concentration at the entrance of an MHD generator.

We estimate the pumping work \( W_p \) required during one cycle of heat exchange to evacuate the heat exchanger from pressure \( p_0 \) to \( p^* \). With \( V \) representing the total volume of the heat exchanger and \( \alpha \) the fraction of the volume occupied by the ceramic structures, the pumping power per unit volume

\[
W_p/V = (1-\alpha) [\rho_0 \ln(p_0/p^*) - p_0 + p^*],
\]

which ranges between 0.4 MJ/m\(^3\) for \( p^*/p_0=10^{-6} \) and 1 MJ/m\(^3\) for \( p^*/p_0=7 \times 10^{-12} \), taking 1 atm for \( p_0 \) and 0.6 for \( \alpha \). If the heat exchanger is assumed to work in the temperature...
range from $T_s$ down to $T_s - \Delta T_s$ during the cycle, then the total energy transmitted to the working gas per unit volume of the heat exchanger

$$W_o/V = \alpha \rho_c c_v \Delta T_s,$$

(13)

where $\rho_c$ and $c_v$ are respectively the specific density and the specific heat capacity of the ceramic. Let $\eta_{ex}$ be the enthalpy extraction efficiency, $\eta_{ex}/\eta_{th}$ the ratio of energy consumed in the MHD generator to the input energy, and $\eta_{th}$ the thermal efficiency of a conventional steam plant, then the total output energy generated by the dual cycle plant per unit volume of the heat exchanger

$$W_e/V = \alpha \rho_c c_v \Delta T_s (\eta_{ex} + \eta_{th} - \eta_{ex} \eta_{th}/\eta_{th}),$$

(14)

If typical values of $\rho_c = 3 \times 10^3$ kg/m³, $c_v = 1$ kJ/kg·K, and $\Delta T_s = 100$ K, are taken, $W_o/V = 84$ MJ/m³ for $\alpha = 0.6$, $\eta_{ex} = 0.2$, $\eta_{th} = 0.4$ and $\eta_{th} = 0.6$.

It has been indicated earlier that the value of the ratio $p^*/p_0$ necessary for efficient non-equilibrium MHD power generation is below $10^{-5}$, the exact value depending on the particular operating condition, hence the ratio $W_p/W_e$ between the pumping work and the total output energy is found from calculation to be less than 1%, in most cases, which is well within practical limits for economical plant operation.

### IV. CONCLUSION

Calculations on the heating of impurity-laden potassium-seeded argon gas by fossil (propane) fuel-fired heat exchanger, have yielded results that can be summarized as follows:

1. Efficient non-equilibrium thermal state can be attained in the presence of ionization instability, when the impurity concentration can be brought below certain limits depending on the operation conditions, lying roughly between 10 and 100 ppm.

2. The power and current densities will not be unduly disturbed by fluctuations in the impurity concentrations when the MHD generator is operated within the above range of the impurity concentration.

3. Among the various properties of gas that can be modified, increase of the Mach number in the supersonic region would appear to be most effective for enhancing the power density.

4. In the case of very low seed fractions, the presence of a certain amount of impurities would appear even to contribute to inhibiting ionization instability due to the onset of ionization of Ar atoms.

5. Pumping work required for the evacuation of the heat exchanger is negligible.

The present calculations have considered only the power produced at the entrance of the generator: The performance characteristics of the MHD generator over the whole channel—taking into account both the relaxation effects of the ionization phenomena, and the chemical non-equilibrium—remain to be studied, although this will incur exorbitant computing time.

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--- REFERENCES ---