Abstract

The present report intends to study preliminarily the performance of "SAKHALIN", a large pulsed MHD generator constructed in Russia, operated with solid fuel with the electric power output of 510 MWe, by time-dependent quasi-one-dimensional analyses in order to obtain data needed for multi-dimensional analyses. A preliminary analysis has indicated that the magnetic Reynolds number is about 0.58 for run No.1, which is much different from many other MHD generators. The induced magnetic flux density is about 20% at the entrance and exit of MHD channel. The flow field experiences the shock wave when the operation voltage becomes low, while the shock wave becomes stronger when the induced magnetic field is taken into account. The electric power output results in 511 MW when the induced magnetic field is not included, while it becomes 509 MW when the induced magnetic field is taken into account. The effects of the induced magnetic field are cancelled out with each other between the first and the second half part of MHD channel.

1. Introduction

Large pulsed MHD generators can be used as an adequate energy source of assistance of the rocket propulsion, because the large DC current can be produced and then a large electromagnetic force can be induced. Many pulsed MHD generators operated with solid fuel were constructed in Russia [1]. The largest pulsed MHD generator was called "SAKHALIN" with a channel length of 4.5m. The MHD generator could demonstrate the electric power output of 510 MWe [2]. There was no report on analysis of the large MHD generator "SAKHALIN". In this paper, the authors have carried out time-dependent one- and two-dimensional analyses with the assumption of monophase flow and two-phase flow, and time-dependent three-dimensional analyses with the assumption of monophase flow [3-8]. The present study intends to study preliminarily the performance of "SAKHALIN" by time-dependent quasi-one-dimensional analyses in order to obtain data needed for planned multi-dimensional analyses.

2. Numerical Scheme

2.1 Gasdynamics

The basic equations used for the gasdynamics are time-dependent one-dimensional compressible conservation equations along the x direction, the main flow direction. The working fluid is weakly ionized plasma which contains about 40 wt% of Al2O3, because the fuel consists of the metal Al. In the present study, however, the assumption of monophase flow is valid, while the assumption of multiphase flow will be used in a near future. The gasdynamics are solved with the MacCormack method [9].

2.2 Electrodynamics

The basic equations used for the electrodynamics are the steady Maxwell equations and the generalized Ohm's law with quasi-one-dimensional approximation [9].

2.3 Thermodynamical Properties

Thermodynamical properties of the working gas of "SAKHALIN" was not reported and therefore the values used for analyses of Pamir-3U are used as:

\[ \frac{\text{Gas constant}}{\text{J/kgK}} = 359.9 + 0.3459 \times 10^{-2} T^2 \] \hspace{1cm} (1)

\[ \frac{\text{Enthalpy}}{\text{J/kg}} = -733600 + 649.9 T + 0.3105 T^2 \] \hspace{1cm} (2)

\[ \frac{\text{Electrical conductivity}}{\text{S/m}} = \exp\left\{(-0.1569 + 0.3194 \times 10^{-4} T) + (-2.020 + 0.2122 \times 10^{-2} T) + (-3.297 + 0.1408 \times 10^{-2} T) / p\right\} / G \] \hspace{1cm} (3)

\[ \frac{\text{Hall parameter}}{\mathbf{B}} = (0.3937 + 0.3025 \times 10^{-2} T^{1/2}) \mathbf{B} / p / G \] \hspace{1cm} (4)

where \( p \) and \( T \) stand for the pressure and temperature of the working gas and \( G \) is a dimensionless parameter.

\[ \beta(p, T, B) = 0.2937 \times 10^{-2} T^4 + 0.3025 \times 10^{-2} T^4 B / p \] \hspace{1cm} (5)

The gasdynamics are solved along the x axis on a 711 mesh grid.
plasma being assumed one (11 a presents

3. Performance of "SKHALIN"

3.1 Brief Summary of Large Pulsed MHD Generator "SKHALIN"

The channel length of the large pulsed MHD generator is 4.5m, the cross section of entrance is 0.9m × 1.0m and 1.6m × 1.0m at the entrance and exit, respectively, where the height along the magnetic field is kept constant with 1.0m. The nominal mass flow rate is 1000 kg/s. The combustor temperature is 3800 to 3900K, while the combustor pressure is 4.0 to 5.6Mpa. The generator was quite powerful, light (only 50tons), and compact, which could demonstrate the electric power output of 510MWe, the specific mass of 0.1 ton/MWe, and the specific volume of 0.3m³/MWe. The air-core magnet was activated to more than 2 T by the MHD generator itself, which is the Faraday type with continuous electrodes made from glass-reinforced plastic plates with graphite [2].

3.2 Design of Air-Core Magnet

The report [2] informs that the design value of magnetic flux density is 2.5 T and the ampere-turn of the magnet is 8.4×10³kA. The number of turn results in 56, because the excitation current of design is 150kA. Our three-dimensional code of magnetic field analysis has, however, shown that the number of turn of 56 is too large, resulting in much higher value of magnetic flux density. Our analyses have indicated that the number of turn must be 33, which can give 2.5 T. The number of turn is, therefore, assumed to be 33 in our analyses.

The experimental results indicated that the constructed magnet could not produce the designed value and we have introduced a modification coefficient which can produce the value of magnetic flux density obtained at the experiment. The modification coefficient used in the present study is shown below:

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Coefficient</th>
<th>Maximum B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.590</td>
<td>2.09 T</td>
</tr>
<tr>
<td>2</td>
<td>0.622</td>
<td>2.20 T</td>
</tr>
<tr>
<td>3</td>
<td>0.424</td>
<td>1.50 T</td>
</tr>
<tr>
<td>4</td>
<td>0.435</td>
<td>1.54 T</td>
</tr>
<tr>
<td>5</td>
<td>0.435</td>
<td>1.54 T</td>
</tr>
<tr>
<td>6</td>
<td>0.438</td>
<td>1.55 T</td>
</tr>
</tbody>
</table>

This table shows that the electric circuit may have changed between Runs 1 & 2 and Runs 3 through 6.

3.3 Induced Magnetic Field

A preliminary analysis has shown that the magnetic Reynolds number is about 0.52 or Run No. 1, while it is about 0.5 in other runs. This difference would be neglected. We use one-dimensional analysis on the above assumption and use the following equation:

\[ B_{\text{eff}}(t) = B_{\text{in}}(t) - B_{\text{ind}} \]

This equation is used in the case of Run No. 1, where we assume that the electric circuit is constant. The induced magnetic field cannot be neglected. Then the one-dimensional analysis has been applied to Ampere's law and the following equation has been derived:

\[ \frac{d}{dt} \int B \cdot dA = \sigma \frac{dI}{dt} \]

Fig. 1 Distributions of magnetic flux density for Run No. 1, where the solid line shows the externally applied field, the dashed line with dots does the induced field, and the dotted line does the effective field. It is revealed that the induced magnetic flux density is about 20% at the entrance of the MHD channel, while it becomes about 19% at the exit, being rather large.

3.4 Estimation of Electrode Voltage Drop

The value of electrode voltage drop can be automatically calculated in the case of multi-dimensional analysis, but the present one-dimensional analysis requires an estimation of the electrode voltage drop. It has been shown that the electrode voltage drop is not negligible and should be included in the calculation. The electrode voltage drop can be estimated by comparing the one-dimensional analysis and the experimental results. The electrode voltage drop can be estimated as follows:

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Voltage Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.350</td>
</tr>
<tr>
<td>2</td>
<td>0.322</td>
</tr>
<tr>
<td>3</td>
<td>0.424</td>
</tr>
<tr>
<td>4</td>
<td>0.435</td>
</tr>
<tr>
<td>5</td>
<td>0.435</td>
</tr>
<tr>
<td>6</td>
<td>0.438</td>
</tr>
</tbody>
</table>

This table shows the electrode voltage drop in volts. The electrode voltage drop is significant and should be included in the calculation.
where $J_y$ is the y-component of the electric current density.

Then a simple linear relation on $J_y$ is assumed as:

$$\Delta V = r_{drp} J_y + \Delta V_0$$

where $\Delta V$ is the electrode voltage drop and $\Delta V_0$ is the constant. The value of constant $r_{drp}$ is estimated so as to agree with the electric output power as shown below:

<table>
<thead>
<tr>
<th>Run No.</th>
<th>$r_{drp}$</th>
<th>$\Delta V_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0143</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>0.0175</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.0022</td>
<td></td>
</tr>
</tbody>
</table>

The value of $\Delta V_0$ is assumed to be 400 volts, which must be estimated with experimental data and/or multi-dimensional analyses. The rather large electrode voltage drop suggests a strong three-dimensional phenomena. This relation is used for all further calculations with or without induced magnetic field.

### 3.5 Effects of Induced Magnetic Field

The induced magnetic field strongly affects the electric current distribution, as shown in Fig.2 and Fig.3. Figure 2 depicts distributions of electric current density ($J_x$ and $J_y$), showing that the peak value of $J_y$ is about 120 kA/m² and the peak value of $J_x$ is about 40 kA/m² for Run No. 1. The existence of large $J_x$ suggests that the three-dimensional phenomena are induced on the $y$-$z$ plane, indicating that three-dimensional analyses are required to understand phenomena in detail.
Fig. 5. Distributions of velocity and Mach number with induced magnetic field (Run No. 1, 2550 [V]; solid line: velocity, dotted line: Mach number). When the magnetic field is taken into account, these values of Mach number become about 2.38, 1.55, and 1.65, showing a slight acceleration along the first half part of the MHD channel because of the reduced magnetic field and a slightly stronger deceleration along the second half part due to the enhanced magnetic field.

Figure 6 depicts distributions of the static pressure and temperature of the working gas for Run No. 1, operated with the load voltage of 2550 volts, showing that the pressure and temperature decrease rapidly along the nozzle because of the strong acceleration. Then, almost constant pressure and temperature are maintained along the MHD channel, and finally, the flow is slightly accelerated again along the diffuser.

Fig. 6. Distributions of pressure and temperature with induced magnetic field (Run No. 1, 2550 [V]; solid line: pressure, dotted line: temperature).

Figure 7 shows distributions of Mach number, indicating effects of the induced magnetic field, where the load voltage is decreased to 1900 volts and the larger current density and stronger deceleration result. Even when the supersonic flow can be maintained along the whole channel without the induced magnetic field, a shock wave is induced at the end region of the MHD channel when the induced magnetic field is considered. This is because the flow is less decelerated along the first half of the MHD channel since the induced magnetic field reduces the effective magnetic field there, whereas the flow experiences stronger deceleration along the second half of the MHD channel due to the enhanced magnetic field.

Fig. 7. Distributions of Mach number (1900 [V]; solid line: without induced magnetic field, dotted line: with induced magnetic field).

Figure 8 depicts distributions of Mach number, where the MHD generator is operated with a lower load voltage of 1600 volts, showing that a slight shock wave is induced even without the induced magnetic field. When the induced magnetic field is considered, a stronger shock wave is produced, and the position of the shock wave moves upwards when the induced magnetic field is taken into account.

Fig. 8. Distributions of Mach number (1600 [V]; solid line: without induced magnetic field, dotted line: with induced magnetic field).

Fig. 9 shows distributions of Mach number, where the load voltage is decreased to 1100 volts and the larger current density and stronger deceleration are needed. Even when the supersonic flow can be maintained along the whole channel without the induced magnetic field, the shock wave is induced at the end region of the MHD channel when the induced magnetic field is considered. This is because the flow is less decelerated along the first half of the MHD channel since the induced magnetic field reduces the effective magnetic field there, whereas the flow experiences stronger deceleration along the second half of the MHD channel due to the enhanced magnetic field when the induced magnetic field is taken into account.
Figure 9 shows distributions of Mach number, when the MHD generator is operated with a load voltage of 1000 volts, indicating that a strong shock wave is induced, a subsonic region is produced at the second half region of MHD channel, and the flow is again accelerated into the supersonic flow along the diffuser even when the induced magnetic field is not taken into account.

In summary, the flow field experiences the shock wave when the operation voltage becomes low in both cases, while the shock wave becomes stronger when the induced magnetic field is included. The flow is less decelerated along the first half channel and the stronger shock wave is induced at the second half part of channel, when the operation voltage becomes lower such as 1000 volts. Our experiences [5,7] tell that the strong shock wave always occurs together with the boundary layer separation, indicating that two- and three-dimensional analyses are required to understand the MHD interaction in detail.

Figure 10 depicts the voltage-current characteristics of the large MHD generator under the operation conditions of Run No. 1. The electric power output results in 511 MW when the induced magnetic field is not included, while it becomes 509 MW when the induced magnetic field is taken into account. The effects of the induced magnetic field are cancelled out with each other between the first and the second half part of MHD channel.

4. Concluding Remarks

The large pulsed MHD generator "SAKHALIN" was studied preliminarily by time-dependent quasi-one-dimensional analyses in order to obtain data needed for planned multi-dimensional analyses. The following results were obtained:

1. The magnetic Reynolds number is about 0.58 for Run No.1, which is much different from many other MHD generators. The induced magnetic flux density is about 20% at the entrance of MHD channel, while it becomes about 19% at the exit.

2. The estimated value of electrode voltage drop becomes 700 volts to 1200 volts, which is much higher than the originally estimated value of 200 volts.

3. The flow field experiences the shock wave when the operation voltage becomes low, while the shock wave becomes stronger when the induced magnetic field is included. The strong shock wave always occurs together with the boundary layer separation, indicating that two- and three-dimensional analyses are required to understand the MHD interaction.

4. The electric power output results in 511 MW when the induced magnetic field is not included, while it becomes 509 MW when the induced magnetic field is taken into account. The effects of the induced magnetic field are cancelled out with each other between the first and the second half part of MHD channel.

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References


2. E.P. Velikhov et al., "Pulsed MHD Power Systems SAKHALIN: The World Largest"


