FACTORS AFFECTING MAGNETOHYDRODYNAMIC GENERATOR PERFORMANCE

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Introduction

A Magnetohydrodynamic (MHD) power generation technique is a nonconventional electric power harvesting modality in which the electricity is generated from an ionized fluid flow under a magnetic field. The ionized fluid moving under a magnetic field works as a moving electrical conductor and the MHD generator generates electrical energy according to the Faraday's electromagnetic principle. The concept of MHD based electric power generation was first time introduced by Michael Faraday in 1832 [1]. The MHD generator use many different working fluids like Plasma and liquid metal. Here in this review we will focus on inert gas non-equilibrium plasma.

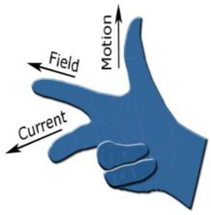

Fig. 1. Fleming's right-hand Rule-Wikipedia

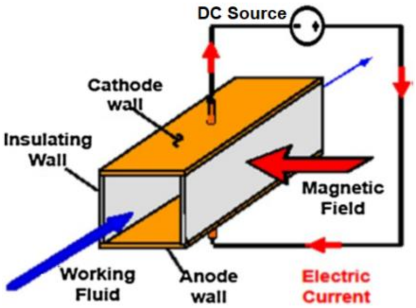

Fig. 2. Principle of a MHD power [2]

The performance of the MHD generator can be illustrated through many indicators:

Enthalpy extraction ratio (EER): which is defined as the ratio of the generated power to the heat input [3]. The practical target is 30%.

Isentropic efficiency: which measures the increase in entropy (the unuseful energy) away from the ideal process (isentropic) through large friction, self-excited Joule heating, shock wave and a boundary layer in the disk MHD channel [6]. Practical target is 80 to 85%.

Plasma Uniformity: The current streamline spacing becomes uniform in the entirety of the generator, which identifies that the plasma is uniform [5]. The current streamline becomes clustered, meaning that the streamline spacing is narrow in the high electron temperature region, indicating that the plasma structure is not uniform [5]. When the characteristic time of the variation in the electron number density is longer than the residence time of the working gas, the uniform plasma is maintained [5]. A nonuniform plasma structure appears originating from the development of ionization instability.

Ionization degree: The ionization degree that is adequate for an experimental-scale MHD generator is of the order of 10^{-3} for seed free plasma [7].

Plasma Ionization instability: It is well-known that in alkali metal-seeded plasma, ionization instability occurs when the seed is partially ionized, resulting in a nonuniform plasma structure in the generator [5]. However, in Xe-seeded plasma, the ionization instability is not always caused by the partial ionization of the seed [5]. According to linear perturbation theory, plasma becomes unstable when the critical Hall parameter is smaller than the Hall parameter [5]. The ionization instability of non-equilibrium plasma decreases the conductivity and the Hall parameter of the plasma which decreases the performance of the generator [6].

Next Factors affecting MHD generator performance: Magnetic field, Plasma velocity, Temperature, Swirl.

Magnetic field

According to the principle of Faraday's electromagnetic induction the amplitude of the generated e.m.f. will be proportional to the magnitude of the magnetic flux density. If the velocity of the fluid and the magnetic field density are denoted by V and B respectively, the e.m.f. induced (E_{ind}) across the MHD conductor is given by $E_{ind} = V \times B$, and perpendicular to the direction of fluid motion and that of the magnetic field.

The increase in magnetic flux density leads to the increase of EER and isentropic efficiency but further increase in magnetic flux density doesn't improve the generator performance but it tends to be saturated [6]. The enthalpy extraction ratio seems to increase with the square of the magnetic flux density [7]. Plasma inhomogeneity depends on magnetic induction intensity [6]. For seed free plasma, plasma stabilization is achieved at a low magnetic flux density even when the inlet total temperature is low [7]. At a low magnetic flux density (B = 2 T), the static pressure is almost the same as that at 0 T because the Lorentz force is weak. At B = 4 T, the static pressure at the end of the generator increases owing to an increase in the Lorentz force. The increase in the static pressure implies flow deceleration at the downstream region. However, the deceleration cannot be so strong judging from the fact that the enthalpy extraction ratio increases with the square of the magnetic flux density [7]. At a high magnetic flux density (B = 3–4 T) and a low inlet total temperature, the plasma is inhomogeneous and unstable as described above. However, the plasma becomes stable and homogeneous at a low magnetic flux density even when the inlet total temperature is low. It is well known that an inhomogeneous plasma structure with ionization instability is enhanced by a strong Hall effect Thus, it is implied that the inhomogeneous structure with ionization instability is suppressed by the low Hall parameter under a low magnetic flux density [7]. High magnetic flux density inhibit the increase of the pressure loss which indicates that the high MHD interaction caused by the high magnetic flux density will not decrease the generator performance [6]. The increase in the magnetic flux density does not largely affect the flow velocity and electrical conductivity in the MHD [7].

Plasma velocity

The amplitude of the generated e.m.f (E_{ind}) will be proportional to the fluid velocity and perpendicular to the direction of fluid motion and that of the magnetic field (Eq 1). Power generation experiments utilizing nonequilibrium supersonic disk MHD generators have been conducting to demonstrate a high isentropic efficiency and a high enthalpy extraction ratio [4]. The disk MHD generator with a supersonic channel had better transient characteristics and a higher steady-state efficiency than with subsonic channel [6].

Temperature

To take into account thermally nonequilibrium state of the plasma, a two-temperature model is used, in which all heavy particles have the same translational temperature T_g, which is called "gas temperature", while the free electrons have a translational temperature, i.e., the electron temperature T_e, different from T_g. High temperature is used in order to obtain high electrical conductivity, high power output, and high enthalpy extraction ratio. For seed free plasma, the enthalpy extraction ratio increases with increasing inlet total temperature and magnetic flux density, but saturates at a high inlet total temperature, this is because the thermal input also increases with the inlet total temperature.

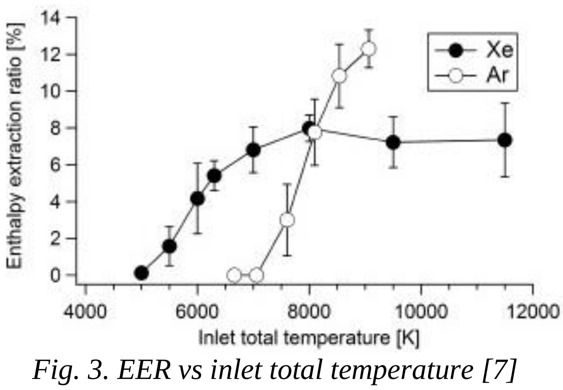

Fig. 3. EER vs inlet total temperature [7]

The inhomogeneous and unstable plasma due to ionization instability at a low inlet total temperature changes to a homogeneous and stable state with an increase in the inlet total temperature [7]. For seeded plasma, there is three zones of electron temperature (seed partial ionization, stable seed full ionization, unstable gas partial ionization at a high electron temperature) [6]. Both low and high electron temperatures will cause plasma instability thereby inhibiting the improvement of the generator performance [6]. There is a range of electron temperatures at which the characteristic time of the variation in the electron number density is longer than the residence time of the working gas (the uniform plasma is maintained) [5]. There is a range of electron temperatures at which the plasma is stable according to linear perturbation theory [5]. The high electron temperature causes the Hall parameter to decrease [5]. The high Hall parameter is resulting from the low electron temperature [5]. The ionization instability is very sensitive to the inlet stagnation temperature [6] It is difficult to achieve full seed ionization at lower gas stagnation temperature (2000 K) [6].

Swirl

Vanes are installed in the nozzle upstream of the generation channel, and positive swirl is produced; this results in a flow combining radial flow and rotational flow. In this case, the Hall e.m.f. is larger, and the Hall current J_r increases as well as the output density (output per generation channel volume). On the other hand, the Faraday current J_q in the negative circumferential direction decreases, and the Lorentz force $J_\Theta \times B$ (which decelerates the flow) weakens, so that the electrical conversion efficiency improves [3]. The introduction of swirl provides a considerable improvement of enthalpy extraction and isentropic efficiency [3]. With a low seed fraction and low load resistance, shock wave-free flow could be obtained. It has been confirmed that such flow, as compared to shock waves, results in higher isentropic efficiency at equal EER [3]. Although the installation of the inlet swirl vanes influences the structure of the plasma, the quite homogeneous form can be achieved under the optimum seed fraction. Moreover, the discharge structure of the swirl generator resembles that of the radial generator in the symmetric appearance. The introduction of the inlet swirl providing a high Hall parameter and electrical efficiency [4]. Swirl blades introduce circumferential velocity which enhance the flow against circumferential Lorentz force, decrease the stagnation pressure loss caused by Joule dissipation and keep the static pressure in the channel at low level [6].

Conclusion

Through the review of the performance indicators of the MHD generators and the factors that affect them, it can be concluded that:

1. Power generation experiments utilizing nonequilibrium supersonic disk MHD generators have been conducting to demonstrate a high isentropic efficiency and a high enthalpy extraction ratio;
2. Introducing swirl has a considerable positive effect on the MHD generator performance;
3. The Temperature for both seeded and seed-free plasma has range for the positive effect on the MHD generator performance;
4. The magnetic flux density increase improves the EER and the isentropic efficiency to certain value and then saturate. On the other hand, the plasma becomes stable and homogeneous at a low magnetic flux density even when the inlet total temperature is low.

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