Disk MHD Accelerator with Swirl Vane and Its Performance

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Keywords: Magnetohydrodynamics, Swirl vane, Disk-shaped

Abstract

The rocket technology has the best reliability and the high acceleration performance currently. In addition, next generation propulsion system is acquired to low cost and high payload percentage at that same time. This work is to improve the performance of Disk-shaped MHD accelerator which is expected as the one of the solution. In this study we have been focusing on the swirl vane. It is so important to know that how the swirl vane contribute the plasma and its performance. As results, the gas velocities of r-component with inlet swirl were increased about over 3000m/s at the channel exit. And then static gas pressure were also reduced, we found that the case with inlet swirl gives the good influence to the acceleration performance. And the difference of the acceleration by positive and negative inlet swirl is that gas velocity of θ–component may operate to the electric field.

I. Introduction

Recently, most of researchers in the field of aerospace have been paying attention on reducing budgets for producing sufficient thrust productivity using in propulsion systems. It has been said that a rocket technology has the best reliability and high acceleration performance for the launching and space exploration mission. With these reasons, many propulsion systems, for example, a linear-shaped MagnetoHydroDynamics (MHD) accelerator as well as a Disk-shaped MHD accelerator are studied as ones of the solutions at the many research centers and universities. In particular, a linear MHD accelerator has been studying for a few decades. However, the properties of a Disk MHD accelerator are seldom presented anywhere and the study of a Disk-shaped MHD accelerator is not yet widely known. Therefore we have started this work using numerical analysis since 2005[1-2] obtaining some fundamental background in comparison with a linear-shaped one. Followings are the results that obtained in the previous studies:

- Heat loss of a shorter channel decreased because of the reduction of a channel surface area.
- Gas velocity increases due to a decrease of the heat loss.
- Heat loss and gas velocity can be improved when we increase a channel height at the exit.
- To improve MHD compression, we adjust a channel height, but a current density j_θ shifts to the generation mode nearly the channel exit to use a Hall connection.
- The performance of both inflow and outflow directions by Q1D analysis program is not so different.
- Channel structure is simpler: because of the amount of electrode and its connection methods of a channel shape.
- The structures of the MHD acceleration such as superconductor magnet coils and cooling unit, control unit for power supply unit and power source, can be made to small.

At the pasted results, we have shown predictable merits were reasonable. However the Disk MHD accelerator has the disadvantages as:

- Influence of circulating gas flow of θ-direction; it means that we evaluate the flow of r-direction Ur but when the flow passes through the nozzle, the compression or loss occurs in the Disk-shaped MHD accelerator.

Although we have found and indicated useful and reasonable results, there might have some issues to study for a better understanding. For the Disk MHD generator, the function of a swirl vane is to flow plasma smoothly because when we obtain output power from plasma fluid, by MHD interaction, plasma flow is varied as circulating flow. So, the purposes of this work are to verify the performance of a swirl vane for Disk MHD accelerator and to study the effect to the plasma. We use a Quasi-1-demensional (Q1D) code to simulate as the analysis method, and to evaluate the key parameters such as acceleration of gas velocity and thermal loss. The results are also presented.

II. Disk MHD Accelerator

A. Principle of Disk MHD Acceleration

Figure 1 shows the schematic of Disk-shaped MHD accelerator by using the cylindrical coordinates system. When the Air plasma gas and potassium, which is used as a seed, flow into the channel in the z-direction, these plasma gas and potassium eventually flow out off the channel in the r-direction. Without the input Hall Current, the j_θ flows in a minus θ-direction. Then, Lorenz force F_r (i.e. $\boldsymbol{j} \times \boldsymbol{B}$) operates in a reverse direction to a flow direction. If the external Hall current provides to the negative internal electric field, F_r operates in the same direction of U_r results in the Magnetic flux density B is created by the upper coil and the lower coil. The U_r is eventually accelerated by the Lorenz force F_r. This is a principle of the MHD acceleration. However, in this study, we consider the connecting of a Disk MHD Channel and Ring diffuser to flow in the z-direction.

On the other hand, in case of the in-flow Disk MHD Accelerator, the Hall Current is supplied in the same direction of the flow direction to accelerate the fluid. The Lorenz force F_r is also operated in the same direction of the flow direction.

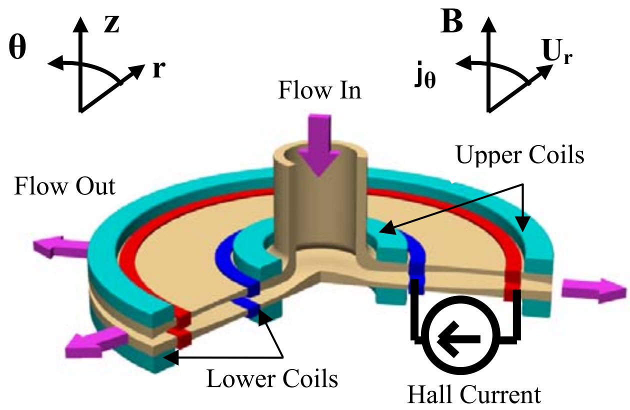


Fig.1 Schematic of Outflow Disk MHD accelerator

B. Accord of Flow Direction

Figure 2 indicates the Disk-shaped MHD channel, which includes the nozzle and the diffuser in the r-z plane. In this case, the fluid flows from the nozzle or the diffuser. The MHD channel connects to the ring-shaped diffuser, which chords the flow directions. The fluid briefly flows through the MHD channel in the z-direction. However, the study employs Q1D numerical analysis code for only the MHD channel region.

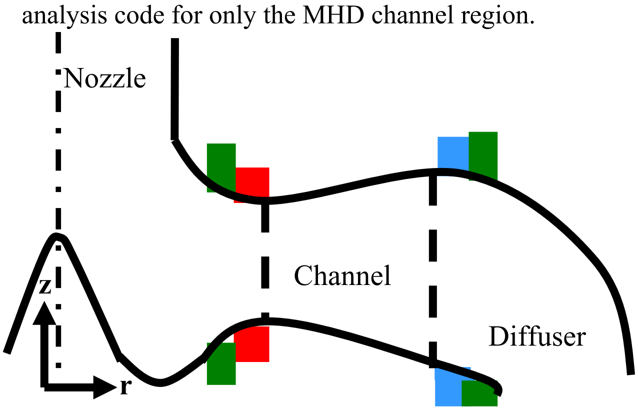


Fig.2 The concept of Disk MHD accelerator including nozzle and diffuser

III. Swirl Vane and Disk MHD Accelerator

The effect of swirl vane should be studied to know how it gives to the plasma fluid and to the performance of the accelerator. For the Disk MHD generator, Without an inlet swirl, a clockwise flow of working gas and negative Faraday current occur in the Disk MHD channel, which results in the clockwise gas flow and magnetic field, i.e. electromotive force $U_\theta \times B$ operates in the –r direction as shown in Fig.3 a). Here, the Disk MHD generator is connected as a generally Hall connection type. So, this electromotive force disturbs the Hall current density J_r. *Harada et al.*[3)] pointed out that the efficiency and power density, i.e. enthalpy extraction increase once an inlet swirl is taken into account. This is because the swirl vane is used to convert the circulating gas flow to the radial gas flow. Therefore, it can be reduced to develop the negative potential at the entrance.

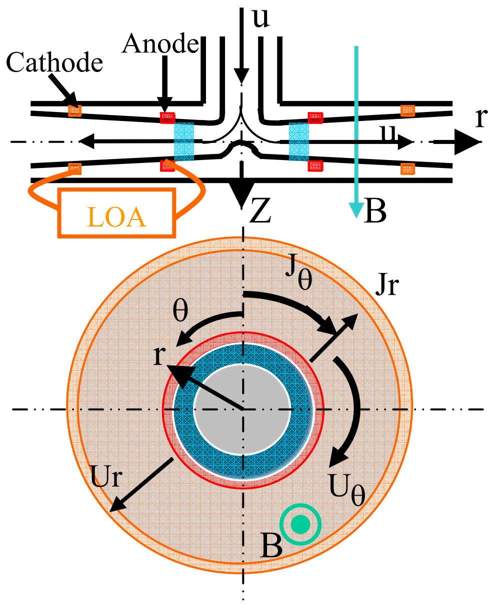
The swirl vane is placed, particularly in the "out-flow", just in front of the MHD region as shown in Fig.3 b). The swirl vane is generally a ratio of velocities component in the r to the θ-directions, and is defined as

$$S_r = \frac{u_\theta}{u_r} \qquad (1)$$

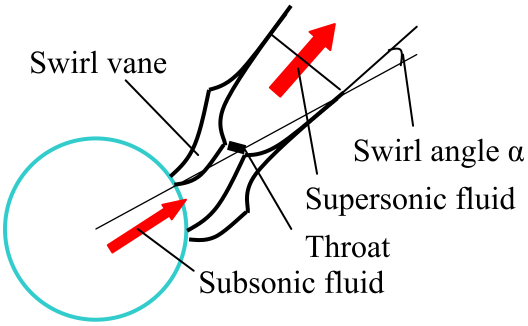
Furthermore, a swirl angle α is also defined in as

$$\alpha = \tan\left(\frac{u_\theta}{u_r}\right)^{-1} \qquad (2)$$

In addition, *Harada et al* pointed out that using a swirl vane is able to reduce static gas pressure at the position close to the channel inlet. This merit is so important for a Disk MHD accelerator, which is a Hall connection. To increase the performance, the channel shape has the increment of expansion along the channel radius. Here, the distribution of Hall current density looks very much like the exponential curve. The more Hall current density is supplied into the Disk MHD channel, the more the gas velocity is accelerated. However, the current density is concentrated at the channel inlet, but it depends on the condition. The MHD compression occurs due to a joule heating. Based on the previous work by Harada, we can predict that the swirl vane might be affected the Disk MHD accelerator. From Eq. (1) and (2), circulating gas flow u_θ may possibly flow both in positive and negative directions. This will be explained in detail in section V (A).



(a) Schematic view of Disk MHD generator and flow direction



(b) Swirl angle and Swirl vane

Fig.3 The location of Swirl vane in the Disk MHD generator

IV. MHD Governing Equations

A. Heavy Particle Equations

Continuous equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (3)$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho \vec{u}) + \nabla \cdot (\rho \vec{u}\vec{u}) = \vec{j} \times \vec{B} - \nabla p - \vec{P}_L \quad (4)$$

where $\vec{P}_L$ is a Pressure loss which causes by the wall friction.

Energy equation

$$\frac{\partial E_s}{\partial t} + \nabla \cdot \{(E_s + p)\vec{u}\} = \frac{|\vec{j}|^2}{\sigma} + \vec{u} \cdot (\vec{j} \times \vec{B}) - Q_L \quad (5)$$

where Q_L is a thermal loss term from the working gas to the wall, and E_s is all energy of the working gas, and is presented as

$$E_s = \rho\left(c_v T_g + \frac{1}{2}|\vec{u}|^2\right) \quad (6)$$

State equation is also defined as

$$p = \rho R T_g \quad (7)$$

B. Electron Equations

Momentum equation (Generalized Ohm's equation)

$$\vec{j} + \frac{\beta}{|\vec{B}|}\vec{j} \times \vec{B} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right) \quad (8)$$

C. Maxwell Equations

The following MHD approximations are made for the calculation.

① Magnetic Reynolds number is small. Therefore, an applied magnetic field is steady.

② Debye length is smaller than the plasma's property distance. It is therefore assumed that plasma is electrically neutral.

③ Not handling an extremely high frequency. The displacement current can be ignored.

The influences of magnetic wave are presented by these simply two approximations.

Faraday's electromagnetic law

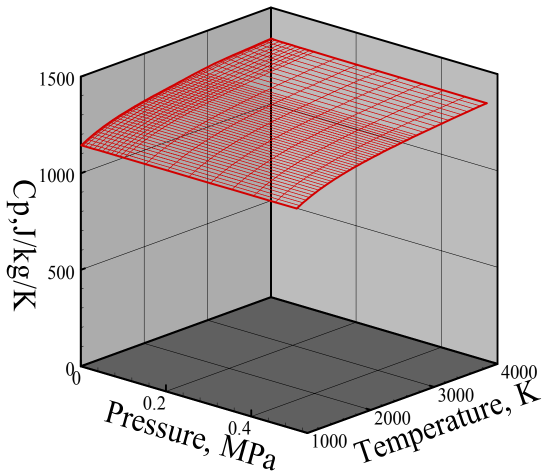
$$\nabla \times E = 0 \quad (9)$$

Current equation

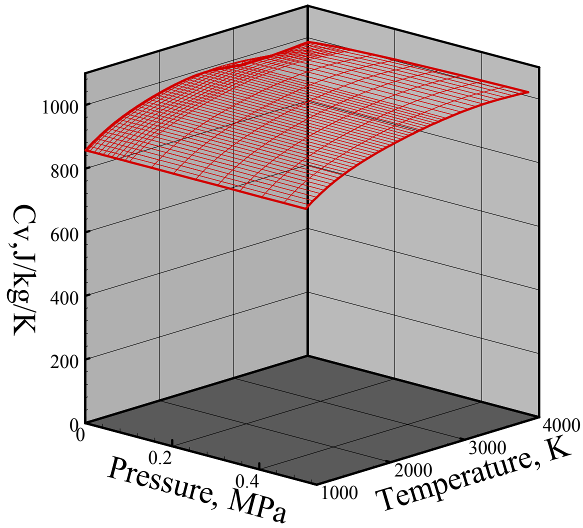
$$\nabla \cdot j = 0 \quad (10)$$

V. Gas Properties of the Plasma

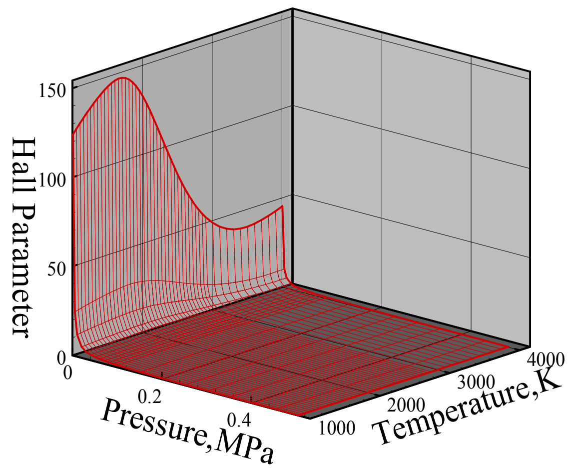
In this study, we use air as the working gas with potassium as a seed material. This working gas is equilibrium plasma, which electron temperature is equal to gas temperature. This means that the high temperature does not use for real experiments to interrupt the MHD channel. With this reason, if the temperature exceeds a limit temperature (4000 K), it then fixes the limit temperature to be in the transient phenomena. In addition, the Q1D analysis program utilize some parameters, which are acquired by air combustion analysis program ETL code developed by Electrotechnical Laboratory, Japan (National Institute of Advanced Industrial Science and Technology, AIST) In this program, the seed is used to cut analysis time. The feature of this code is based on the experimental data of the air combustion with potassium as a seed material. Each parameter is shown in Fig.4. It is noted that each parameter depends on gas temperature and pressure, particularly the temperature is so effective to the parameter. Here, it is found that the results agree with the actual phenomenon. Therefore, we don't have to solve the continuous and energy equation in Electron equations.



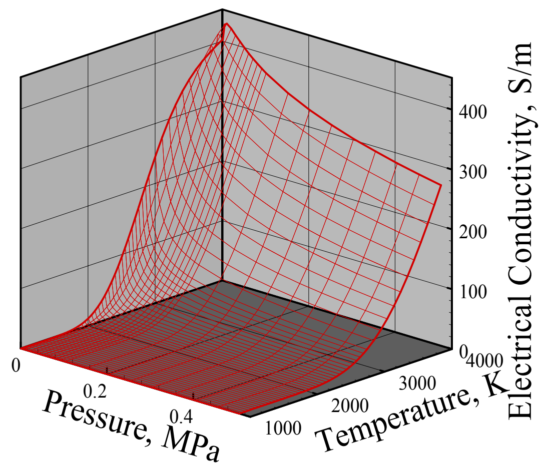
(a) Specific heat constant pressure C_p



(b) Specific heat constant volume C_v



(c) Hall parameter β



(d) Electrical conductivity σ

Fig.4 Air-plasma properties of seed fraction of 0.5%

VI. Simulation Conditions and its Aim

Comparison with-and-without Inlet Swirl for Disk MHD Accelerator

In this section, to verify the properties, we apply a Linear MHD Accelerator MAPX, which has been experimented at the NASA Marshall Space Fright Center, as the channel cross section area and the input conditions. Figure 3 shows channel cross section and channel shape. To utilize the data for MAPX is easy to compare with the previous results[1]. In addition, it is reasonable to drive for the MHD channel. The simulation and analysis conditions are indicated in Table 1. Here, the channel length is set to be 0.045 m. The swirl ratio is varied from -1.0 to 1.0. In general, the fluid flows smoothly to set a swirl vane in case of the Disk MHD Accelerator. If we set a swirl vane, the thermal input will change too. This implies by the present Q1D program, and probably the influence to the fluid is serious even if it is good or bad. Therefore, it is important to study the performance with a swirl ratio.

Working gas	Air+K
Thermal input,MW	0.61-0.43
Flow direction	Outflow
Seed fraction,wt%	0.5
Magnetic field,T	2
Wall temp.,K	1000
Stagnation temp.,K	3530
Stagnation pressure,Pa	914400
Inlet mach number	1.346
Swirl ratio	-1.0,0,1.0
Input power,MW	0.56-0.50
Input current,A	500
Channel length,m	0.045
Mesh space,mm	0.5

Table 1 Analysis Conditions

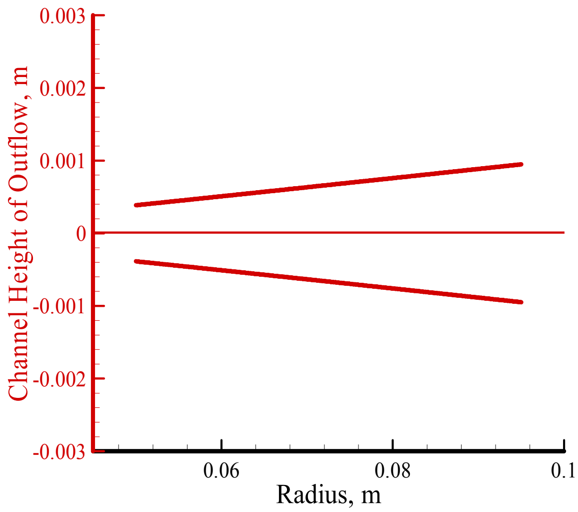


Fig.5 MHD Channel-Shapes of Out-flow

VII. Results and Discussion

Figure 6 (a) to (f) and Fig .7 (g) to (h) show the performance of the Disk MHD accelerator with and without inlet swirl, when the swirl ratio of -1.0 upto 1.0 is varied and used for the calculations. The acceleration performance, radial gas velocity u_r and circulating gas velocity u_θ are indicated in Fig.6 (a) and (b) respectively. When the swirl angle is varied, gas velocity at the channel inlet is also changed to coincide with the swirl ratio. At the channel inlet, a swirl ratio S_r of 0.0 shows the highest velocity. The velocity of about 1400m/s is estimated. However, the velocity distribution is almost flat at a position very close to the channel entrance in spite the channel is expanded. For a swirl ratio of 1.0, there might be the MHD compression slightly. It is noted that there is no dramatically increase in gas pressure, but the increment changes only in the certain area, and to be seen in the graph of static gas pressure in Fig.6 (d). On the other hand, the results of velocities with swirl vane at the swirl ratio of 1.0 and -1.0 are accelerated about 1000m/s at the beginning, then increase and get over the velocity of a swirl ratio of 0.0 at the channel exit. The velocities of about 3000m/s and over 3200m/s are calculated for the swirl ratio of 1.0 and -1.0, respectively. Here, we can say that the swirl vane influences and suppresses the MHD compression results in increase the velocity. Moreover, it can increase steeply at the back of the MHD channel comparing with the results without a swirl vane.

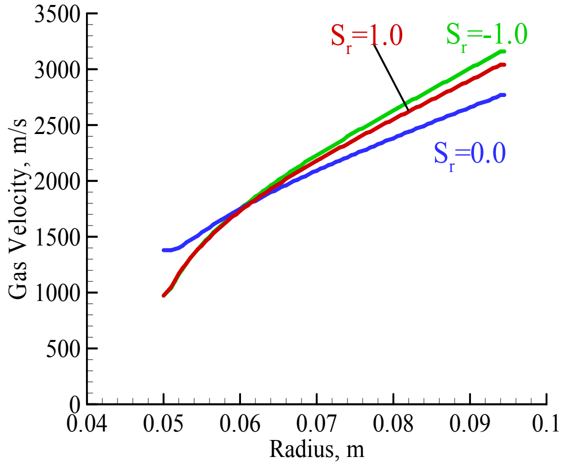
As mentioned in the section III, another MHD interaction, i.e. the unfavorable phenomenon for Disk MHD generator without a swirl vane occurs by the negative circulating gas flow u_θ and the magnetic field B. Therefore, it is necessary to set the positive swirl angle for the Disk MHD generator to suppress it. Figure 6 (b) shows gas velocity of the θ–component. For the velocity of a swirl ratio of 0.0, it decreases to the negative direction of the θ–component along the radius of the channel. The winded force is obtained by the Hall current and the magnetic field. The gas velocity separated by a swirl vane is highest at the channel inlet, but it decreases gradually. This inclination can observe at the other distribution curves, as well, in case of the swirl ratio of 1.0 and -1.0. It is noted that the intensity of Lorenz force F_r influences the distribution of the circulating gas flow, in particularly the velocity of swirl vane of 1.0 decrease from 1000 m/s to 250m/s. The variation of 750m/s is estimated. The swirl vane of -1.0 for The MHD channel region increases from -1000 to -750m/s. Here, the variation of 250m/s is observed.

The distribution of gas temperature is indicated in Fig.6 (c). One can see that results of all swirl ratios are almost flat. To be more precise, results of static gas temperature with a swirl vane show slightly higher than those of without one. For the results of stagnation gas temperature, the green line (swirl ratio of -1.0), shows the highest value among others. Here, it is possible to say that it shows the worst in terms of the heat loss. In fact, the heat loss of about 10.8% is estimated. Figure 6 (d) could be understood the effect of swirl vane for Disk MHD generator, i.e. if we set an inlet swirl, the static gas pressure will decrease. It is then converted to the velocity by the strong Lorenz force that is kept higher than without an inlet swirl. Therefore, the pressure energy might be converted to the velocity effectively, because the stagnation gas pressure in case of the swirl ratio of -1.0 increases dramatically at the back of the MHD channel.

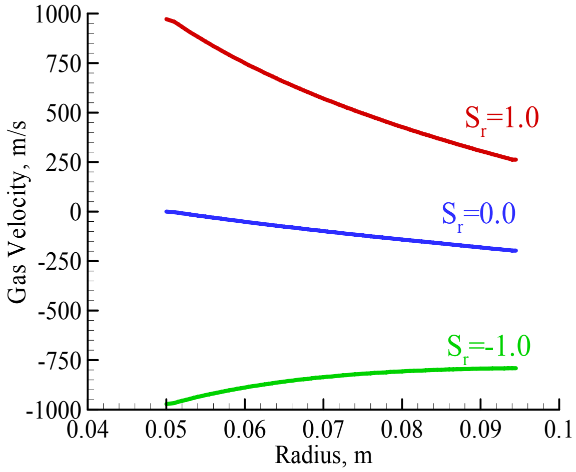
The plasma conductivity is proportional to the temperature, while the insensibility is in reverse proportional to pressure as shown in Fig.4 (d) in section V. Figure 6 (e) shows the distribution of gas temperature. The Hall parameter is the one of the importance parameters for this channel shape and connection method. Results of Hall parameter with an inlet swirl indicate very good results due to the pressure. Moreover, the distribution of the electric field is shown in Fig.6 (f). We can see that the distribution of a swirl ratio of -1.0 performs the highest values throughout the channel, particularly at the back of the MHD channel, and to be see in the green line which increases in counter clockwise of the gas flow. Figure 7 (g) and (h) show Hall and Faraday current density respectively. The inclinations of Hall current density j_r exponentially decreases. The difference from the distribution of the Faraday current density is that steeply intensity of the static gas pressure. The difference of the performance in both cases, positive and negative inlet swirl, is defined in the third term on the right of the following expression.

$$E_r = \frac{1+\beta^2}{\sigma} j_r - \beta u_r B - u_\theta B \tag{11}$$

Eq. (11) is so effective and the Lorenz force is so strong throughout the MHD region for the negative inlet swirl.

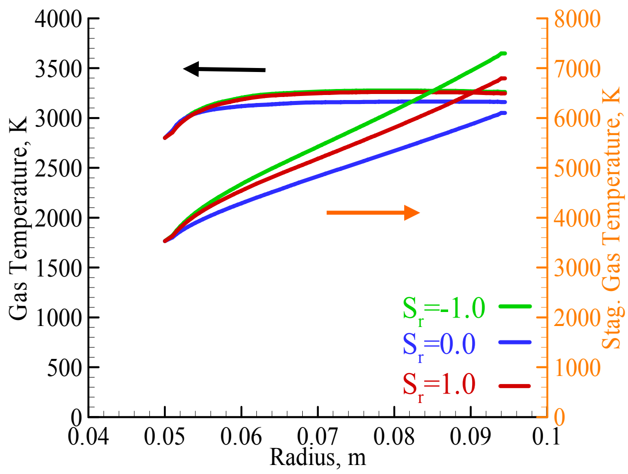


(a) Gas velocity of r-component

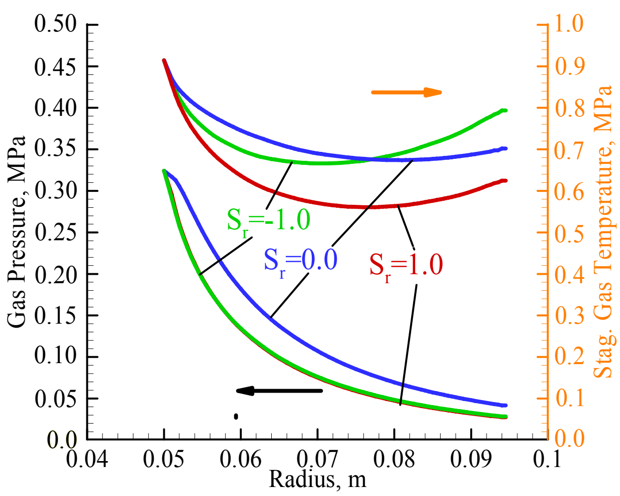


(b) Gas velocity of θ-component

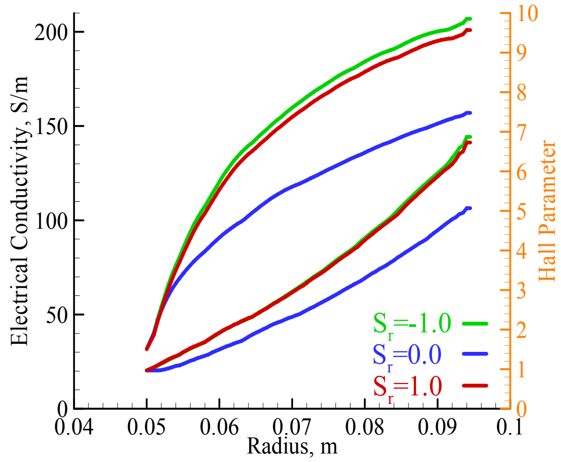
Fig.6 The performance of Disk MHD accelerator with swirl vane part 1



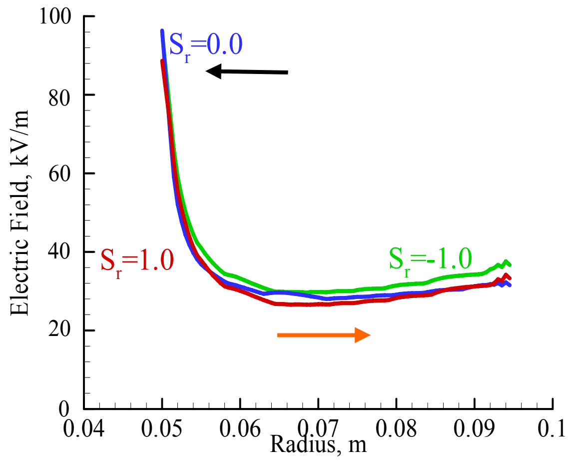
(c) Static and Stagnation gas temperature



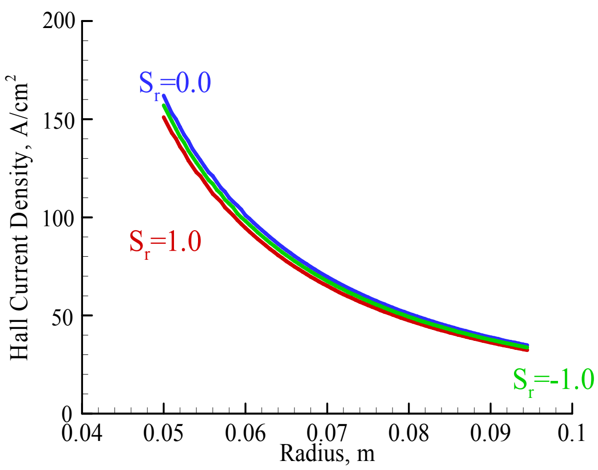
(d) Static and Stagnation gas pressure



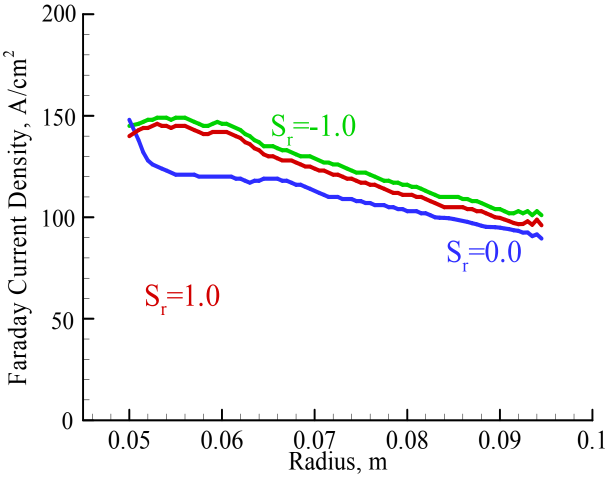
(e) Electrical conductivity and Hall parameter



(f) Electric field



(g) Hall current density



(h) Faraday current density

Fig.7 The performance of Disk MHD accelerator with swirl vane part 2

VIII. Conclusion

This study was to show the comparative analysis of Disk MHD accelerator with-and-without an inlet swirl in order to know its fundamental properties. So far, the following conclusions can be made.

- To set the swirl vane, MHD compression was improved.
- The swirl ratio of -1.0 showed the most acceleration of the r-direction velocity. The velocity of about 3100m/s at the exit of the channel was obtained.
- The limit value of input current at swirl ratio of 1.0 was below 600A. The higher the swirl ratio, the smaller its limit was obtained.
- When we varied the increment of the inlet swirl, the performance was improved. The swirl vane, in particular the inlet swirl of the negative one showed the best performance. There was an influence to the electric field, and this caused by the counter clockwise of the gas flow and the strong Lorenz force.
- The function of the inlet swirl is effective. However, to improve the performance for Disk MHD accelerator, we need to take the most-suited condition into account.

Nomenclature

u	=	gas velocity, m/s
E	=	electric field, V/m
j	=	current density, A/m^2
σ	=	electrical conductivity, S/m
β	=	Hall parameter
ρ	=	gas density, kg/m^3
B	=	magnetic flux density, T
T	=	temperature, K
P_L	=	pressure loss, Pa
Q_L	=	thermal loss, W
C_P	=	specific heat at constant pressure, J/kg/K
C_V	=	specific heat at constant volume, J/kg/K
E_S	=	total enthalpy, J/m^3
R	=	gas constant, J/kg/K

Subscript

stag	=	stagnation
g	=	gas
r, θ	=	cylindrical coordinate direction

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