Numerical Analysis of Acceleration Obtained from Pulsed-Linear-MHD Accelerator Using Model Rocket Engine

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To improve the thrust efficiency of a pulsed magnetohydrodynamic (MHD) accelerator, we perform numerical calculations that simulate the experimental conditions, which were used earlier, in an apparatus that include a model rocket engine. The one-fluid one-dimensional-MHD simulation results show agreement between the experimental and numerical results. We discuss simulation results for temporal and spatial distributions of the electrical conductivity and current density.

Keywords: Pulsed-MHD accelerator, numerical analysis, current density, magnetic flux density, Lorentz force

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Among the efficient options for long-distance propulsion systems that can be used to explore the Universe, electric propulsion systems offer the advantage of providing a high specific impulse [1]. Further, a magnetohydrodynamic (MHD) accelerator, which uses the Lorentz force to accelerate a working fluid, has the potential of providing both a high thrust force and a high specific impulse. In an earlier paper, we proposed a pulsed-MHD accelerator and conducted experiments using a model rocket engine [2, 3]. However, in the experimental efforts, it was difficult to understand the behavior of the working fluid in the channel. The purpose of this study is to analyze the working fluid behavior in the channel using a simulation that models the experimental condition and apparatus.

The experimental conditions and apparatus are schematically shown in Fig. 1 [3]. The MHD accelerator is a linear Faraday type with a channel length of 75 mm and a channel cross-section of $20 \times 20\,\mathrm{mm}^2$. To obtain acceleration via the Lorentz force and the thermal pressure, a current is applied by a pulse-forming network. Figure 2 shows the applied pulsed-current waveform. The maximum current is approximately -1.2 kA, and the current duration of full width at half maximum is estimated to be 120 μs. The electrode area is $20 \times 50\,\mathrm{mm}^2$ and is located at the center of the channel. Figure 3 shows the distribution of the applied magnetic flux density, which is applied by neodymium magnets that are located at the center of the channel [3]. In the numerical simulation, the Gaussian distribution is assumed as shown in Fig. 3. The combustion gas produced by a model rocket engine was used as the working fluid for a compact MHD accelerator experiment [3].

In this study, a one-fluid one-dimensional simulation in the direction of flow was numerically performed. Because the working fluid is a combustion gas, thermal equilibrium is assumed. The MHD governing equations consist

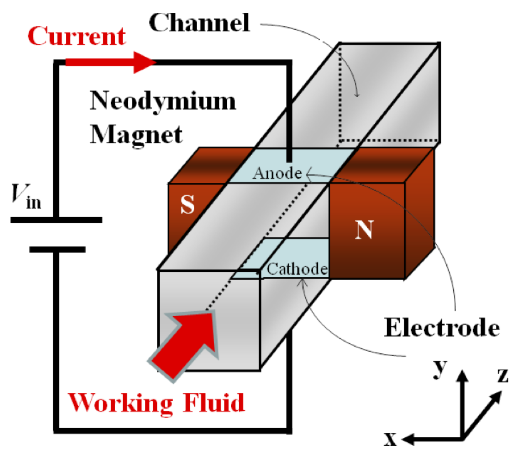

Fig. 1 Experimental setup for pulsed-MHD accelerator.

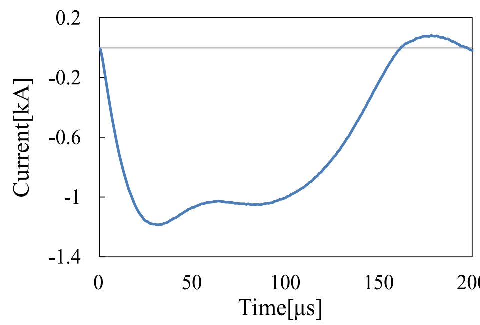

Fig. 2 Applied pulsed-current waveform.

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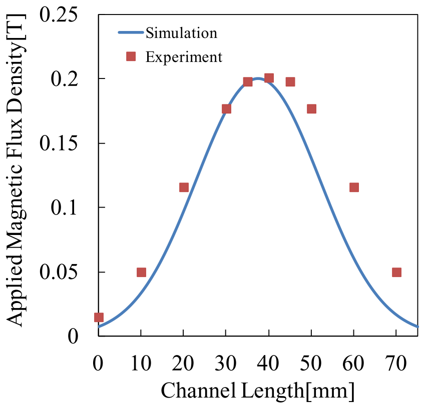

Fig. 3 Distribution of applied magnetic flux density.

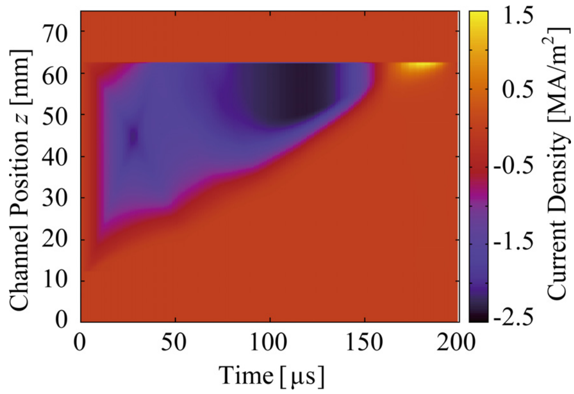

Fig. 5 Temporal and spatial distribution of current density.

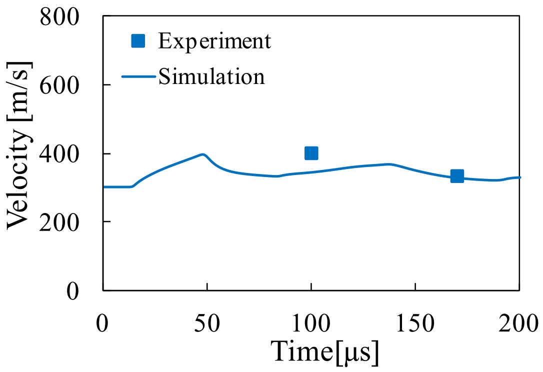

Fig. 4 Experimental and simulation results for fluid velocity at the outlet of the channel.

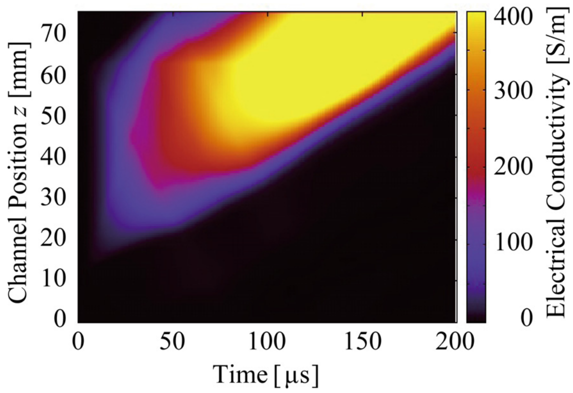

Fig. 6 Temporal and spatial distribution of electrical conductivity.

of continuity, momentum, and energy equations, as well as the ideal gas equation of state [4]. The model for electrical conductivity depends on the gas temperature [5], and the spatial distribution of current reflects the electrical conductivity distribution in the channel. The initial condition was assumed to be a steady flow of 300 m/s at 1900 K [3] with a density of 1.293 kg/m^3 in the whole channel. The inlet boundary condition (at channel position z = 0 mm) was also set to 300 m/s, 1900 K, and 1.293 kg/m^3.

For confirmation, Fig. 4 shows the calculated and the experimental results for the velocities at the outlet of the channel. The fluid velocity is increased due to the applied current. From the comparison, the experimental and numerical results for the time evolution of the velocity at the outlet of the channel show similar behavior.

The thrust F at the channel outlet is estimated by $F = u\,dm/dt$, where u is the velocity at the channel outlet (Fig. 4) and dm/dt is the mass flow rate. Because of the input current, the thrust increased from 46.5 N at the initial state to 99.1 N (the maximum value) at 46 μs.

Figure 5 shows the temporal and spatial distributions of current density. The electrode was placed between z = 12.5 mm and 62.5 mm. Although the current was applied entirely to the electrode during the pulse duration, the distribution was gradually localized towards the downstream side from the center of the channel.

The current path depends on the distribution of electrical conductivity. Figure 6 shows the temporal and spatial distribution of the electrical conductivity. Because of Joule heating, the electrical conductivity at the electrode increases with the increase in temperature. The electrical conductivity evolved with the behavior of the working fluid, as shown in Fig. 6. For this reason, the current density was partially distributed at the downstream side, as shown in Fig. 5.

Higher magnetic flux density was obtained around the center of the channel, as shown in Fig. 3. However, higher current density was achieved around the downstream side from the center of the channel, as shown in Fig. 5. Because the Lorentz force is generated by the multiplication of the current and magnetic flux density, the disagreement causes lower acceleration. Thus, in the present experimental condition and apparatus, it is difficult to obtain efficient acceleration by the Lorentz force in the latter half of the applied pulse current.

In this study, it was found that the working gas flows cause localized electrical conductivity and current density distributions. To obtain acceleration in the experiment, it is necessary to optimize the magnetic flux density and applied current distributions by appropriately selecting the arrangements and sizes of magnets, the pulse duration and waveform of the applied current, the electrode width and arrangement, among others.

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