

Original Research Article On the Reality of the Self-Field Lorentz-Force Accelerators

ABSTRACT

The electromagnetics is a source of plasma generation and acceleration in magnetoplasmadynamic thrusters. The Lorentz force and the Joule heating are the momentum and energy sources which act on the flow field there. In the present study, their effects are analyzed theoretically and numerically. It is shown that the effect of the Joule heating is much more than the Lorentz force effect especially in the self-field thrusters. Also the effect of the Lorentz force depends on the Mach number beside the direction of action. The results show that it is almost impossible to have the self-field Lorentz force accelerator.

Keywords: Electromagnetic, Lorentz force, Magnetoplasmadynamic, Numerical simulation, Self-field, Thruster.

NOMENCLATURE

$\vec{B}$	=	magnetic flux density vector
e	=	total specific energy
$\vec{E}$	=	electric field intensity vector
h	=	total specific enthalpy
$\vec{j}$	=	electric current density vector
p	=	local pressure
q	=	heat flux
$\vec{u}$	=	velocity vector
u	=	axial component of velocity
v	=	radial component of velocity
x	=	axial coordinate
y	=	radial coordinate
μ	=	magnetic permeability
σ	=	electric conductivity
θ	=	angular coordinate
τ_{ij}	=	stress tensor

1. INTRODUCTION

The low specific impulse of the chemical propulsion systems imposes some restrictions for space applications. This is due to the propellant's limited stored energy. To overcome such

limitations, additional energy can be supplied from external sources to increase the exhaust velocity and the specific impulse of thruster, like what happens in electric propulsion devices. The magnetoplasmadynamic thrusters (MPDT) are one kind of electric propulsion systems which heat the working gas up to an ionized state, and then accelerate the plasma. These thrusters may be used for deep space missions such as satellite station-keeping, due to the low thrust levels which required. Anyway, they offer much higher specific impulses in comparison with chemical rockets.

The initial idea of electric propulsion systems is about one hundred years old, and they have about forty five years operational history. There are also some experimental and numerical studies have been particularly done on MPDTs. These studies analyze the effects of geometry and propellant type [1-5], instability [6-9], electrode's erosion [10-11], or try to predict the thrust, electric power and specific impulse [12-20] in these propulsion devices.

MPDTs operate in two different modes: applied magnetic field and self induced magnetic field. In the self-field mode, the magnetic field is azimuthally induced due to the applied electric field, according to the Ampere's law. The coupling between applied electric field and applied or induced magnetic field produces an electromagnetic force which is called the Lorentz force. The combination of the Lorentz force and the Joule heating is the source of the working gas acceleration in MPDTs. The significance of the positive role of the Lorentz force in this process has been seemed high enough that these thrusters are sometimes called Lorentz-Force Accelerators [19, 21-22].

In the present study, the question is about the existence of an accelerator in which the Lorentz force is the driver of the compressible continuum fluid. So, the effects of Lorentz force and Joule heating in plasma flow acceleration in two-dimensional channel are analyzed using the physics of gas dynamics and numerical simulation. In addition, the plasma dynamics in an axisymmetric flow between concentric electrodes is studied both to show the importance of the momentum and energy's source terms in magnetoplasmadynamics. The results help understanding the mechanisms which have positive contribution in plasma acceleration, especially in self-field MPDTs.

2. GOVERNING EQUATIONS AND NUMERICAL PROCEDURE

In this study, the quasi steady, compressible, inviscid, fully ionized, isothermal, and single fluid plasma flow field is analyzed in a self induced magnetic field mode. To complete the governing equations, the electromagnetic field is considered using the Maxwell's equations. The axisymmetric flow governing equations in a conservative form are presented as [23]:

$$\frac{\partial U}{\partial t} + \frac{\partial(F)}{\partial x} + \frac{\partial(G)}{\partial y} + \frac{G + G'}{y} = ST \quad (1)$$

Where

$$U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \end{bmatrix} F = \begin{bmatrix} \rho u \\ \rho uu + p \\ \rho uv \\ \rho uh \end{bmatrix} G = \begin{bmatrix} \rho v \\ \rho vu \\ \rho vv + p \\ \rho vh \end{bmatrix} G' = \begin{bmatrix} 0 \\ 0 \\ -p \\ 0 \end{bmatrix} ST = \begin{bmatrix} 0 \\ J_y B_\theta \\ -J_x B_\theta \\ J_x E_x + J_y E_y \end{bmatrix} \quad (2)$$

The source terms in the flow equations are due to the electromagnetic field which affects the flow field due to the applied momentum and energy sources:

The Lorentz force (momentum source):

$$\vec{j} \times \vec{B} \quad (3)$$

80 And the Joule heating (energy source)

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$$\vec{j} \cdot \vec{E} \quad (4)$$

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83 The Maxwell's relations are the combination of the Faraday's, Ohm's, and Ampere's law
84 respectively as:

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$$\nabla \times \vec{E} = 0 \quad (5)$$

$$\vec{j} = \sigma(\vec{E} + \vec{u} \times \vec{B}) \quad (6)$$

$$\nabla \times \vec{B} = \mu \vec{j} \quad (7)$$

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87 The Lorentz force, Joule heating and the Ohm's law correlate the flow and electromagnetic
88 fields together.

89 Here, the cell centered finite volume method is used to discretize the equations. Diffusion
90 terms are computed using a central scheme and the flow field is treated using an AUSM+
91 method to express the numerical flux on cell faces [24]. The developed numerical procedure
92 has been successfully utilized to study different aero-thermodynamic problems [25-28].
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94 3. RESULTS AND DISCUSSION

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96 At first, the plasma flow within a two-dimensional channel is considered where the uniform
97 electric and magnetic fields are assumed in the mid part as Fig. 1. Therefore, the flow field's
98 equations are just considered with constant source terms due to the uniform applied fields.
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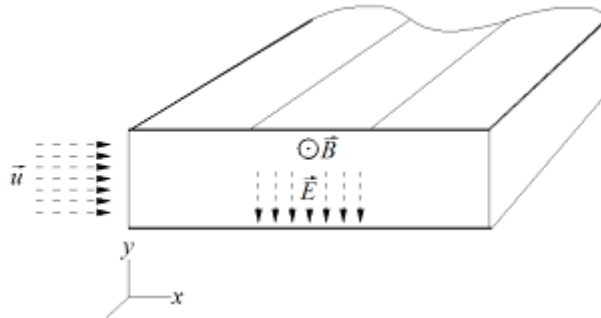


Fig. 1: Schematic of the flow with applied constant fields.

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103 The Joule heating is a positive term which increases the energy of the fluid flow and isn't
104 related to the field's direction. On the other hand, the Lorentz force depends on the field's
105 direction; if the applied fields are as seen in Fig. 1, the Lorentz force is in opposite direction
106 of the flow, but if the magnetic field is applied in opposite direction (into the plate), the
107 Lorentz force acts in the flow direction.

108 The question is how the Lorentz force and Joule heating accelerate the compressible
109 continuum flow. Before the numerical analysis, it is better to flash back to the Fanno and
110 Rayleigh flows in gas dynamics. There can be summarized that the friction force accelerates
111 the subsonic flow and decelerates the supersonic flow. Also the heat addition accelerates
112 the subsonic flow and decelerates the supersonic flow.

113 Therefore, this is obvious that the Joule heating's contribution depends just on the Mach
114 number, but the contribution of the Lorentz force depends both on the Mach number and the
115 force's direction; that is if the Lorentz force be in the flow direction, it has an accelerating
116 effect just in supersonic flow but has decelerating effect on subsonic flow. Such behavior is

117 due to the continuity and the coupling of the momentum and energy in compressible flows. It
118 can be summarized in Table1.

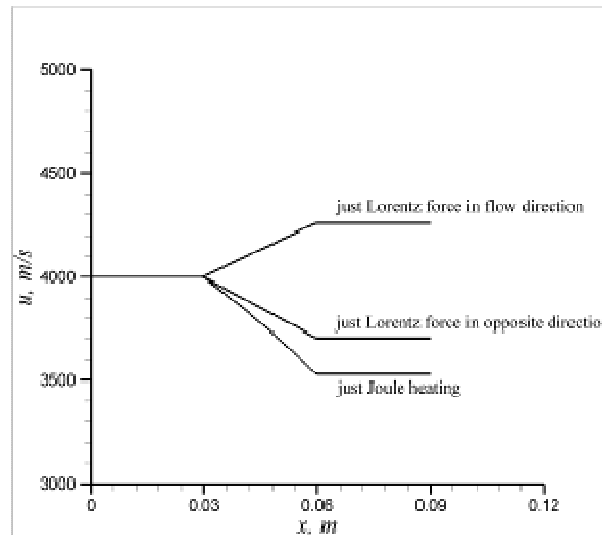
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Table1: Electromagnetics effects on flow field's acceleration.

Driver	Subsonic flow	Supersonic flow
Joule heating	positive	negative
Lorentz force in flow direction	negative	positive
Lorentz force in opposite direction	positive	negative

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The numerical simulations confirm this behavior. To show that, the supersonic flow of an Argon in a channel is studied here. The channel length is 0.09 m which the fields are applied on the one-third of the mid part. The inlet temperature, pressure, and velocity are 5000 K, 1 kPa, and 4000 m/s respectively, and the electric conductivity equals 1000 A/Vm. Inlet Mach number is about 3.74. The magnitude of the applied electric and magnetic fields are 1.5 kV/m and 0.02 T respectively. The axial distribution of the velocity is shown in Fig. 2. Just aligned Lorentz force has individually an accelerating effect.



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Fig. 2: Velocity distribution in a channel under applied fields.

134 It should be noticed that both Lorentz force and Joule heating exist simultaneously in
135 MPDTs. So, when is the flow accelerated? There are three cases where the acceleration will
136 occur: if the Lorentz force is applied in opposite direction in subsonic flow; if the effect of
137 Joule heating is more than the Lorentz force in subsonic flow; or if the Lorentz force is
138 applied in flow direction in supersonic flow and the effect of Joule heating is less than the
139 Lorentz force.

140 These show that if the contribution of the Joule heating is more than the Lorentz force, there
141 is no acceleration due to the aligned Lorentz force. The author believes that the magnitude
142 of an induced magnetic field in self-field MPDTs is not high enough to produce a comparable
143 Lorentz force effect with the Joule heating influence. In addition, it will be shown that the
144 induced magnetic field is not in a unique direction; the sign changes from negative to
145 positive in flow direction. So, the Lorentz force has both accelerating and decelerating

146 effects in a flow field. Therefore there is no self-field Lorentz force accelerator as sometimes
 147 referred!
 148 In a previous example, the magnetic field should be more than about 0.034 T into the plate
 149 to neutralize the negative role of the Joule heating and accelerate the fluid. But, this critical
 150 value is so much. It should be considered that the induced magnetic field is the outcome of
 151 the electric current and to increase it, the electric field should be increased and so the Joule
 152 heating is magnified again.
 153 Here, the axisymmetric flow between concentric cylinders with 0.09 m length is considered
 154 where the flow conditions are like before. The outer and inner radiuses are 0.04 m and 0.01
 155 m respectively in which the electric potential difference of 50 V is applied on electrodes with
 156 0.03 m length in a mid part of the cylinders. After the solution of the Maxwell's relations, the
 157 electric and the induced magnetic fields are shown in Fig. 3 and Fig. 4 respectively.
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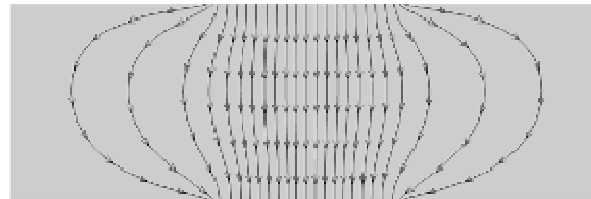


Fig. 3: Electric field between concentric electrodes.



Fig. 4: Induced magnetic field between concentric electrodes.

163 The tangential induced magnetic field is negative in the first half of the chamber and is
 164 positive in the second half, and its maximum magnitude is about 0.01 T. The Lorentz force is
 165 first aligned and then is in opposite direction of the flow. So the supersonic plasma is first
 166 accelerated and then decelerated due to the Lorentz force in concentric electrodes, as
 167 demonstrated in Fig. 5. It is shown that the Lorentz force has no effect in such
 168 configurations.
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Fig. 5: Axial velocity contours due to the Lorentz force effect.

The numerical simulation of this problem with applying both source terms leads to interesting results. The decelerating effect of the Joule heating is much that the velocity decreases to the subsonic value and the shock wave appears in the chamber as Fig. 6. Such phenomenon could be seen in Rayleigh flow in gas dynamics. Here, the average exit velocity is about half of the inlet velocity.

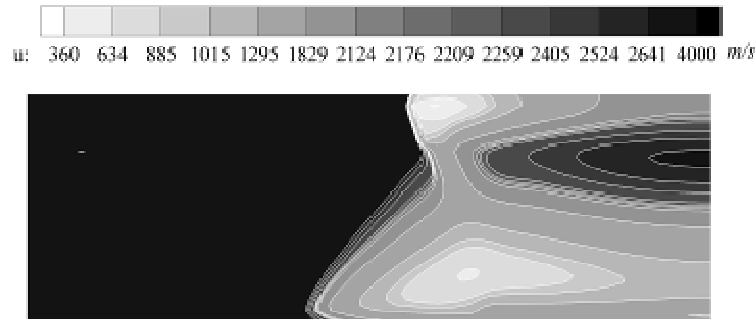


Fig. 6: Axial velocity contours due to the electromagnetic effects.

As mentioned before, the Joule heating has the main effect on the self-field magnetoplasma dynamic thrusters and it has accelerating role only in subsonic plasma flows. In applied magnetic field thrusters, one can use a powerful magnetic coil to increase the role of the Lorentz force and use it to accelerate the supersonic plasmas.

4. CONCLUSION

In the present study, the theoretical analysis and numerical simulation is used to show the contribution of the Lorentz force and the Joule heating in plasma acceleration in magnetoplasma dynamic thrusters. It is explained that the Lorentz force in opposite direction and the Joule heating can accelerate the subsonic but just aligned Lorentz force can accelerate the supersonic flows. It is shown that the effect of Joule heating is more than the Lorentz force especially in self induced MPDTs. Also the Lorentz force effect in some configurations is totally disappeared due to anti-symmetry of the induced magnetic field. So it is concluded that there is no self-field Lorentz force accelerator and there is just subsonic plasma accelerator using the Joule heating process. In applied field thrusters, amplifying the magnetic field may lead the considerable Lorentz force to accelerate the supersonic plasmas. In supersonic self-field thrusters it is better to use the electromagnetics to accelerate the plasma just before the throat and then increase the exit velocities using divergent nozzles, based on gas dynamics; electric current existence in a divergent part will reduce the performance of the accelerator.

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