British Journal of Applied Science & Technology
8(6): 595-601, 2015, Article no.BJAST.2015.237
ISSN: 2231-0843

SCIENCEDOMAIN *international*
www.sciencedomain.org

On the Reality of the Self-field Lorentz-Force Accelerators

A. M. Tahsini[1*]

[1]*Aerospace Research Institute, Ministry of Science, Research and Technology, Tehran, Iran.*

Author's contribution

The sole author designed, analyzed and interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/BJAST/2015/17533
Editor(s):
(1) João Miguel Dias, Habilitation in Department of Physics, CESAM, University of Aveiro, Portugal.
Reviewers:
(1) Alejandro Morales-Bayuelo, Chemistry, University of Talca, Chile.
2) Anonymous, India.
(3) Anonymous, Taiwan.
Complete Peer review History: http://www.sciencedomain.org/review-history.php?iid=1074&id=5&aid=9152

Original Research Article

Received 18th March 2015
Accepted 17th April 2015
Published 8th May 2015

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*

**Corresponding author: E-mail: a_m_tahsini@yahoo.com;*

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

$$U=\begin{bmatrix}\rho\\ \rho u\\ \rho v\\ \rho e\end{bmatrix} F=\begin{bmatrix}\rho u\\ \rho uu+p\\ \rho uv\\ \rho uh\end{bmatrix} G=\begin{bmatrix}\rho v\\ \rho vu\\ \rho vv+p\\ \rho vh\end{bmatrix} G'=\begin{bmatrix}0\\ 0\\ -p\\ 0\end{bmatrix} ST=\begin{bmatrix}0\\ J_yB_\theta\\ -J_xB_\theta\\ J_xE_x+J_yE_y\end{bmatrix} \quad (2)$$

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):

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

And the Joule heating (energy source)

$$\vec{J}.\vec{E} \quad (4)$$

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

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

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

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

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

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

3. RESULTS AND DISCUSSION

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

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

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

Therefore, this is obvious that the Joule heating's contribution depends just on the Mach number, but the contribution of the Lorentz force depends both on the Mach number and the force's direction; that is if the Lorentz force be in the flow direction, it has an accelerating effect just in supersonic flow but has decelerating effect on subsonic flow. Such behavior is due to the continuity and the coupling of the momentum and energy in compressible flows. It can be summarized in Table1.

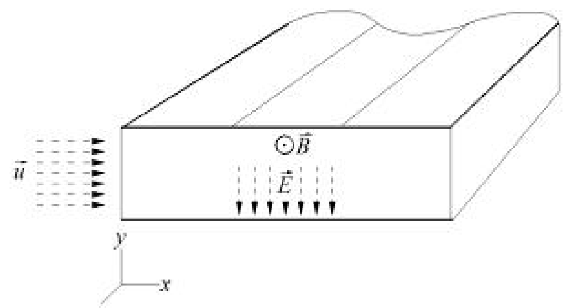

Fig. 1. Schematic of the flow with applied constant fields

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.

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

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

In a previous example, the magnetic field should be more than about 0.034 T into the plate to neutralize the negative role of the Joule heating and accelerate the fluid. But, this critical value is so much. It should be considered that the induced magnetic field is the outcome of the electric current and to increase it, the electric field should be increased and so the Joule heating is magnified again.

Here, the axisymmetric flow between concentric cylinders with 0.09 m length is considered where the flow conditions are like before. The outer and inner radiuses are 0.04 m and 0.01 m respectively in which the electric potential difference of 50 V is applied on electrodes with 0.03 m length in a mid part of the cylinders. After the solution of the Maxwell's relations, the electric and the induced magnetic fields are shown in Fig. 3 and Fig. 4 respectively.

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

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.

Table 1. 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

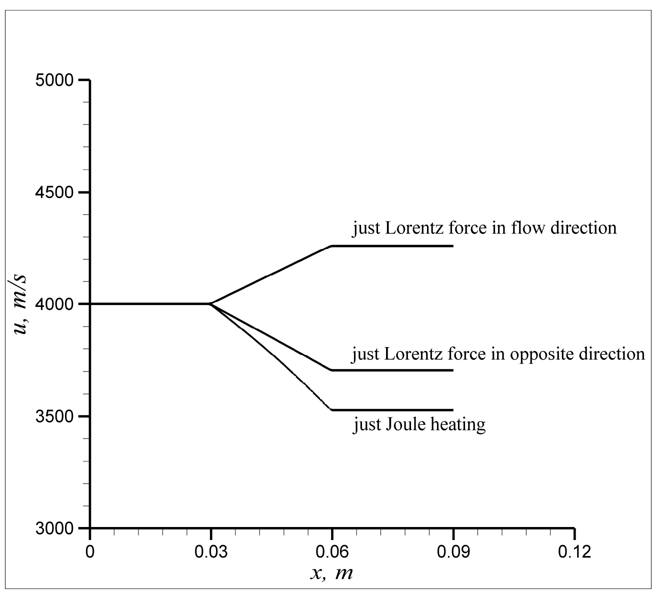

Fig. 2. Velocity distribution in a channel under applied fields

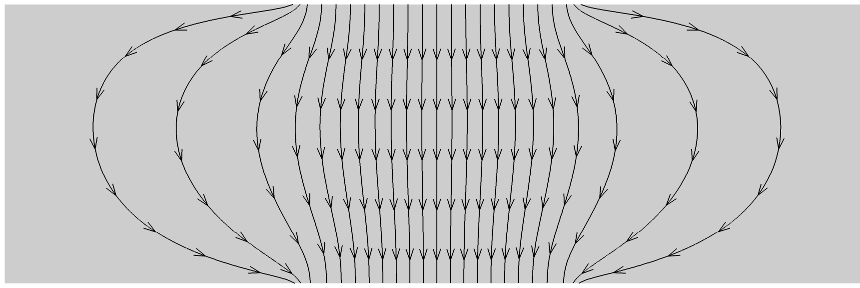

Fig. 3. Electric field between concentric electrodes

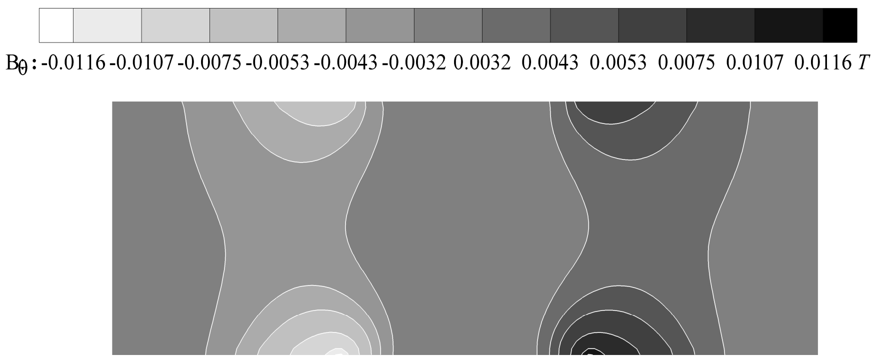

Fig. 4. Induced magnetic field between concentric electrodes

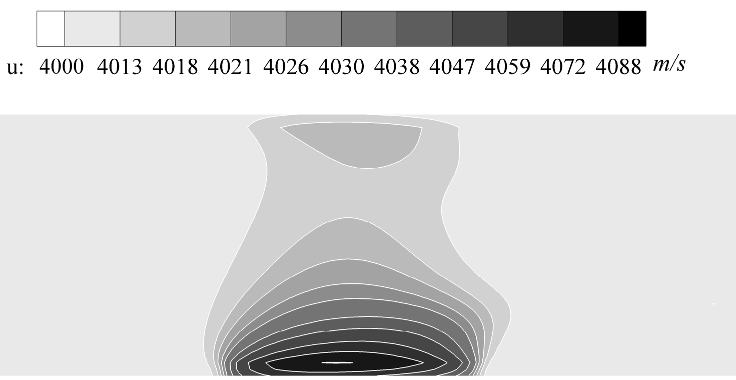

Fig. 5. Axial velocity contours due to the Lorentz force effect

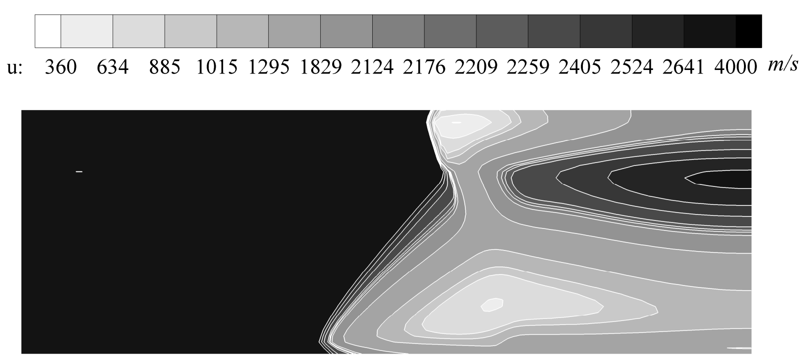

Fig. 6. Axial velocity contours due to the electromagnetic effects

Such phenomenon could be seen in Rayleigh flow in gas dynamics. Here, the average exit velocity is about half of the inlet velocity.

As mentioned before, the Joule heating has the main effect on the self-field magnetoplasmadynamic 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 magnetoplasmadynamic 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.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Colasurdo G, Casalino L. Optimal geometry of self-field magnetoplasma-dynamic thrusters. Journal of Propulsion and Power. 2001; 17(2):472-474,
2. Mahendhran M, Kumar A. Numerical sturdy on the effect of electrode geometry in MPD thrusters. 32nd International Electric Propulsion Conference; 2011. Germany, IEPC-2011-228, 2011.
3. Nakata D, Toki K, Funaki I, Shimizu Y, Kuninaka H, Arakawa Y. Experimental verification of the nozzle shape optimization for self-field MPD thruster. 29th International Electric Propulsion Conference; 2005. Princeton Univ., IEPC-2005-163, 2005.
4. Sato H, Kubota K, Funaki I. Modeling and numerical simulation of a two-dimensional MPD thruster using a hydrogen propellant. 32nd International Electric Propulsion Conference; 2011. Germany, IEPC-2011-258, 2011.
5. Lapointe MR. Numerical simulation of cylindrical self-field MPD thrusters with multiple propellants. NASA Lewis Research Center; 1994. NASA-C-R-194458.
6. Uribarri L, Choueiri EY. Creation of onset voltage hash by anode spots in a magnetoplasmadynamic thruster. Journal of Propulsion and Power. 2009;25(4):949-957.
7. Wagner HP, Kaeppeler HJ, Auweter-Kurtz M. Instabilities in MPD thruster flows: investigation of drift and gradient driven instabilities using multi-fluid plasma models. Journal of Physics D: Applied Physics. 1998;31:529-541.
8. Tilley DL, Choueiri EY, Kelly AJ, Jahn RG. Microinstabilities in a 10-Kilowatt self-field magnetoplasmadynamic thruster. Journal of Propulsion and Power. 1996;12(2):381-389.
9. Subramaniam VV, Lawless JL. Onset in magnetoplasmadynamic thrusters with finite-rate Iionization. Journal of Propulsion and Power. 1988;4(6):526-532.
10. Schrade HO, Auweter-Kurtz M, Kurtz HL. Cathode erosion studies on MPD thrusters. AIAA Journal. 1987;25(8):1105-1112.
11. Myers RM, Suzuki N, Kelly AJ, Jahn RJ. Cathode phenomena in a low power magnetoplasmadynamic thruster. Journal of Propulsion and Power. 1991;7(5):760-766.
12. Choueiri E. Scaling of thrust in self-field magnetoplasmadynamic thrusters. Journal of Propulsion and Power. 1998;14(5):744-753.
13. Mikellides PG. Modeling and analysis of a megawatt-class magnetoplasmadynamic

thruster. Journal of Propulsion and Power. 2004;20(2):204-210.
14. Auweter-Kurtz M, Kurtz HL, Schrade HO, Sleziona PC. Numerical modelinf of the flow discharge in MPD thrusters. Journal of Propulsion and Power. 1989;5(1):49-55.
15. Heierman J, Auweter-Kurtz M. Numerical and experimental investigation of the current distribution in self-field magnetoplasmadynamic thrusters. Journal of Propulsion and Power. 2005; 1(1):119-128.
16. Sankaran K, Choueiri EY, Jardin SC. Comparison of simulated magnetoplasma-dynamic thruster flowfields to experimental measurements. Journal of Propulsion and Power. 2005; 21(1):129-138.
17. Kubota K, Funaki I, Okuno Y. Numerical study of plasma behavior in a magnetoplasmadynamic thruster around critical current. Journal of Propulsion and power. 2009;25(2):397-405.
18. Gallimore AD, Kelly AJ, Jahn RG. Anode power deposition in magnetoplasma-dynamic thrusters. Journal of Propulsion and power. 1993;9(3):361-368.
19. Choueiri E, Ziemer JK. Quasi-steady magnetoplasmadynamic thruster performance database. Journal of Propulsion and power. 2001;17(5):967-976.
20. Andreussi T, Pegoraro F. Magnetized plasma flows and magnetoplasmadynamic thrusters. Physics of Plasmas. 2010;17(063507):1-11.
21. Sankaran K. Simulation of plasma flows in self-field lorentz force accelerators. PhD thesis, Princeton Univ., Princeton, NJ; 2005.
22. Rock B, Blandino JJ, Anderson KR, Polk JE. Thermal analysis of a lithium vaporizer for a high-power magnetoplasmadynamic thruster. Journal of Propulsion and power. 2006;22(5):1098-1110.
23. Kuo KK. Principles of Combustion, Chapter 3, 2nd edition, Wiley and Sons; 2005.
24. Liou MS. A sequel to AUSM: AUSM+. Journal of Computational Physics. 1996;129:364-382.
25. Tahsini AM. Heat Release Effects on Drag Reduction in High Speed Flows. International Journal of Heat and Mass Transfer. 2013;57(2):657-661.
26. Tahsini AM. Ignition delay time in swirling supersonic flow. ACTA Astronautica. 2013;83:91-96.
27. Tahsini AM. Piloted ignition of solid fuels in turbulent back-step flows. Aerospace Science and Technology. 2012;18(1):8-14.
28. Tahsini AM. Turbulence and Additive Effects on Ignition Delay in Supersonic Combustion. IMechE Journal of Aerospace Engineering. 2013;227(1):93-99.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history.php?iid=1074&id=5&aid=9152