

INVESTIGATION OF PLASMA VISCOSITY AND MAGNETIC FORCES IN COAXIAL PLASMA DISCHARGE DEVICE

Hanaa Abdelfattah El-Sayed, Tarek Mohamed Allam, Ahmed Abdallah Lashin*, Kamal Mohamed Ahmed, and Hanaa Mohamed Soliman

Received: May 17, 2024; Revised: July 02, 2024; Accepted: July 24, 2024

Abstract

This paper investigates the axial plasma current sheath, PCS viscosity force, and its correlation with other magnetic forces acting on it at three different radial positions (2.625, 3.625, and 4.125 cm) within the annular space between the coaxial electrodes system of plasma discharge device (12 kV-56 kA) with positive central electrode. The rate of change of PCS momentum was also investigated at these axial and radial positions. The discharge processes are carried out with an argon gas pressure of 0.8 Torr. Experimental results of azimuthal magnetic induction as a function of axial and radial positions and Navier Stokes equation were employed to compute exactly, the rate of change of PCS momentum, axial magnetic force, magnetic pressure gradient force, and viscosity force.

Keywords: Coaxial Plasma Discharge; Magnetic Forces; Plasma Current Sheath Mass; Viscosity Force

Introduction

Plasma focus (PF) devices have attracted much attention in the most recent years owing to their simple design and low operating costs. These devices have the capability to generate and intensify the current layer to create a compact and highly concentrated pinch that lasts for a brief duration, usually around tens of nanoseconds (Soto, 2005). In typical DPF operation, the plasma current sheath is first formed along the insulator surface on the inner electrode and ahead by the forces of $J \times B$. In most cases, a fill gas at a pressure of 1 Torr is employed. At the end of the inner electrode, the sheath expands and collides to form a high-density

($n_e \sim 10^{19}$ - $10^{20}/\text{cm}^3$ and $T_e \sim 1$ -10 keV) z-pinch plasma (Krompholz *et al.*, 1977; Bertalot *et al.*, 1980; Rhee, 1980; Stygar *et al.*, 1982).

In the initial phase (Bruzzone and Grondona, 1999; Bhuyan *et al.*, 2003) and the axial acceleration phase (Chow *et al.*, 1972; Mathuthu *et al.*, 1996) of the dense plasma focus (DPF) device, the magnetic probe provides a straightforward and inexpensive diagnostic for measuring the arriving of the current sheet (as well as its velocity), the magnitude of the azimuthal magnetic field, and the spatial distribution of the current sheet's magnetic field.

Plasma and Nuclear Fusion Department, Nuclear Research Center, Egyptian Atomic Energy Authority, Cairo, Egypt.
E-mail: hanaa.elshamy@yahoo.com; tarekmya@hotmail.com; ahmedlashin27@yahoo.com*; kamal_hagag@yahoo.com; hanaa.soliman1@hotmail.com

* Corresponding author

DOI: <https://doi.org/10.55766/sujst-2024-04-e04858>

Suranaree J. Sci. Technol. 31(4):030216(1-8)

Thus, point measurements of magnetic field fluctuations inside the plasma can be obtained quantitatively by inserting magnetic probes into the discharge chamber of plasma-producing machines. Consequently, they have found extensive application, despite the fact that they can occasionally have substantial unsettling effects on the plasma. It is common practice to employ numerous probes, which can provide sufficiently precise information from an individual discharge, to determine the spatial distributions of the fields, which requires measurements at several locations (Berglund *et al.*, 1963; EL-Sayed *et al.*, 2015a; Lashin *et al.*, 2021).

Viscosity is one of the important parameters of fluid state condition (Yunus, 2010), it reveals details on the forces of friction in a fluid motion. Positive viscous force causes a reduction in plasma flow velocity (Landau and Lifshitz, 1987; Balescu *et al.*, 2000). Sivashinsky and Yakhat (Sivashinsky and Yakhat, 1985) mathematically demonstrated that when applied flow fluid is in a certain direction, which may be a magnetic field or secondary flow field then, the effective viscosity becomes negative or positive according to the orientation of the applied field.

The minimal viscosity results from the temperature-dependent effects of kinetic and potential contributions to the transmission of momentum (Saigo and Hamaguchi, 2002; Liu and Goree, 2005). The variations in viscosity with exterior magnetic fields can be characterized by considering the kinetic as well as potential components of shear stress under these fields (Feng *et al.*, 2017).

Our work aims to investigate the plasma viscous force and its correlation with magnetic forces such as axial magnetic force (Lorentz force) and magnetic pressure gradient force acting on plasma current sheath propagation during the axial phase of coaxial discharge and at different radial distances. The rate of change of PCS momentum is also investigated at the same axial and radial positions.

Materials and Methods

A schematic of the 2.2 kJ Egyptian Atomic Energy Authority-Plasma Focus 1 (EAEA-PF1) device with its electrical circuit and diagnostic techniques is shown in Figure 1. The diagnostic techniques include the 3-set of identical tiny magnetic probes, which were installed at the annular space between the two coaxial electrodes to measure the azimuthal magnetic field induction during the axial phase. Additionally, a Rogowski coil was employed to measure the discharge current from the capacitor bank ($3 \times 10 \mu\text{F}$) to the coaxial electrode system. Further examination of the EAEA-PF1 device's construction and its electrical circuit was conducted in our earlier article (Lashin *et al.*, 2019).

Table 1 summarizes the parameters and materials of each component of the EAEA-PF1 device under study. The chamber of the EAEA-PF1 was evacuated to a vacuum with a pressure of less than 8×10^{-3} Torr. Then, Ar gas was fed to the chamber with a pressure of 0.8 Torr. To maintain the intended pressure and reduce the impurities inside the discharge chamber, it is refilled with Ar gas after 9 shots.

Table 1. Parameters and materials of the EAEA-PF1 device

	Inner Electrode, IE	Outer Electrode, OE	Insulator
Radius	2.25 cm.	4.5 cm.	Inner radius of 2 cm. and thickness of 0.3 cm.
Length	10.5 cm.	18 cm. (8 rods each of 1 cm diameter)	2.2 cm.
Material	Brass	Brass	Cylindrical Pyrex glass

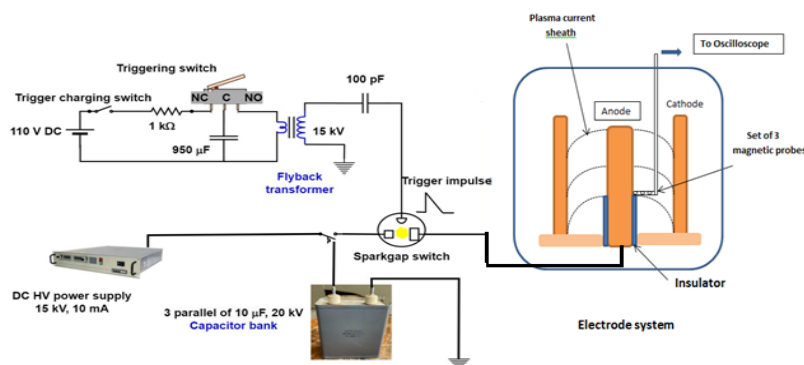


Figure 1. Schematic of 2.2 kJ EAEA-PF1 device with its electrical circuit and diagnostic techniques

At the beginning of the discharge process, the capacitor bank is charged to the desired voltage via an air-spark gap switch; then, a discharge is initiated between the median part of the anode directly above the glass tube and the base of the cathode. Following that, the plasma current sheath is created and moved axially towards the coaxial electrode muzzle.

Three magnetic probes are placed on various radial positions within the annular space between the inner electrode (IE) and the outer electrode (OE), at radial positions $r = 2.625, 3.625$, and 4.125 cm from the centerline of the electrode system.

Results and Discussion

Experimental work in this paper was carried out and focused on the third half cycle of discharge current, I_{dis} . The maximum value of $I_{dis} = 56$ kA at charging voltage = 12 kV. Figure 2 shows the I_{dis} signal, we noticed a smooth I_{dis} signal and no appearance of a dip in the current signal, indicating that no PF action formed during this period. The experimental results of inclination angle, θ of PCS with axial distance, z confirmed the observation of defocus phenomena during this period.

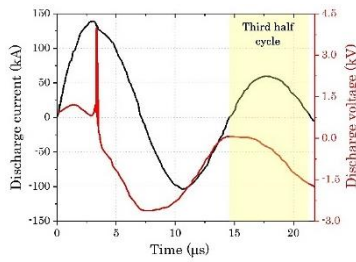


Figure 2. Discharge current (black) and voltage (red) signals

The angle θ at the IE surface on average = 82° along the axial PCS propagation is estimated from the arrival time of PCS as a function of z distance by using magnetic probe techniques, as previously described in reference (Lashin *et al.*, 2021). Then the PCS propagates approximately axially perpendicular to the z -axis during the axial phase and the convergent of PCS at coaxial electrodes muzzle was not presented (Lashin *et al.*, 2019).

All the above results illustrated that the PF radial phase is not formed during this period of discharge and the PF device was operated as a coaxial plasma discharge accelerator with positive IE polarity.

Investigations of viscosity force and its correlation with magnetic forces acting on the plasma current sheath (PCS) movement during the axial and the radial positions (z, r) respectively within the annular space of the coaxial electrode system of our device, were estimated by using Navier Stokes equation with data of measured azimuthal magnetic field induction signals for discharge current of a maximum value of 56 kA. The rate of change of PCS momentum was also computed at the same discharge conditions and positions (z and r).

Navier Stokes equation assumed that the rate of change of momentum is equal to the sum of the forces acting on PCS (Chen, 1974),

$$\frac{d}{dt}(mv_z) = \int [J_r \times B_\theta - \nabla P + \frac{\eta}{3} \nabla(\nabla \cdot v_z) + \eta \nabla^2 v_z] dV \quad (1)$$

where; m is the PCS mass
 J_r is the radial PCS current density
 B_θ is the azimuthal magnetic field induction
 ∇P is the pressure gradient in the inter-electrode space of the coaxial electrode system
 v_z is the axial PCS velocity
 η is the viscosity coefficient
 dV is the PCS element volume = $(2\pi r dr) \lambda$, where λ is the PCS thickness.

Then the PCS volume, $V_{PCS} = \lambda \int_a^r 2\pi r dr = \pi(r^2 - a^2) \lambda$

The L.H.S term of equation (1) represents the rate of change of PCS momentum or total forces, F_t acting on PCS

$$\frac{d}{dt}(m v_z) = m \dot{v}_z + \dot{m} v_z \quad (2)$$

$$m = \rho f_m V_{PCS} = \rho f_m \pi(r^2 - a^2) \lambda \quad (3)$$

Table 2. Data of λ and f_m at different z and r positions

$z \times 10^{-2}$ (m)	$r = 2.625 \times 10^{-2}$ (m)		$r = 3.625 \times 10^{-2}$ (m)		$r = 4.125 \times 10^{-2}$ (m)	
	$f_m \times 10^{-3}$	$\lambda \times 10^{-2}$ (m)	$f_m \times 10^{-3}$	$\lambda \times 10^{-2}$ (m)	$f_m \times 10^{-3}$	$\lambda \times 10^{-2}$ (m)
3	3.9	0.15	5.5	0.42	1.47	0.387
5	5.3	0.205	2.65	0.265	5.86	0.533
8	4.22	0.539	6.53	0.965	4.6	0.839
9	2.75	0.236	9.7	0.576	3.2	0.3456
10	3.024	0.21	1.69	0.254	3.53	0.4748

where ρ is the argon gas density = 1.71×10^{-3} kg/m³ at $P = 0.8$ Torr. The f_m is the mass shedding factor. λ and f_m , were estimated by the same method as previously (Bhuyan *et al.*, 2003; El-Sayed *et al.*, 2015b). Table 2 shows the data of λ , and f_m at different z and r positions.

The PCS arrival time, t as a function of z and r was estimated from $\frac{dB_\theta}{dt}$ signals which are measured by magnetic probe tools are presented in Figure 3. The axial PCS velocity, $V_z = \frac{dz}{dt}$ and acceleration $v_z = \frac{dv_z}{dt}$ as a function of z and t for different r positions are shown in Figure 4 (a), Figure 4 (b), and Figure 5, respectively.

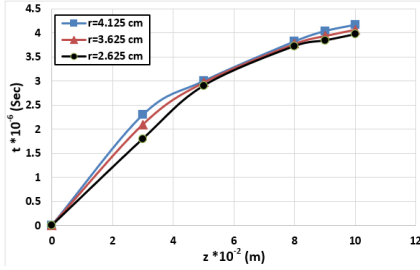


Figure 3. PCS arrival time, t as a function of z and r .

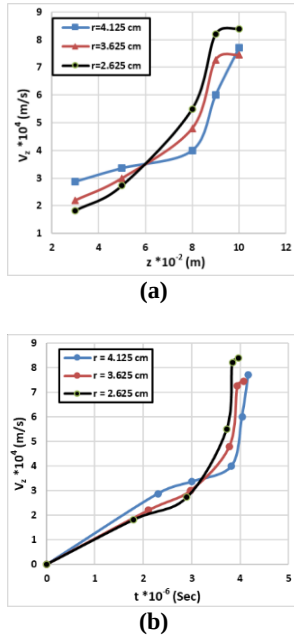


Figure 4. PCS axial velocity, V_z as a function of z (a) and t (b) for different r positions

According to Figure 5, the maximum values of v_z varies between 8 and 10 cm for different r positions, reaching its maximum at an axial distance close to the muzzle of the coaxial electrodes.

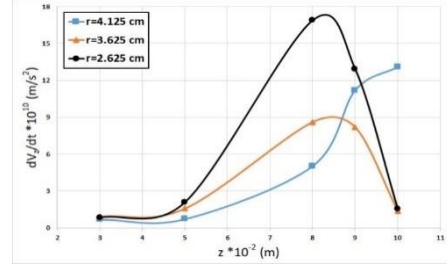


Figure 5. PCS axial acceleration, $\dot{V}_z$ as a function of z at different r positions

The distribution of PCS mass, m versus t and z respectively are shown in Figure 6(a) and Figure 6(b) for different r positions.

These distribution profiles may be related to f_m and PCS thickness, λ .

m' can be estimated from Figure 6 as a function of z for different r positions, Figure 7 shows the mass flow rate, m' versus z at different r positions.

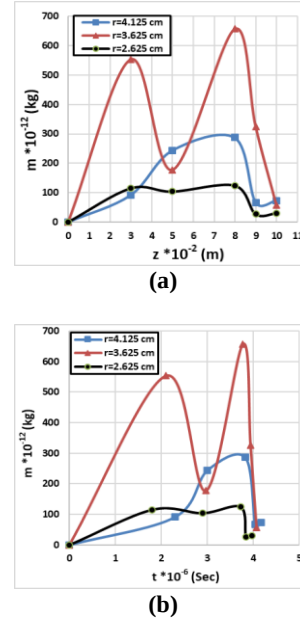


Figure 6. Variation of m (a) with z and (b) with t for different r distances

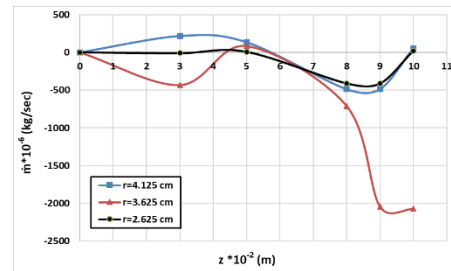


Figure 7. Axial distribution of m' at different r

Substitute the data of Table 2, Figures 4, 5, 6 (a), and 7 in equation (2), then the rate of change of PCS momentum or total force acting on PCS (L.H.S) of equation (1) is evaluated as a function of z and r . Figure 8 (a) and Figure 8 (b) show $\frac{d}{dt}(mv)$ variation with z and at different r values. Profiles of Figure 8 (a) and Figure 8 (b) are related to the distribution of PCS mass and acceleration as a function of t and z . Also, the total force has approximately the same profile and it has a peak negative value at axial distance, z approaches to coaxial electrodes muzzle, $z = 9$ cm for all r positions under consideration.

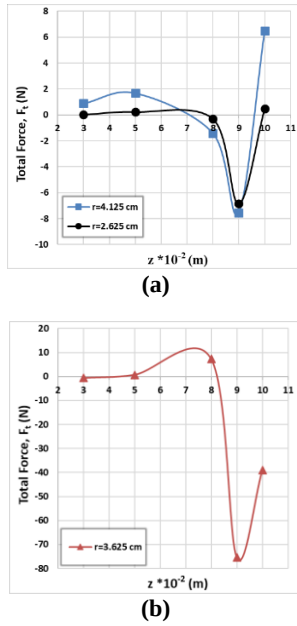


Figure 8. Distribution of rate of change of momentum (total force) acting on PCS as a function of z for (a) $r = 2.625$ and 4.125 cm and (b) $r = 3.625$ cm

The first term of R.H.S of equation (1), represents the axial magnetic force (Lorentz force), F_L is given by:

$$F_L = \int (J_r \times B_\theta) dv = \int_a^r \frac{B_\theta^2}{2\mu_0} \times 2\pi r dr$$

where μ_0 is the magnetic permeability $= 4\pi \times 10^{-7}$ H/m

$$\text{Then, } F_L = \frac{B_\theta^2}{8 \times 10^{-7}} (r^2 - a^2) \quad (4)$$

Figure 9 shows the variations of B_θ^2 as a function of z and r . Substitute the data of this figure in equation 4 to evaluate the variations of Lorentz force, F_L , with z at different values of r as shown in Figure 10. This figure illustrates that F_L has a maximum value of 12.925 N at $z = 9$ cm and $r = 3.625$ cm.

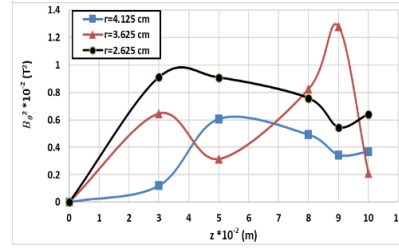


Figure 9. Variations of B_θ^2 as a function of z and r

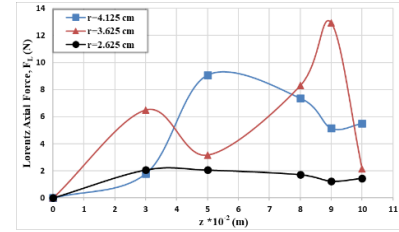


Figure 10. Variations of F_L with z and r

Figure 10 shows that, the maximum value of F_L is detected at $z = 3, 9$, and 5 cm for $r = 2.625, 3.625$, and 4.125 cm, correspondingly.

The second term of R.H.S of equation (1) represents the magnetic pressure gradient force, F_p .

$$F_p = \frac{1}{2\mu_0} \frac{\partial B_\theta^2}{\partial z} \int_r^a 2\pi r \lambda dr = \frac{\partial B_\theta^2}{8 \times 10^{-7} \partial z} (r^2 - a^2) \lambda$$

Figure 11(a) and Figure 11(b) show the relation between the magnetic pressure gradient force, F_p , and axial distance, z for different r positions. This figure revealed that F_p has maximum positive and negative values at $z = 8$ cm and $z = 10$ cm respectively for $r = 3.625$ cm.

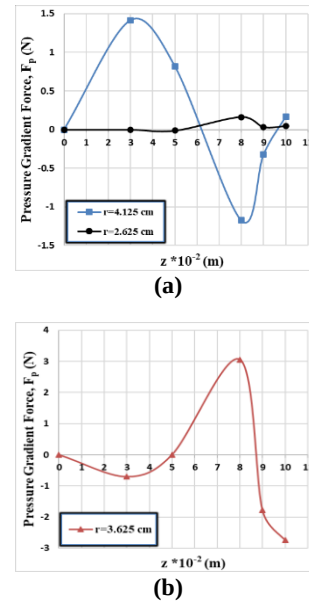


Figure 11. Relation between F_p and z for (a) $r = 2.625$ and 4.125 cm (b) $r = 3.625$ cm

Figure 11(a) and Figure 11(b) show that the maximum value of F_p , is detected approximately at $z = 8$ cm for all r -positions under consideration.

The summation of the third and fourth terms of R.H.S of equation (1) represents the PCS viscosity force, F_v , which is given by:

$$F_v = \int \left(\frac{\eta}{3} \nabla(\nabla \cdot v_z) + \eta \nabla^2 v_z \right) dv$$

The third term:

$$\int \frac{\eta}{3} \nabla(\nabla \cdot v_z) dV = \int \frac{\eta}{3} \nabla \frac{\partial v_z}{\partial z} dV = \int \frac{\eta}{3} \frac{\partial}{\partial z} \left(\frac{\partial v_z}{\partial z} \right) dV = \frac{\eta}{3} \frac{\partial^2 v_z}{\partial z^2} \pi(r^2 - a^2) \lambda \quad (5)$$

The fourth term:

$$\int \eta \nabla^2 v_z dV = \eta \left[\frac{1}{r} \left(r \frac{\partial^2 v_z}{\partial r^2} + \frac{\partial v_z}{\partial r} \right) + \frac{\partial^2 v_z}{\partial z^2} \right] \pi(r^2 - a^2) \lambda \quad (6)$$

In our study we suppose $v_z \neq f(r)$, then the equation (6) becomes:

$$\int \eta \nabla^2 v_z dV = \eta \frac{\partial^2 v_z}{\partial z^2} \cdot \pi(r^2 - a^2) \lambda \quad (7)$$

The PCS viscosity force, F_v , is obtained by adding equation (5) to equation (7) to become:

$$F_v = \frac{4}{3} \eta \frac{\partial^2 v_z}{\partial z^2} \pi(r^2 - a^2) \lambda \quad (8)$$

From Figure 4 (a), the distributions of $\frac{\partial v_z}{\partial z}$ and $\frac{\partial^2 v_z}{\partial z^2}$ with z and r positions are shown in Figure 12(a) and Figure 12(b).

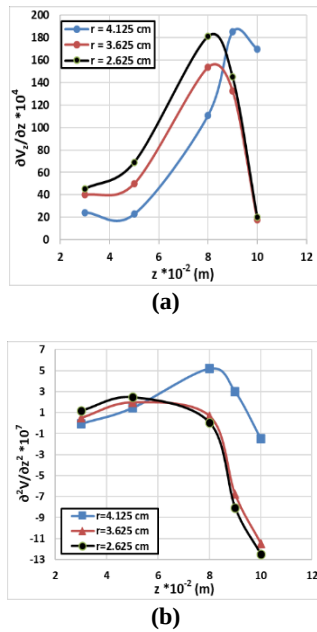


Figure 12. $\frac{\partial v_z}{\partial z}$ and $\frac{\partial^2 v_z}{\partial z^2}$ versus z for different r values

Then the viscous force, F_v , and viscosity coefficient η are estimated from the data of equation (1), $\frac{\partial^2 v_z}{\partial z^2}$ and equation (8).

Figure 13(a) and Figure 13(b) represent the PCS viscosity force, F_v , as a function of z and at different r values. From this figure, it is seen that F_v has a peak value at $z = 9$ cm for all r positions under consideration and it has a maximum absolute value of 90 N at $z = 9$ cm and $r = 3.625$ cm.

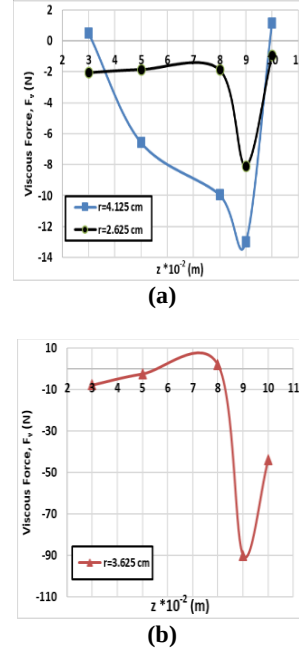


Figure 13. PCS viscosity force, F_v as a function of z for (a) $r = 2.625$ and 4.125 cm (b) $r = 3.625$ cm

The viscosity coefficient, η , is given from equation (8) $= \frac{3F_v}{4 \left(\frac{\partial^2 v_z}{\partial z^2} \right) \pi(r^2 - a^2) \lambda}$, Figure 14(a) and Figure 14(b) show the viscosity coefficient, η against axial distance z at different r values. This figure illustrates that η has positive and negative values along z and at different r positions. This behavior may be related to a combination of the distribution of F_v and $\frac{\partial^2 v_z}{\partial z^2}$. The maximum absolute value of $\eta = 0.735$ kg/ms at $z = 8$ cm and $r = 2.625$ cm.

Axial variations of total force (rate of change of PCS momentum) and viscosity forces acting on PCS for different r positions are shown in Figure 15(a) and Figure 15(b).

Figure 15(a) and Figure 15(b) illustrate that the axial distribution of the total force (rate of change of PCS momentum) and viscosity force have approximately the same behavior, i.e., the viscosity force is the dominant force acting on PCS in our case.

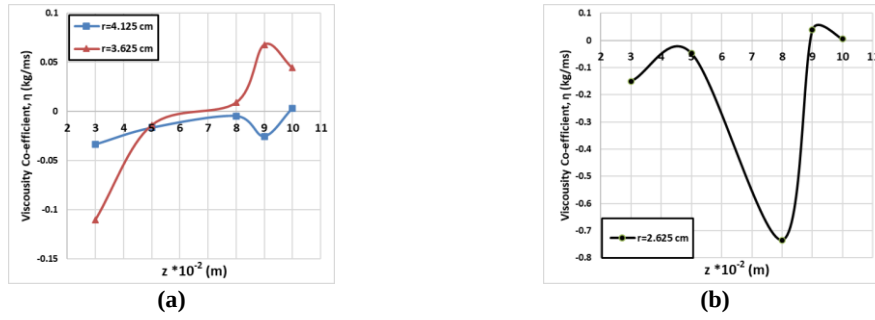


Figure 14. The viscosity coefficient, η versus z for (a) $r = 3.625$ and 4.125 cm (b) $r = 2.625$ cm

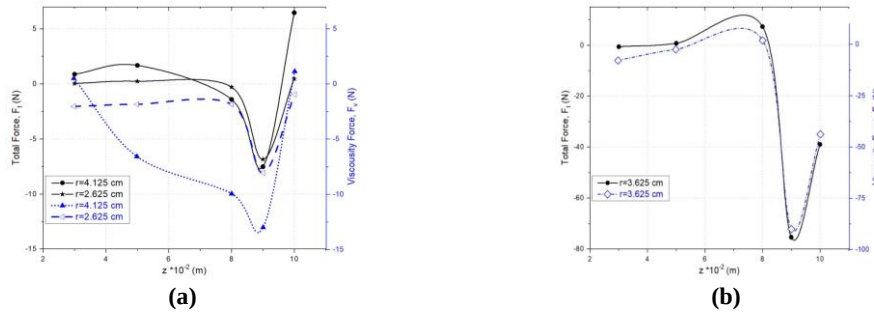


Figure 15. Variations of total force and viscosity force for (a) $r = 2.625$ and 4.125 cm (b) $r = 3.625$ cm

Conclusions

The present study was done on a 2.2 kJ EAEA-PF1 Mather-type PF device. All experimental data were registered at the third half-cycle of discharge current with a maximum value of 56 kA. During this period, the central electrode of the coaxial electrode system had a positive polarity. The results of the discharge current signal and the inclination angle of PCS with z -direction $\approx 82^\circ$ during the axial phase confirmed that the radial phase is not presented, thus no plasma focus region was established i.e., our PF device during this period was operated as coaxial plasma accelerator device. Magnetic probe data were applied to the Navier-Stokes equation to compute the rate of change of PCS momentum with time and the different magnetic forces acting on PCS such as axial magnetic force (Lorentz force), magnetic pressure gradient force, and viscosity force during the axial direction, z and at different r directions.

Results of the rate of change of PCS momentum with time illustrated that, at an axial distance close to the coaxial electrodes muzzle, it had negative values at different r values. Its peak value was observed at $z = 9$ cm for each r value under consideration. These results may be related to a distribution of the rate of change of PCS mass with time, $\dot{m}$ as well as the inefficiency snow-plough action process and f_m values. The results of Lorentz force, F_L , as a function of (z and r) positions cleared that its maximum value = 12.9 N which was

detected at $z = 9$ cm and $r = 3.625$ cm, this may be due to the axial B_θ distribution at different r values as well as the area of PCS. Results of magnetic pressure gradient force, F_p distribution for (z and r) directions showed that it had positive and negative values, which were related to B_θ profiles during the axial phase and consequently the rate of change of B_θ^2 with axial distance, z , as well as values of f_c . This force had a maximum value of 3.054 N at $z = 8$ cm and $r = 3.625$ cm. The above results of Lorentz force and magnetic pressure gradient force cleared that the maximum values of them were located close to the axial electrodes muzzle and at $r = 3.625$ cm, this may be due to less inefficient snow-plough action that was detected at this region i.e., the PCS captures more mass than other radial distances ($r = 2.625$ cm and 4.125 cm).

Axial distribution of viscosity force, F_v , at different r positions showed that F_v data have negative values at most axial distances, z . As we know negative values of viscosity force are generally developed from PCS interaction with the dominant magnetic field (Bhaduri, 2021).

In our study, dominant magnetic fields were induced from azimuthal magnetic field induction, B_θ , and magnetic field induced from disturbance inside the plasma flow (vortex).

Results of axial distribution of F_L , (dv_z/dt) , and $(\partial v_z/\partial z)$ as a function of radial distances showed that each of these axial distributions increases mostly with increasing magnitude of negative viscosity

force, F_v , due to increasing viscous stimulation effect which tends to accelerate the PCS motion.

To summarize, our EAEA-PF1 device operates as a coaxial plasma accelerator during the third half cycle of the discharge current, exhibiting a defocus action. So, the radial phase of the discharge process is hard to establish. At the same time, during the axial phase, the PCS travels rapidly from the coaxial electrode's breech to the muzzle. Therefore, this device has the potential to be utilized in a wide range of industrial and material processing applications.

Future studies will be conducted to entirely investigate the viscous stimulation effect to develop a PCS capable of generating a significant axial force at high acceleration, using coaxial electrodes. Furthermore, we will examine the correlation between negative viscosity and the enhanced performance of the PCS vortex.

References

- Balescu, R., Prigagine, I., and Giavannini, A. (2000). *Equilibrium Statistical Mechanics*. World Scientific.
- Berglund, S., Westerlund, S., and Svennerstedt, S. (1963). A magnetic probe for plasma measurement. *Journal of Scientific Instruments*, 40(5):250-252. <https://doi.org/10.1088/0950-7671/40/5/319>
- Bertalot, L., Herold, H., Jäger, U., Mozer, A., Oppenländer, T., Sadowski, M., and Schmidt, H. (1980). Mass and energy analysis and space-resolved measurements of ions from plasma focus devices. *Physics Letters A*, 79(5): 389-392. [https://doi.org/10.1016/0375-9601\(80\)90272-8](https://doi.org/10.1016/0375-9601(80)90272-8)
- Bhaduri, S. (2021). The negative viscosity induces more disturbances in a flow, arXiv preprint arXiv: 2101.05045. <https://doi.org/10.48550/arXiv.2101.05045>
- Bhuyan, H., Mohanty, S.R., Neog, N.K., Bujarbarua, S., and Rout, R.K. (2003). Magnetic probe measurements of current sheet dynamics in a coaxial plasma accelerator. *Measurement Science and Technology*, 14(10):1769-1776. <https://doi.org/10.1088/0957-0233/14/10/305>
- Bruzzzone, H. and Grondona, D. (1997). Magnetic probe measurements of the initial phase in a plasma focus device. *Plasma Physics and Controlled Fusion*, 39(9):1315-1326. <https://doi.org/10.1088/0741-3335/39/9/004>
- Chen, F.F. (1974). *Introduction to Plasma Physics and Controlled Fusion*. Plenum Press.
- Chow, S.P., Lee, S. and Tan, B.C. (1972). Current sheath studies in a co-axial plasma focus gun. *Journal of Plasma Physics*, 8(1):21-31. <https://doi.org/10.1017/S0022377800006905>
- El-Sayed, H.A., Allam, T.M., and Gaber, W.H. (2015a). Axial distribution profile of magnetic field and plasma sheath velocity in argon plasma focus device. *Journal of Advances in Physics*, 11(2):2990-3000. <https://doi.org/10.24297/jap.v11i2.520>
- EL-Sayed, H.A., Allam, T.M., and Soliman, H.M. (2015b). Investigation of induced force distribution profiles in coaxial plasma device. *Arab Journal of Nuclear Science and Applications*, 48(4):76-87. <https://doi.org/10.21608/ajnsa.2019.16003.1256>
- Feng, Y., Lin, W., and Murillo, M.S. (2017). Viscosity of two-dimensional strongly coupled dusty plasma modified by a perpendicular magnetic field. *Physical Review E*, 96(5):053208. <https://doi.org/10.1103/PhysRevE.96.053208>
- Krompholz, H., Michel, L., Schonback, K., and Fischer, H. (1977). Neutron-, ion-, and electron-energy spectra in a 1 kJ Plasma Focus. *Applied Physics*, 13(1):29-35. <https://doi.org/10.1007/BF00890716>
- Landau, L.D. and Lifshitz, E.M. (1987). *Causes of Theoretical Physics*, vol. 6: Fluid Mechanics 2nd Ed. Pergamon Press.
- Lashin, A.A., Allam, T.M., EL-Sayed, H.A., Ahmed, K.M., Ward, S.A., Soliman, H.M., and Abouelatta, M.A. (2021). Magnetic field induction and magnetic force distribution profiles in plasma focus discharge device. *Plasma Science and Technology*, 23(7):075405. <https://doi.org/10.1088/2058-6272/ac01d2>
- Lashin, A.A., Allam, T.M., Ahmed, K.M., EL-Sayed, H.A., Ward, S.A., Anwar, M. and Soliman, H.M. (2019). Plasma Current Sheath Dynamics and Energy Dissipation in a Low-Energy Plasma Focus Device. *Arab Journal of Nuclear Sciences and Applications*, 53(1):222-233. <https://doi.org/10.21608/AJNSA.2019.16003.1256>
- Liu, B. and Goree, J. (2005). Shear Viscosity of Two-Dimensional Yukawa Systems in the Liquid State. *Physical review letters*, 94(18):185002. <https://doi.org/10.1103/PhysRevLett.94.185002>
- Mathuthu, M., Zengeni, T.G., and Gholap, A.V. (1996). Measurement of magnetic field and velocity profiles in 3.6 kJ United Nations University/International Center for Theoretical Physics plasma focus fusion device. *Physics of Plasmas*, 3(12):4572-4576. <https://doi.org/10.1063/1.871583>
- Rhee, M.J. (1980). Heavy-ion beams produced by high-voltage pulse-powered plasma focus. *Applied Physics Letters*, 37(10):906908. <https://doi.org/10.1063/1.91854>
- Saigo, T. and Hamaguchi, S. (2002). Shear viscosity of strongly coupled Yukawa systems. *Physics of Plasmas*, 9(4):1210-1216. <https://doi.org/10.1063/1.1459708>
- Sivashinsky, G. and Yakhat, V. (1985). Negative viscosity effect in large-scale flows. *Physics of Fluids*, 28(1):1040-1042. <https://doi.org/10.1063/1.865025>
- Soto, L. (2005). New trends and future perspectives on plasma focus research. *Plasma Physics and Controlled Fusion*, 47(5A):361-381. <https://doi.org/10.1088/0741-3335/47/5A/027>
- Stygar, W., Gerdin, G., Venneri, F., and Mandrekas, J. (1982). Particle beams generated by a 6-12.5 kJ dense plasma focus. *Nuclear Fusion*, 22(9):1161. <https://doi.org/10.1088/0029-5515/22/9/003>
- Yunus, A.C. (2010). *Fluid Mechanics: Fundamentals and Applications (Si Units)*. Tata McGraw Hill Education Private Limited.