Efficiency of Energy Transfer in a Small Plasma Focus Device

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Abstract. A study of energy transfer in a small plasma focus device has been carried out during its axial phase. The snow-plough model has been used in the simulation as a basic model for the calculation of plasma dynamics. The energy transferred to the plasma is calculated by considering the work done by the electromagnetic piston during the axial phase. It was found that the plasma energy calculated by this model agrees well with the experimental data within the pressure range of 1 mbar to 4 mbar if the mass shedding effect is included in the model. According to the present computation, the energy transferred into the plasma, in the case of a plasma focus with 2.3 kJ initial energy operated with nitrogen gas within the pressure range of 1 to 4 mbar, is between 224 J to 250 J. This corresponds to energy transfer efficiency of 9.6% to 10.7%. The mass shedding factor decreases from 0.23 to 0.069 with increasing pressure. Correspondingly, the energy transfer efficiency changes slightly at a higher pressure.

Introduction

A plasma focus device is a high power pulsed discharge which is able to produce a compressed dense plasma at the end of its coaxial electrodes. This system has also been found to be an intense source of neutrons, x-ray, ion and electron beams \cite{1}. The device can be used in many applications including x-ray imaging, lithography and surface modification of materials. The electrical input energy of the plasma focus dictates the dynamics of the plasma and hence the focusing process itself.

The dynamics of the plasma focus are commonly divided into four main phases: the initial breakdown and lift-off phase, the axial run-down phase, the radial compression phase, and the final focusing phase. These phases can be physically described as follows; the gas breakdown occurs initially due to a large voltage applied across a glass insulator separating the inner and outer electrodes. The resultant current sheath is lifted off and accelerated axially by the $\mathbf{J} \times \mathbf{B}$ force during the axial phase, where $\mathbf{J}$ is the radial component of current density and $\mathbf{B}$ is that self-induced magnetic field in the azimuthal direction. In the radial compression phase, the current sheath collapses radially inward when it reaches the top of the inner which leads to the final focusing phase. This is where the hot and dense focused plasma is formed. The abrupt change induces high electric field that drives the ions axially away from the center electrode and electrons towards the center electrode to form ion and electron beams. An emission of intense x-ray is also observed at the same time. \cite{2}.

The initial electrical energy of the plasma focus can be calculated from the capacitance and the charging voltage. During the plasma focus discharge, the energy is converted into various forms of energy including the internal energy of the plasma, the kinetic energy of the plasma slug and radiation. In order to have an efficient operation of the plasma focus device, it is important to optimize the efficiency of energy transfer into the plasma. In this study, a snow-plough model with coupled circuit equation has been used to simulate the dynamics of a 3 kJ plasma focus device and hence the energy input to the plasma is calculated based on the plasma current and plasma...
inductance obtained from the model. A comparison of the energy calculated from the model and that deduced from the experimental current and voltage waveforms is made to determine the mass shedding effect. In this way the model is adjusted empirically to fit the experimental energy curve and hence the actual amount of energy input to the plasma can be calculated.

**Method and Results**

The dynamic model used to simulate the axial phase of the plasma is the snow-plough model with coupled circuit equation [3]. The schematic diagram of the plasma focus dynamics and its equivalent circuit is shown in Figure 1 and Figure 2 respectively.

![Figure 1. Diagram of a model of the current sheath during axial phase of a plasma focus.](image1)

![Figure 2. An equivalent circuit diagram of a plasma focus device.](image2)

In the dynamic equation, the current sheath is assumed to be accelerated by the $\mathbf{J} \times \mathbf{B}$ force and it sweeps the gas along its path. As such it acts as an electromagnetic piston with continually changing mass. The equation of motion of this piston can be written as,

$$\frac{d}{dt} \left[ \rho \pi (b^2 - a^2) z \left( \frac{dz}{dt} \right) \Gamma \right] = \frac{B^2}{2\mu} 2\pi dr . \tag{1}$$

where $\rho \pi (b^2 - a^2) z$ is the mass of the plasma slug and $\Gamma$ is the “mass shedding factor”. This factor is the fraction of mass that is swept by the electromagnetic piston during the plasma axial phase. On the other side of the equation $\frac{B^2}{2\mu} 2\pi dr$ is deduced from the Lorentz’s force.

The current flow in the plasma focus can be obtained from the plasma focus equivalent circuit by using Kirchhoff law. The equation is written as;

$$V_0 = \frac{d}{dt} [(L_0 + L_p)I] + I(R_0 + R_p) + \int \frac{Idt}{C} . \tag{2}$$

where $V_0$ is the discharging voltage, $L_0$ and $R_0$ are the inductance and the resistance of the circuit respectively while $L_p$ and $R_p$ are the inductance and the resistance of the plasma respectively. $C$ is the capacitance of the capacitor bank and $I$ is the current.

By using equation 1 and equation 2, the position and the speed of the piston as well as the current and voltage change during an axial phase can be calculated at each time interval. The motion of the plasma slug in the plasma focus can be simulated this way. In the experiment, a model of 3 kJ UNU/ICTP Plasma Focus device is used with 12.5 kV initial charging voltage and variable nitrogen gas pressures.
According to B. Shan et al [4], the input electrical energy will be divided into energy into the circuit external to the plasma focus tube and the energy input to the plasma focus tube which in turn is divided into energy stored inductively, piston work and joule heating. Since the model used in this work assumes an inductive plasma load, the energy input into the plasma focus tube ($W_{\text{model}}$) is written as

$$W_{\text{model}} = \int I_p^2 \frac{dL_p}{dt} \, dt + \int I_p L_p \frac{dI_p}{dt} \, dt = W_m + W_p.$$  \hspace{1cm} (3)

Part of this energy is stored as magnetic energy of the system which is given by

$$W_m = \frac{1}{2} I_p^2 L_p^2 = \frac{1}{2} \int \left( \frac{dL_p}{dt} \right)^2 \, dt + \int I_p L_p \frac{dL_p}{dt} \, dt,$$  \hspace{1cm} (4)

and the part of the energy actually goes into the plasma as internal and kinetic energies (neglecting radiation loss) is

$$W_p = \frac{1}{2} \int I_p^2 \frac{dL_p}{dt} \, dt.$$  \hspace{1cm} (5)

Experiments are performed on the UNU/ICTP Plasma Focus with the standard operating parameter, where the voltage and current signals are obtained from a voltage probe and a Rogowski’s coil [2,3], respectively. The experimental results of the energy input to the plasma system is calculated from

$$W_{\text{experiment}} = \int I_p V_p \, dt.$$  \hspace{1cm} (6)

The values of $W_{\text{experiment}}$ are compared with the energies obtained from the simulation $W_{\text{model}}$ given by equation 3. The gas operating pressure is also varied from 1 to 4 mbar. From the simulation, the mass shedding factor, $\Gamma$, is adjusted such that the simulated energy fits to the experimentally measured energy in the axial phase. The efficiency of the energy transferred to the plasma motion is the ratio of the simulated energy input to the plasma ($W_p$), when the plasma reaches the end of the center electrode ($z = z_o$), and the input energy. Figure 3 shows plots of the energies obtained from experiment $W_{\text{experiment}}$ and that calculated by the model $W_{\text{model}}$ for the case of mass shedding factor $\Gamma = 0.23$ in comparison with $W_p$. The position of the current sheath as a function of time is also shown in the same graph. It is found that the fraction of the energy transferred at the end of the axial phase in the plasma focus varies with pressure. The efficiency decreases as the pressure is increased. This corresponds to the decrease in the mass shedding factor as shown in Figure 4.

![Figure 3](https://example.com/fig3.png)  \hspace{1cm} Figure 3. Calculated energies $W_{\text{experiment}}$ and $W_{\text{model}}$ as function of time showing good fitting when $\Gamma = 0.23$ for 1 mbar pressure. Also shown in this graph are the axial positions of the current sheath and the actual energy input into the plasma.

![Figure 4](https://example.com/fig4.png)  \hspace{1cm} Figure 4. Energy transfer efficiency into plasma, and $\Gamma$ as a function of pressure.
It can be observed that, for a 2.3 kJ plasma focus, the actual energy input to the plasma (neglecting radiation energy) calculated from the model is between 224 J to 250 J.

Conclusion
It was found from the calculation based on the results obtained from the modeling of the plasma focus dynamics that within the pressure range of 1 mbar to 4 mbar, the actual energy input into the plasma is between 224 J to 250 J in the case of a 2.3 kJ initial energy nitrogen plasma focus discharge. The efficiency of energy transferred calculated is found to have values between 9.6% to 10.7%. The simulated speed of the plasma sheath is between 3 to 8 cm/µs. It is interesting to note that, the speed of the plasma slug can be measured for the same condition to have a value between 3 to 7 cm/µs [2]. This good agreement between the experiment and simulation, together with the good agreement between $W_{\text{experiment}}$ and $W_{\text{model}}$ as shown in the present study, confirm our assumption that the plasma focus during its axial acceleration phase is purely inductive and that the joule heating effect is insignificant.

References