THERMODYNAMICS EFFECTS ON THE COMPRESSION DYNAMICS OF SOFT X-RAY EMISSION IN PLASMA FOCUS

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To my beloved parents & family

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ABSTRACT

In a plasma focus operation, the X-ray radiation properties are dependent on the thermodynamics data such as ion fraction (α), effective ion charge number (Z_{eff}), and effective specific heat ratio (γ) at different temperatures. In Corona Model (CM), the value of ion fraction was first obtained from McWhirter's equation and was subsequently used in determining the Z_{eff} and γ values. The state-of-the-art ion fraction calculation based on Mazzotta's (Mazz) in Modified Corona Model (MOCM) was compared with McWhirter's (McW) computations for neon, argon and nitrogen gases. The implementation of McW's and Mazz's ion fraction calculation in CM and MOCM cases respectively showed deviations in terms of temperatures. The aim of this study is to investigate the Z_{eff} and γ values based on the ion fraction values determined from Mazz's and McW's computations and applied in numerical experiment of plasma focus device emphasizing on radial compression plasma dynamics and parameters of soft X-ray (SXR) emission. The Z_{eff} and γ for both computations were incorporated in Lee code for numerical experiment on SXR yield. Lee code version RADPF5.15K has been used with the incorporation of Z_{eff} and γ computation based on CM and MOCM operating in various gas pressures. The parameters of SXR yield played important role as they were affected by these different thermodynamics data calculation used in CM and MOCM in the Lee Model. Among these three operating gases, argon plasma of MOCM showed tremendous significant effect towards the results in SXR yield which cannot be disregarded. Thus, it is concluded that the ion fraction values derived from Mazz's computation has a significant effects on Z_{eff}, γ, higher SXR yield and enhances radial compression phase performance.

ABSTRAK

Dalam pengendalian plasma fokus, sifat radiasi sinar-X bergantung kepada data termodinamik seperti pecahan ion (α), bilangan cas ion berkesan (Z_{eff}), dan nisbah haba tentu (γ) pada suhu yang berbeza. Dalam Model Corona (CM), nilai pecahan ion pada dasarnya diperoleh daripada persamaan McWhirter dan kemudiannya digunakan dalam menentukan nilai Z_{eff} dan γ. Pengiraan pecahan ion terkini berdasarkan Mazzotta (Mazz) dalam Model Corona Diubahsuai (MOCM) dibandingkan dengan pengiraan McWhirter (McW) untuk gas neon, argon dan nitrogen. Pelaksanaan pengiraan pecahan ion McW dan Mazz dalam CM dan MOCM masing-masing menunjukkan sisihan dari segi suhu. Tujuan kajian ini adalah untuk mengkaji Z_{eff} dan γ berdasarkan nilai pecahan ion yang ditentukan daripada pengiraan Mazz dan McW dan seterusnya diaplikasikan kepada simulasi peranti plasma fokus khususnya kepada mampatan jejarian dinamik plasma dan parameter pancaran sinar-X lembut (SXR). Z_{eff} dan γ berdasarkan kedua-dua pengiraan telah dimasukkan dalam kod Lee untuk simulasi hasil SXR. Kod Lee versi RADPF5.15K telah digunakan dengan kemasukan pengiraan Z_{eff} dan γ berdasarkan CM dan MOCM yang beroperasi dalam pelbagai tekanan gas. Parameter hasil SXR memainkan peranan penting kerana dipengaruh dengan perbezaan pengiraan data termodinamik yang digunakan dalam CM dan MOCM dalam Model Lee. Antara ketiga-tiga gas beroperasi, plasma argon dalam MOCM menunjukkan kesan yang ketara terhadap keputusan dalam hasil SXR yang tidak boleh diabaikan. Oleh itu, kesimpulannya nilai pecahan ion yang diperoleh daripada pengiraan Mazz ini mempunyai kesan yang besar ke atas Z_{eff}, γ, hasil SXR yang lebih tinggi dan meningkatkan prestasi fasa mampatan jejarian plasma.

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LIST OF ABBREVIATIONS

PF	-	Plasma Focus
RADPF	-	Radiative Dense Plasma Focus
UNU/ICTP	-	United Nations University/International Centre for Theoretical Physics
MOCM	-	Modified Corona Model
CM	-	Corona Model
SXR	-	Soft X-ray
NIST	-	National Institute of Standards and Technology
NIFS	-	National Institute for Fusion Science

LIST OF SYMBOLS

A - Atomic Weight

a - Anode Radius

α_z - The fraction of the plasma which is ionized to the zth ionized

B - Magnetic Field

b - Cathode Radius

c - Ratio of Cathode to Anode Radius

C_o - Capacitor bank for energy storage

C - Ionization rate coefficient

Cp - Specific heat capacity at constant pressure

Cv - Specific heat capacity at constant volume

D - Departure coefficient

dQ - External Input Energy

EINP - Energy input into plasma

E_I - The energy stored in the tube inductance

E_i - Ionization energy

ξ - Normalized Axial Position

ζ - Number of outer electrons

χ - Ionization potential

γ - Specific Heat Ratio

Γ - Shock density ratio

f_m - Axial mass factors

f_c - Axial current factors

f_{mr} - Radial mass factors

f_{cr} - Radial current factors

f_{AB} - Absorption factor

f - Degree of freedom

$\mathrm{F_z}$ - the axial force on plasma sheath

$\mathrm{F_{zr}}$ - the radial force on plasma sheath

h - Focus Enthalpy

h - Plank’s Constant

h_L - leakage resistance in the plasma tube

ι - Normalised Current

I - Discharge Current

$\mathrm{I_P}$ - Pinch Current

I_{max} - Peak Discharge Current

I_{PB} - Pease-Braginskii Current

I_z - Total energy required to raise one ion from its unionized state to its zth ionized state and

J - Current Density

$j \times B$ - driving Magnetic force

$\mathrm{k_B}$ - Boltzman Constant

$\mathrm{k_eV}$ - kilo electron volt

$\mathrm{K_P}$ - Normalised Magnetic Piston Position

$\mathrm{K_s}$ - Normalised Shock Front Position

l_v - The mean free-path

L_o - The fixed circuit inductance

L_p - Changing plasma tube inductance.

$\mathrm{L_e}$ - Plasma Inductance Spark Gap Inductance

$\mathrm{L_o}$ - External (stray) Inductance

$\mathrm{L_1}$ - Inductance of Capacitor C1

$\mathrm{L_2}$ - Inductance of Capacitor C2

MW - Molecular weight

M - Photonic excitation number

m_i - The mass of atom or ion.

n - Number Density of ions and electrons

$\mathrm{n_i}$ - Ion Density (in the code)

N_i - Ion number density

N_e - Electron number density

N - Line density

N_{z+1} - State populations of ionization stage z+1
N_z - State populations of ionization stage z
ρ - Mass density
ρ_o - Ambient gas density
PF - Plasma focus
P_K - Kinetic pressure
P_B - Magnetic pressure
P_p - Piston pressure
P - Rate of Radiation Loss
P_J - Rate of Joule heating
P - Pressure
P_{max} - Maximum pressure
P(x,t) - The pressure distribution
P_L - Line radiation power density
P_b - Bremsstrahlung power density
P_r - Recombination power density
P_{rad} - Net power density
Q - Total electric charge
r_{min} - Minimum pinch radius
q_o - Speed of the shocked gas
q - Speed of the ambient gas
Q_{rad} - Radiation energy
Q_s - Radiation loss per unit length
R_s - Particle position
RC - Integration time constant
r_p - Slug external radius
r_s - Slug internal radius
r - The boundary radius of curvature
r_c - Critical radius
R_o - The circuit resistance
Ro - Universal gas constant
R_p - Plasma resistance
RR - Radiative recombination rate coefficient

T - Shock temperature
$t_{p\text{-}s}$ - Transmission time
t_a - Characteristic axial run down time
$\boldsymbol{\tau}$ - Confinement time
τ - Normalised time
T - Plasma temperature
T_e - Electron temperature
μ_o - Permeability of Free Space
V_o - Capacitor voltage
V_{Slug} - Volume of plasma slug
V - Plasma volume
U - Internal energy
υ_{Ti} - Thermal velocity of ion
υ_s - Shock front speed
ω_g - Statistical weight of the ground state of the ion
W - Total de-excitation rate could be
W_e - Collisional de-excitation rate
Y_{sxr} - Soft X-ray yield
Z - Atomic number
z - Instantaneous current sheath position
Z_{eff} - Effective (average) charge number of one ion
z_o - Length of anode
z_f - Radial elongation pinch length

CHAPTER 1

INTRODUCTION

1.1 Background of research

High current plasma focus (PF) device discharges is a versatile machine known to be the sources of producing high density of plasma with emission of intense radiation such as neutron [1] and abundant amount of soft X-ray (SXR), hard X-ray (HXR), highly energetic ions and electrons [2]. With performance as source of such radiations, the plasma focus machine had gained much interest in the research around the world especially in improving and optimizing the machine for various purposes. Different types of plasma focus devices were discovered by Mather [3] and Filippov [4] in the early 1960’s named Mather-type and Filippov-type plasma focus devices.

The dynamical plasma formation and structure of the plasma focus has been examined with a two-dimensional numerical fluid model [5]. A two-dimensional, three-fluid code based on the two-fluid Potter code was developed for simulating the plasma focus discharge and for modelling the ionization and recombination phenomenon by treating neutral gas as plasma medium [6]. A simple plasma focus (3.3kJ) device was specifically designed in earlier work [7, 8] from the prospect of educational value, reliability and cost-effective device.

There are various theoretical models have been generated to simulate plasma dynamics in plasma focus device [9]. In 1984, a 2-phase radiative plasma focus model [10] was developed by S. Lee [7] called Lee Model numerical experiments to characterize any conventional Mather-type plasma focus. The improvement of this model was executed progressively until 1991 with the development of 5-phase model [10]. Based on Corona Model, radiative plasma focus model was established [11] with the capability of yielding trajectory and structure of plasma [12] thus showing good agreement with the experimental measured values.

Corona Model computation for all ionization balance [13] was utilized for thermodynamics data calculations involving specific heat ratio and charge number as function of temperature [10, 14]. The improvement in Lee Model code has been done specifically on the SXR radiation part [12] using line radiation calculation in 1998. The code was then modified for adapting the plasma behaviour in Filippov-type plasma focus operation [15]. Comprehensive range of numerical experiments have been studied to attain scaling laws on neutron yield and neon soft X-ray yield in terms of storage energy and pinch current for optimizing machine parameters and operating parameters [16] in Lee Model.

The modification and improvement of the model is feasibly needed for better continuum and emission processes. The investigation of the calculation of plasma ionization balance for X-ray radiation has become very keen so far [17-22]. In the modelling of plasma focus, the approach used for ionization balance from Corona Mode has been computed using McWhirter’s calculation [17].

This had given opportunity for us to continually improve and modify the nominal area of the dependable aspect for SXR radiation, so that predictable altered dynamics in particles emission yields and radiations could be achieved numerically.

Results assembled from the numerical experiments and data collected from actual experimentations are useful to enable in obtaining a greater insight of the physics of the real processes in a plasma focus device. Therefore, the numerical method for improving plasma dynamics in the plasma focus devices that will affect the radiation yields especially for the plasma compression is investigated. This is a highly cost effective method for exploring a lot of complex physical phenomena which are not possible by actual experiments.

1.2 Problem statement

Extensive research in increasing the X-ray yield and expanding its application in the plasma focus has become an interest in the public domain. In spite of this, there is minimal study in the area of plasma thermodynamics data concerning plasma ionization balance effect which requiring more recent data and calculation. Since the production of X-ray is dependent on this thermodynamics data, hence it is feasible to make some modification for this ionization balance to see the effects on X-ray yield that is unobtainable until now. In this study, the analysis of X-ray yield in the plasma focus device is obtained for plasma ionization balance effect and its influence on various parameters in a Mather-type plasma focus. This study will look into how much deviations of plasma ionization balance data for the case of modified calculation and previous calculation as well as other thermodynamics data such as ion charge number and specific heat ratio affected due to the occurred deviations. Also, how much deviations occur in the X-ray yield and its properties as well as the compression dynamics during the pinch phase due to the deviations in plasma ionization balance data.

1.3 Objectives of research

The present research is mainly to investigate the deviations of the ionization balance and its effects on thermodynamics data involving ion charge number and specific heat ratio as well as the X-ray emission and its related properties numerically. The study specifically included as below:

- To determine the effects of plasma ionization balance towards the ion charge number and specific heat ratio in Corona Model.
- To find the Lee Model code with the incorporation of modified Corona Model subroutines within the code comprising the modified ion charge number and specific heat ratio.
- To compare the thermodynamics data obtained based on the modified Corona Model and previous Corona Model subroutines in Lee code.
- To characterize the effects of the thermodynamics data in Lee Model emphasizing on radial plasma compression dynamics and related properties of X-ray emission.

1.4 Scope of research

This research covered numerical experimentation of plasma thermodynamics data using Corona model which then be further used in the Lee model for plasma focus operation. In this present project, the evaluation of plasma ionization balance corresponding to temperature will be firstly studied. The investigation of the effect of plasma ionization balance towards the ion charge number and specific heat ratio in neon (Ne), argon (Ar) and nitrogen (N_2) gases will also be included in the Corona Model. The incorporation of Corona Model subroutines within the Lee Model code which comprising the thermodynamics data calculations for Ne, Ar and N_2 will be utilized in this scope. To produce reliable X-ray in this code, the thermodynamics data is the crucial part that needs to be estimated appropriately. Consequently, the effects of these thermodynamics calculations towards X-ray yield will be investigated emphasizing on the plasma compression dynamics during the final phase and to the related parameters of X-ray yield in Lee Model. Numerical experimentation will be done to study the effects of X-ray yield based on the modified version of Corona Model and then results will be compared with the previous Corona Model used for those three gases.

1.5 Significance of research

The study of plasma focus device has been widely and actively researched for its concept, design, construction, various physics phenomena operation as well as the proper and better improvement of diagnostics techniques for each application purpose. Apart from application purpose, the research is also important to be investigated numerically for development in educational area. Therefore, by incorporating the numerical modification of thermodynamics data based on extensive improvement of plasma ionization balance calculation, more realistic design and product is possibly achieved for better yield and energy resolution in plasma focus study. This study will improvise the calculations in consideration which was yet to be explored. Thus, it contributes to the comprehension of the ionization balance concept by providing a demonstration in the numerical experiments and explaining the uncovered aspects of this phenomenon.

1.6 Thesis Organization

In chapter 1, the introductory description is covered with the background, brief history of the plasma focus research, followed by the problem statement, objectives of research, scope of research and its significance to the current research. In chapter 2, the review of different approaches of plasma ionization balance and plasma dynamics in plasma focus as well as soft X-ray compression dynamics of plasma focus will be discussed regarding the literature review. In chapter 3, the theoretical aspects of plasma and plasma focus devices are covered including the dynamics of plasma focus operation, general concepts of X-ray emission from plasmas including the collisional ionization balance theory. In chapter 3, the methodology used in numerical experiments of Lee Model along with the proposed modification in the existing Corona Model is presented. The results presentation of the numerical experiments in graphical and tabulated form is included in chapter 4 and depicts an elaborated discussion by interpreting the obtained data. In chapter 6, the conclusion of the research findings is included. It also suggests some aspects to be investigated for the future study in the area of research of the plasma focus devices.

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