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Thermal Analysis of Vacuum Chamber of Q-Machine

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ABSTRACT

Plasma is a partially ionized gas in which a certain portion of electrons are free rather than being bound to an atom or molecule. The steady state plasma is produced by a machine named Q- Machine as the plasma is formed by Quiescent. In this device the Plasma source is a hot plate "heated to 2700K by electron bombardment. The vacuum chamber of Q-machine is a part of an experimental proposal for cesium plasma confined in a multi-cusp magnetic field at IPR. In this paper study the temperature distribution of a vacuum chamber by using ANSYS 13 software is to carried out thermal analysis..

Introduction

In this paper, this plasma source (hot plate assembly of the Q-machine) is studied by developing and testing its prototype as it is a part of an experiment proposal for cesium plasma confined in a multi-cusp magnetic field at IPR. The dimensional data are taken from the research paper (Coaxial Cathode Design for Plasma Sources, Chen, 1969[6] and book of Q-Machine, Plasma Physics Laboratory Princeton University, New Jersey[5]). The whole structure is coaxial and all parts of the prototype are manufactured and assembled. The hot plate, made of Stainless Steel, is an electron emitting plate and is acting as a 'Cathode' in plasma source. The hot plate is heated through electric power supply by using filaments as a heating element. Calculations for electric power required for heating of tungsten plate at 2700 K are done. Thermal analysis of that plate is done to know temperature distribution and to verify the design of the plate. Also find suitable material and temperature for Q-Machine by comparing to old one.

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Nomenclature

K	Kelvin
eV	Electron volt
Q	Quiescent

Basic Fundamental of Q-Machine

The main problem in studying basic plasma is the very unstable nature of plasma. The development of a quiet, steady plasma source avoids complications introduced by large currents and magnetic fields. In 1960, two independent groups, one led by Nathan Rynn and Nick D'Angelo at Princeton University, and the other by Knechti and Wada at the Hughes Research Laboratories, were successful in developing sources of magnetically confined alkali plasmas, or Q-machines. Plasma produced by Q-machine is quiet and steady. The letter Q stands for the word "Quiescent".[1]

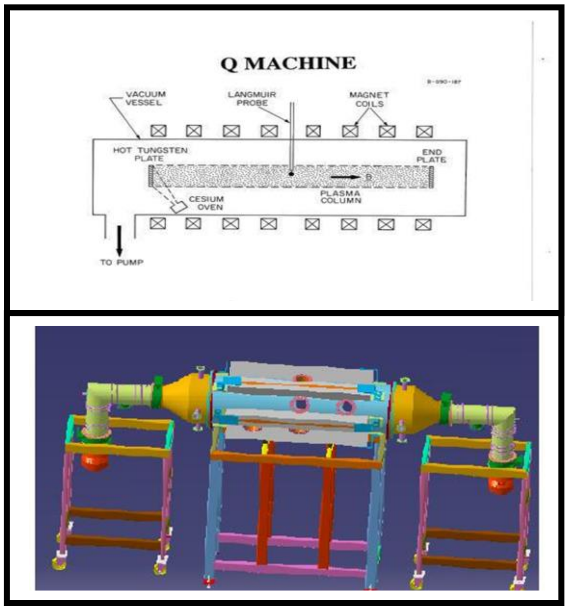

Fig. 1. (a) Q-Machine; (b) Whole Set up.

Working and Experimental setup

The set up of the machine is made at this institute for experiments as shown in the figure (b) and it makes the magnetically confined cesium plasma. The whole set up contains four sub-assemblies.

1. Magnets
2. Vacuum system
3. Hot plate or Ionizer
4. Cesium vapor oven

Magnets and Cusp Formation

In the experiment at this institute, a cusp field is proposed to confine the plasma. Here, magnetic coils are placed axially rather than radially as mentioned above This type of arrangement is done by expecting that since in a cusp configuration, the field in the center is nearly zero, the drift wave oscillations observed before will be absent in the center and it will be effective only in the edges.

Magnetic Cusp

Even the edge dominant drift wave oscillations are expected to die in a few ion larmor radius scale length. So in the central region where the ions are not magnetized will be having a really quiescent plasma. This collision-less plasma is expected to be quiescent because the temperature of both the species (ions and electrons) would be same as the temperature of the plate (~0.2 eV).

In this experiment it is being proposed to have a cusp field to confine the Q-machine like plasma. It is expected that since in a cusp configuration, the field in the center is nearly zero, the drift wave oscillations observed before will be absent in the center and it will be effective only in the edges. Even the edge dominant drift wave oscillation is expected to die in a few ion larmor radius scale length. So in the central region where the ions are not magnetized will be having a really quiescent plasma.

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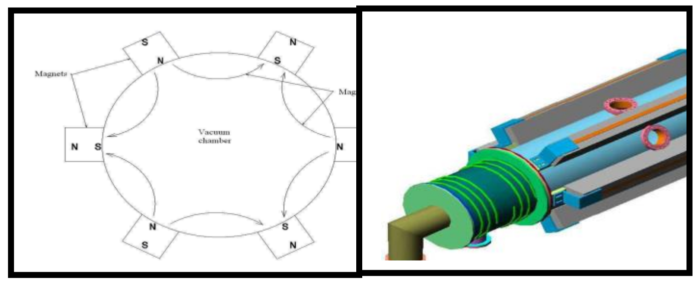
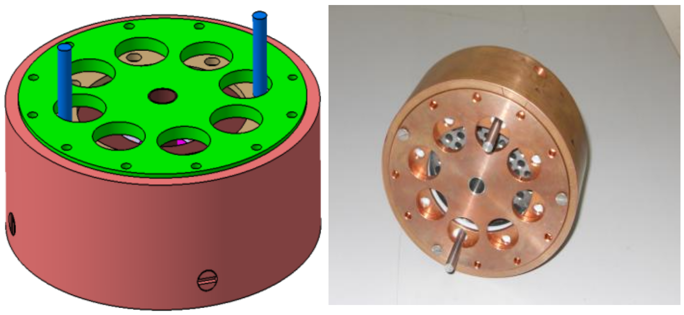


Fig. 1. (c) Magnetic Cusp Arrangement; (d) Vacuum chamber with magnets.

A non-magnetic cylindrical chamber with inner diameter 40 cm which can withstand 1×10^{-7}mbar vacuum. Since the hot cesium ions will hot the inner surface, the chamber has to bear the ion temperature (0.2 eV ~ 2300 K), though the density will be very less ($<10^{11}$ /cc). Apart from this, it is intended not to have any cooling for either magnets or the chamber, which might influence the radial gradient of ions inside the chamber. [1] This contains a main chamber inside which the hot plate will be held by the end flanges. These flanges would also have big holes for pumping. The extended chamber will have baffled path with cooling. There will be two gate valves between the main chamber and the extended chamber for enabling cesium recovery in a vacuum later.

Tungsten Hot Plate Ionizer

The hot plate is an important part of the assembly. It acts as a cathode in the Q-machine to produce magnetically steady plasma. The hot plate is an electron emitting plate and the source of plasma. It is heated up to the temperature 2700 K through an electron bombardment from filaments located just behind the plate. A temperature of 1200 K is enough to produce cesium ions. But since to produce plasma, the plate is heated to a temperature above 2700 K, so that the thermionic electron emission from the plates and the cesium ions combined will give the neutral plasma. As the assembly is operated in vacuum, there are no any ions for collision. So, the losses can be neglected and the temperature of filaments and the plate are approximately same. Also, it is desirable that the temperature distribution on the surface of the plate facing towards cesium must be uniform to produce magnetically confined plasma at uniform temperature.[3]



(e) (f)

Fig. 1. (e) Tungsten Hot plate Ionizer; (f) Actual fabricated Tungsten Hot plate Ionizer

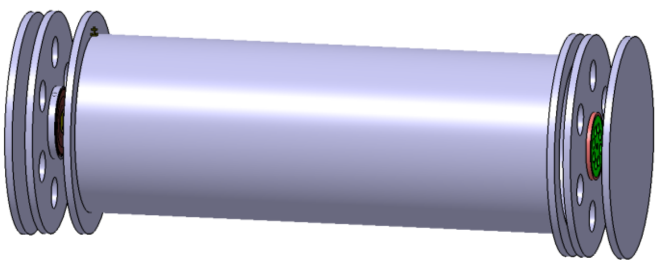


Fig.1.(g) CATIA V5 model of vacuum chamber with ionizer assembly

Tables

A high–Temperature sustain property of materials are choose for the vacuum chamber with ionizer assembly analysis at 2700^{0}K temperature. These materials can bear high temperature and posses' very low thermal expansion. All the material for analysis purpose is taken from the literature review study. These materials are somewhat expensive than materials used in prototype. The list of materials used in actual model of vacuum chamber with ionizer assembly is shown in the table1 below.

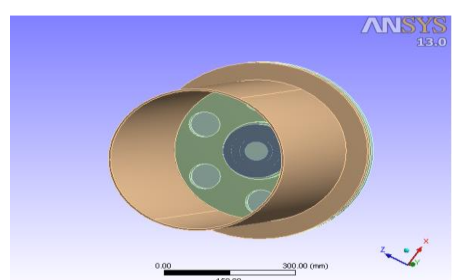
Table 1.List of materials for Actual model of a table.

Part Name	Material in Prototype	Material in Actual model
Hot Plate	Stainless steel	Tungsten
Tungsten Ionizer Body	Copper	Copper
Vacuum Chamber	SS304	SS304

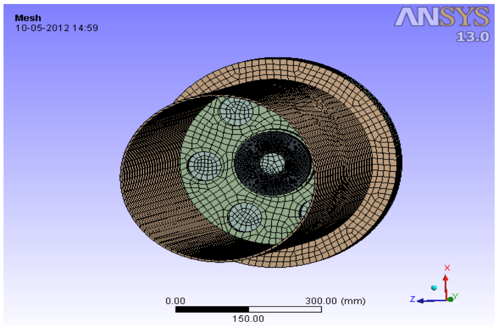
Steady-State Thermal Analysis of Vacuum Chamber

A steady-state thermal analysis follows basically the same procedures as a transient thermal analysis. The main difference is that most applied loads in a transient analysis are functions of time. To specify time-dependent loads, both use the Function Tool to define an equation or function describing the curve. Transient analysis is time dependent process the thermal load is applied on the vacuum chamber assembly for the time 1800 seconds. In such analysis free air convection is considered.

The vacuum chamber with tungsten hot plate ionizer assembly is some parts are fabricated in to the IPR workshop and remaining parts are manufactured in the Bangalore, "VACUUM PUMP PVT.LTD." and whole experimental set up is modeled by CATIA V5 and import in to the ANSYS 13 Workbench. The symmetric parts of the assembly are taking in to the analysis and import in to the ANSYS 13 Workbench. In the Fig.1.(h) show the CATIA V5 symmetric model import into the ansys workbench analysis. The vacuum chamber material stand on high temperature at 2700 K having tensile yield strength in the SS304 steel is 207 MPa. And tensile ultimate yield strength is 586 MPa, the compressive yield strength of SS304 is 207 MPa. In the vacuum chamber model medium meshing is applied on the whole model. The minimum edge length of the mesh element is 0.227760mm. In the Fig.1.(i) shows the mesh model of the vacuum chamber with ionizer holding flange assembly.



(h)



(i)

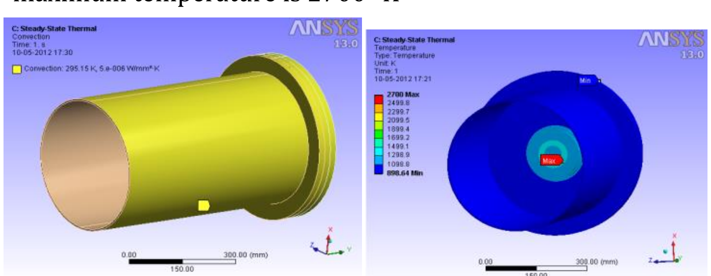
Fig. 1. (h) Imported models from CATIA V5 to ANSYS Workbench; (i) Mesh Model

The “Hex Dominant Method” which is used for the meshing .The Quad/Tri type mesh is used in this analysis.

Convection Condition

The convection condition is applied on the vacuum chamber assembly consider the free air convection in the Fig.1.(j) the convection film coefficient parameter at required temperature. Free air convection is considered for such analysis. Convective heat transfer coefficient value for the free air convection is 5-25 ($W/m^2.K$) .In the present analysis we use the convection value of C = 5 ($W/m^2.K$) and obtained the certain result for obtaining more precise result consider the forced convection. The force convection method is suitable for such analysis .The force convection value ranges between 10-200($W/m^2.K$).The extra forced cooling arrangement is required for the hot plate ionizer assembly experiment set up. The experimental set up is continuous operating 24 hours so more chances of overheating for avoid such thing forced cooling is required.

The steady state thermal analysis result is obtained as shown in the Fig.1.(k)The minimum temperature is obtained on the steady state condition is 898.64 ^0K and maximum temperature is 2700 ^0K



(j) (k)

Fig. 1. (j) Convection Condition on vacuum chamber assembly; (k) Steady-State Thermal analysis result

The overall effect of temperature variation is gradually decreased when thermal load is applied in the vacuum. The specified temperature is suitable for the set-up of Q-Machine. In a steady state 18 kW of power is being spent to keep the ionizers at a surface temperature of about 2700K.

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Mathematical Calculation

Estimation of chamber temperature

From both the ionizer operation, the chamber will be getting loaded by 18kW of power. The chamber will disperse this by convection of air at room temperature and by radiation to the environment.

The heat convection ,

Q_{conv} = Hc * area of the chamber * Temp.Difference

Where, Hc = convective heat transfer coefficient of the process (*W/m^2K or $W/m^2\ ^0C$*) has usually a value of 5, curved surface area (CSA) of the main chamber, and Temp. Difference is the difference between the room temperature and the chamber temperature.

The radiation from the chamber ,

Q_{rad} = € * density * $(Temp.)^4$ * Area of the chamber

Where, € is emissivity of the steel at the required temperature, Stefan Boltzmann constant (5.67×10^{-8} W/(m^2 K^4)).The emissivity of the steel at 500 ^0C = 0.25.The heat energy is handled by only the curved surface of the chamber.

Now to find curved surface area of the chamber

Length of the chamber = 120 cm

Diameter of the chamber = 40cm

Thickness = 1cm

Curved surface area = 2* π *(diameter + thickness/2) * Length

= 2* π * (40+1)/2)*120

= 15456.63586 cm^2

= 1.5457 m^2

Now at steady state condition

$Q_{total=}$ 18kJ = Q_{conv} + Q_{rad} = Hc * CSA *Delta T+ € * Density*$(T)^4$ *CSA

18000/CSA = Hc*T_{cham} + € *Stefan Boltzmann Constant * $[(T_{cham})^4 - (T_{amb})^4]$

$$18000/1.5457 = 5*295 + 0.25 * 5.67\times10^{-8} * (T_{cham})^4$$

$$11645.20929 = 1.4175\times10^{-8} * [(T_{cham})^4 - (T_{amb})^4] \quad (1)$$

Compare this equation (1) to quadratic equation $Ax^4+Bx^3+Cx^2+Dx+E = 0$

$A= 1.4175\times10^{-8}$, B=0, C=0, D=5, E= -13220

$$x = \frac{B}{4A} + \frac{\pm W \pm \sqrt{-3\propto +2Y \pm 2\beta/W}}{2}$$

…………………………… (1)

$$x = 887.237\text{K}$$

4. Result and Discussion

The analytical result compare with ANSYS workbench result. The initial step of the steady state analysis of the vacuum chamber assembly for 1800 sec considering the heat transfer coefficient value 5 the outcome is attained in the thirty three stages and the minimum time step is 30 sec. The temperature result is obtained after the analysis is 898.64^0K. The temperature effect which is found after the analytical calculation is 887.24 ^{0}K. ANSYS workbench result is compare with the analytical result the 1.26 % error is obtained that is permissible.

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