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SIMULATION OF A 10 mm DIAMETER CASCADED PLASMA WINDOW

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Abstract

As a windowless vacuum device, the 10 mm diameter 60 mm long plasma window designed by Peking University only achieved to separate 28.8 kPa from 360 Pa experimentally with 50 A direct current and 2.5 kW power. Based on our 10 mm diameter plasma window, we have proposed a cascaded plasma window to achieve the isolation of atmosphere and high vacuum. In this paper, a numerical 2D FLUENT-based magneto-hydrodynamic simulation on 10 mm diameter cascaded plasma window was developed. The gas inlet, arc creation and plasma expansion segments are all contained in this model. A set of parameters including pressure, temperature, velocity and current distribution were obtained and analysed. In our first simulation, the isolation of 100 kPa and 50 Pa pressure has been realised, and some interesting phenomena occurred.

INTRODUCTION

Plasma window was invented by Ady Hershcovitch [1] in 1995, which has been designed to generate the needed plasma by discharging the gas to separate vacuum from high pressure. As a windowless vacuum seal device, plasma window has many advantages over conventional solid windows that degrade the beam quality and its energy. It can provide lossless transmission of high purity and mono-energetic beams due to its lower equivalent thickness. To explore the application of plasma window on high current heavy ion beams, three plasma windows with 3 mm diameter, 6 mm diameter and 10 mm diameter, respectively, have been built and studied in Peking University [2-4]. As the diameter increased, the sealing effect of the plasma became worse. The 10 mm diameter 60 mm long plasma window only achieved to isolate 360 Pa from 28.8 kPa, experimentally. Lengthening the plasma channel is one way to improve the vacuum sealing ability, but the experiments we did before shows that the longer the plasma channel, the more difficult it is to discharge. Therefore, we proposed a cascaded plasma window to achieve the isolation of atmosphere and high vacuum. Theoretical analysis of a 10 mm diameter cascaded plasma window in axis symmetrical configuration using argon has been performed with a numerical 2D FLUENT-based magneto-hydrodynamic simulation model by using ANSYS [5]. In simulations, the governing equations expressed in cylindrical coordinates are mass conservation, momentum conservation in axial direction, momentum conservation in radial direction and energy conservation. Thermodynamic and transport properties including thermal conductivity, viscosity, density, sound speed, specific heat and electrical conductivity are functions of plasma temperature and pressure, interpolated as user defined functions under Local Thermal Equilibrium (LTE) model [6].

SIMULATION OF THE PLASMA WINDOW

The first cascaded plasma window model we designed is shown in Fig. 1. The simulation results plotted in Fig. 2 are calculated under the boundary conditions that pressures of inlet and outlet are 100 kPa and 50 Pa, respectively, the electric potential of cathode1 and cathode2 are -80 V and -60 V, respectively, and the electric potential of anode are 0 V. Although the isolation of 100 kPa and 38.8 Pa pressure has been achieved, the argon gas between the anode1 and cathode2 are ionized and electric current has formed leading to high temperature. Considering the cathode chamber could not endure high temperature, especially the cathode tube, we designed another cascaded plasma window with a common anode, see Fig. 3.

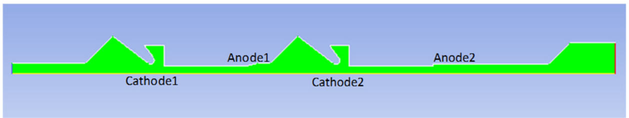

Figure 1: The calculation model of the first cascaded plasma window.

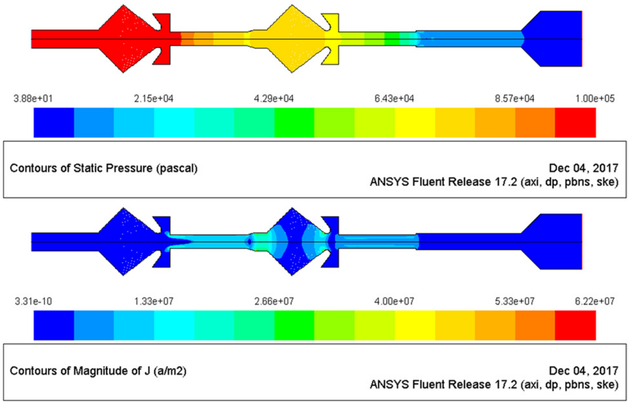

Figure 2: Computed pressure and current distributions within the plasma window.

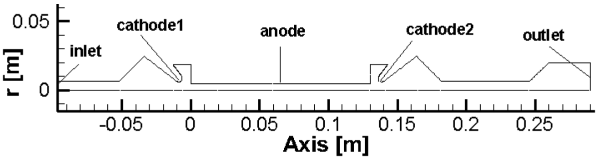

Figure 3: The calculation model of cascaded plasma with a common anode.

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Using the new calculation model, we obtained the mass flow rate and current under the different electric potential of cathode2 with inlet pressure of 100 kPa, outlet pressure of 50 Pa, and the electric potential of cathode1 of -80 V. The results are listed in Table 1. It can be seen that the mass flow rate increases with cathode2 voltage decreasing and the change of cathode2 voltage affects the current of cathode1. In the simulation, the voltage cannot be decreased any further; otherwise, the arc will be broken. Similar situation happens in the simulation of our 10 mm diameter 60 mm long plasma window. This is because our simplified model is totally based on Local Thermal Equilibrium (LTE) model. Dual temperature model might improve the accuracy of the simulation. From the former experiments on 10 mm diameter 60 mm long plasma window, we believe that arc can be generated by lower cathode voltage, experimentally.

Table 1: The Values of Mass Flow Rate, Current and Power Under the Electric Potential of Cathode1 of -80 V and Different Electric Potential of Cathode2

Cathode2 voltage (V)	Mass flow rate (g/s)	I1 (A)	I2 (A)
70	1.36	579.46	610.73
69	1.38	569.82	594.85
68	1.39	556.62	577.03
67	1.41	539.38	559.42

With inlet pressure of 100 kPa, outlet pressure of 50 Pa, electric potential of cathode1 and cathode2 of -80 V and -60 V and electrical potential of anode of 0 V， the computed pressure, temperature, current density and velocity distributions within the plasma window are illustrated in Fig. 4. Due to the thermal blocking effect and viscosity flow at the narrowest part of the channel, pressure gradually decreases from the inlet to the outlet. The electric current flow between cathode and anode produces and radiates heat load leading to high temperature in the discharge channel. The rushing flow with high temperature could not be cooled down immediately, thus the temperature of the fluid in the cathode2 chamber and the section after it is still high. A new cooling design for cahtode2 chamber might be required to protect the cathode tube from high temperature. The unusual temperature distribution near the outlet can be explained as back flow occurs and turbulent energy is left there.

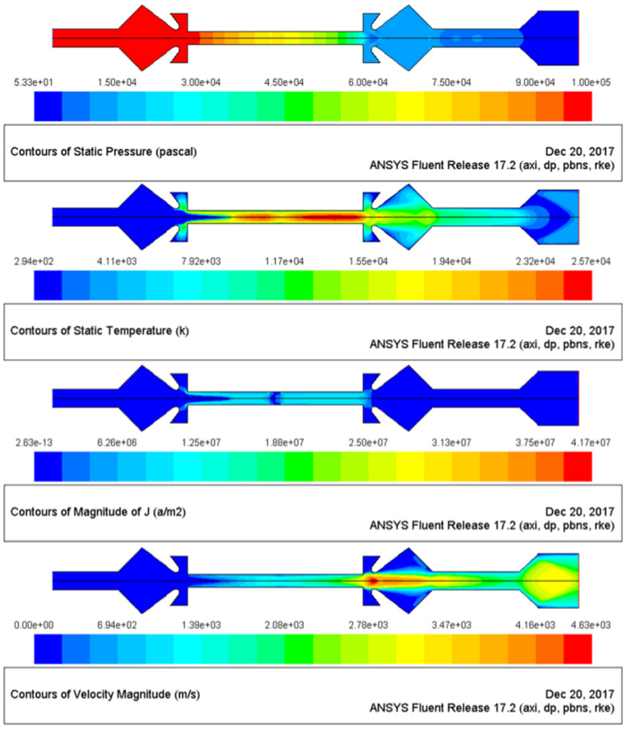

Figure 4: The computed pressure, temperature, current density and velocity distributions within the plasma window.

The pressure together with temperature and velocity distributions along the axis is shown in Fig. 5. Before the plasma channel, the pressure hardly decreases. First pressure drop (from 100 kPa to 70 kPa) happens in the charge channel between cathode1 and anode. Then, the pressure decreases greatly (from 70 kPa to 6.6 kPa) through discharging channel between anode and cathode2, where the plasma is fully developed and the temperature becomes steady. At the cathode2, as the high temperature plasma expands suddenly, the flow is accelerated to the highest velocity due to the transformation from internal energy to kinetic energy, which causes the steep pressure drop. At the same time, shock wave forms at this regime. After the first shock, the velocity drops and pressure increases. A reversed process happens. After that, another weaker shock wave happens and that is why we see oscillation in velocity, pressure and temperature field at this section. As the plasma is compressed into a narrow cylindrical section at the end of the cathode2 chamber, oscillation formed again. Then, the plasma ejects through a cone shaped nozzle to the buffer chamber. Within this divergent segment, the pressure drops quickly from 10 kPa to 53 Pa.

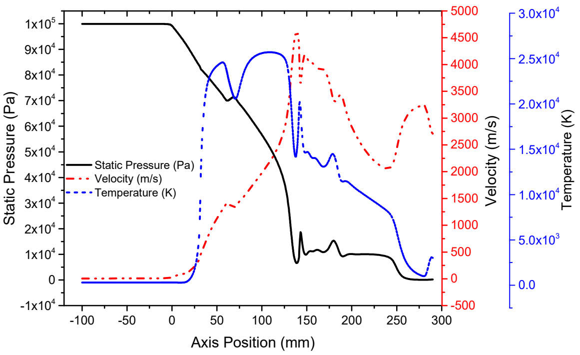

Figure 5: The computed pressure, velocity and temperature distributions along the plasma window axis.

The flow is considered approximately as laminar. According to Poiseuille's equation [7], the pressure distribution is given by

$$P=\sqrt{P_0^2-\frac{16}{\pi}\eta\frac{l}{r^4}\frac{m}{M_0}kT}, \qquad (1)$$

where P_0 is the pressure at inlet, r and l are the tube radius and length, respectively, m the mass flow rate, M_0 the Moore molecular mas,η the dynamic viscosity coefficient, k the Boltzmann constant and T is the temperature. The mechanism of the pressure drop in the plasma window is very complicated which interacts with both the temperature and dynamic viscosity coefficient and is closely related with the shape of the flow channel. For a plasma window with fixed dimensions, the pressure drop is mainly caused by the thermal blocking effect and viscosity flow. While, in our case, as the temperature in the discharge channel are nearly 25000 K, the value of the viscosity is relatively low, see Fig. 6. Therefore, the thermal blocking effect has the advantage over viscosity flow.

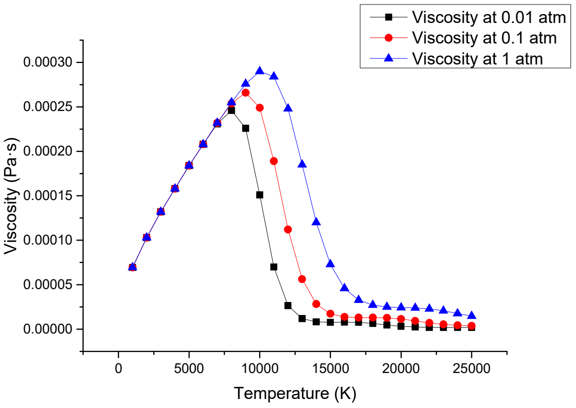

Figure 6: The viscosity of argon as functions of temperature at different pressures 0.01 atm, 0.1 atm and 1 atm, respectively [4].

DISCUSSION

The main reason to develop the cascaded plasma window is to apply it on the high intensity hadron accelerators as windowless vacuum device. However, this cascaded plasma has a disadvantage of long discharge channel, which could lead to divergence of the beam. Theoretically, the beam quality could be sustained if we apply a solenoid around the plasma channel. Although it will make the whole device complex, it can bring some advantages. The magnetic field in the solenoid might promote the spiral movement of electrons, which could help with the full ionization of the gas and stabilization of discharge.

CONCLUSION

We have proposed a 10 mm diameter cascaded plasma window for high intensity hadron accelerators and verified its sealing ability from the theoretical simulations. The isolation of 100 kPa and 50 Pa pressure has been realised. The final prototype must consider the effect of long distance transmission of beams.

ACKNOWLEDGEMENT

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