SIMULATION OF PLASMA WINDOW FOR GAS TARGET OF NEUTRON SOURCE

Sheng Huang, Kun Zhu*, BenLiang Shi, and Yuanrong Lu
State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing China

Abstract

Plasma window is one of the windowless vacuum sealing techniques which can separate high pressure cavity from a vacuum condition by plasma. In this paper the theory of establishing a high pressure gap by plasma window is concluded into three main effects. These are viscosity flow effect, thermal block effect and cooling effect. Further, a preliminary model is constructed by combining laminar flow and joule-heating equations to verify the theory. The simulation results of plasma window are also presented in the paper.

INTRODUCTION

The demand of intense mono-energy fast neutron beams grows quickly in many neutron application fields. The compact mono-energy neutron source is attractive all over the world. Reactor can't produce intense mono-energy fast neutron beam although it can produce intense neutron beam. D(d,n) 4He reaction based on accelerator is a proper way to produce intense mono-energy fast neutron beam. Now accelerators can produce high current beam. For example, radio-frequency quadrupole (RFQ) accelerators can supply several mA to 10mA deuteron beam. The design of the target system becomes the core problem which will affect the neutron yield and mono-energetic properties a lot. Traditional deuteron gas target usually uses several μm thick alloy window to seal the D_2 gas [1]. The alloy window's life is very short because of the high current beam bombardment. Plasma window can provide an effective separation between the vacuum and atmosphere, which therefore can be a valid substitution of the traditional foil window. Plasma window was first used on electron beam welding [1] successfully, and the pressure of rough vacuum can reach 47Pa and higher vacuum degree can be obtained by more differential pumps. The windowless high pressure gas target has many potential advantages. The power dissipation of the high-energy injecting beam is effectively handled through heat exchange in the gas flow causing no damage at all. In addition, there are no decrease and disperse of beam energy so that the maximum neutron output is achieved utilizing the accelerated beam energy. Further, there will be much less production of γ rays.

In order to verify the theory of the plasma window for the gas target of neutron source, three main pressure-drop effects are concluded and a neutral gas joule-heating and laminar flow model is constructed to simulate the plasma window, from which the pressure distribution, temperature field and velocity field are presented.

THEORY OF PLASMA WINDOW

Plasma window can be used as an efficient windowless seal for the high pressure gas target. There are mainly three effects enabling a plasma window to provide such a high pressure gap between vacuum and atmosphere.

The very first effect is due to the gas dynamic viscosity and friction. It is known the pressure will drop while a laminar gas flowing through a tube, which can be roughly described by the Poiseulle's equation [2] for compressible ideal gas

$$p_1^2 - p_2^2 = \frac{16}{\pi}\eta\frac{l}{r^4}NRT \tag{1}$$

where r and d are the tube radius and length, N represents the mole number of gas flow, η is the dynamic viscosity coefficient. The viscosity of plasma gas depends highly on temperature [3],

$$\eta = 2\times10^7\frac{\sqrt{m_i/m_p}}{\lambda}T^{5/2} \tag{2}$$

where m_i and m_p are ion mass and proton mass, and λ is Coulomb logarithm. Consequently, the pressure drop from P1 at the inlet to P2 at the outlet will increase rapidly as the temperature becomes higher.

The second effect is called thermal block. As the plasma arc heats the inlet gas to a high temperature immediately, the gas will expand and be accelerated to a high speed. The acceleration of the flow leads to pressure drop [4]

$$p_1 - p_2 = \frac{m}{\pi r^2}\frac{He}{1+He}v_2 \tag{3}$$

where m is mass flow, ν2 is the outlet velocity and $He = \frac{s_0}{c_p T_0}$ is called heating coefficient which represents the rate of heating energy to the initial internal energy $c_p T$ of unit mass. As a large part of the power of the arc is assigned to increase the internal energy of the gas and the residual of it causes the gas accelerating, the pressure drop from the thermal block effect is limited compared to the viscosity effect. In real case, because the temperature of the arc at the wall is much lower and the density becomes much higher than the center, most of the mass flow of the gas will cross through the low temperature area. Consequently, the block effect will be weakened actually.

The third effect is cooling effect. While the high temperature plasma gas flowing out from the plasma

---

*This work was supported by a grant from the National Natural Science Foundation of China（No. 91026012）
Author email: zhukun@pku.edu.cn

window to vacuum vessel which is cooled by cooling system, its temperature drops rapidly. For ideal gas, the pressure is given by

$$p = nRT \tag{4}$$

where n is the gas or plasma density, and R is the molar gas constant. As a result the pressure of the gas flow will decrease further after the plasma is cooled down.

SIMULATION OF PLASMA WINDOW

The assumptions to derive the simplified equations (1) and (3), such as isothermal, one dimension and none-compressible assumptions, are no longer valid in the plasma window, as the temperature and pressure varies rapidly along both the radius and axis direction. A more accurate but relatively simple way to simulate such case is to combine the Navier-Stokes equations with the energy conservation equation neglecting the chemical procedure, which are expressed as follows:

conservation of mass:

$$\nabla \cdot (\rho \vec{u}) = 0 \tag{5}$$

conservation of momentum:

$$\rho(\vec{u} \cdot \nabla)\vec{u} = \tag{6}$$

$$\nabla \cdot [-p\vec{I} + \eta(\nabla\vec{u} + (\nabla\vec{u})^T - (2\eta/3 - k_{dv})(\nabla \cdot \vec{u})\vec{I}] + \vec{F}$$

conservation of energy:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{v} \cdot \nabla T = \nabla \cdot (\lambda \nabla T) + \sigma E^2 \tag{7}$$

The equations (5)-(7) are constructed on the following assumptions:

- The flow is laminar and the viscosity varies with the temperature [5] but independently with pressure.
- The plasma is in neutral state which enables one to assign a unique temperature for all the particles, and the transport and thermo properties are independent of pressure. The function of the electric conductivity, heat capacity and conductivity of the plasma are determined by temperature [5].
- The arc is considered as optically thin and the energy loss of radiation is neglected because it is rather small comparing to the heat conduction effect.

When considering a plasma window, sketched in Fig. 1, which indicates the position of the cathode, anode, and the plasma stream. The Argon gas of the inlet at room temperature is heated up to 10000K by the DC arc which is provided by three cathodes of high current. And then the partially ionized gas is ejected into a vessel at low pressure pumped by a differential pump system.

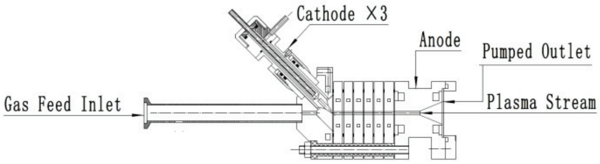

Figure 1: Diagram of plasma window.

Firstly, the model is solved at normal temperature condition for argon. The inlet pressure of the model is set as 1atm as a constant, and the model is calculated with the outlet Ar gas flow rate of volume varying from 1L/m to 50L/m. Fig. 2 shows the gas flow and the equivalent gas consumption at standard condition varies with the outlet pressure. For the Ar gas at normal temperature, the bumping rate is the main direct reason that determines the outlet pressure. Especially when the outlet pressure drops below 0.1atm, the bumping speed is needed higher and higher as lower outlet pressure is required. Accordingly, the real gas consumption at standard state increases when outlet pressure begins to drop but finally reach a limited value. In this case, the argon gas consumption is about 0.3SLM.

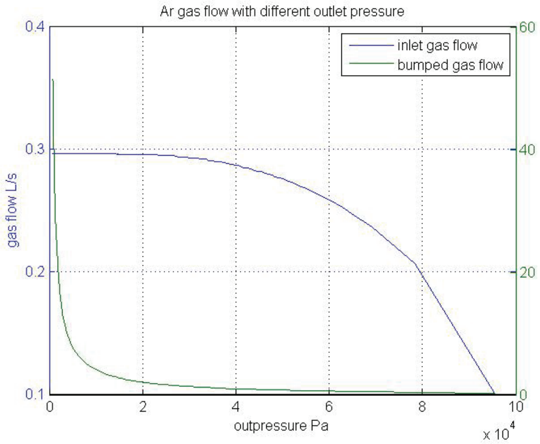

Figure 2: The gas flow and the equivalent gas consumption at standard condition varies with the outlet pressure.

To compare the effect of the plasma window for pressure drop, the model is calculated with and without DC arc at the same bump speed 30L/s. For the DC plasma calculation, the model is run for a total current of 40A, and the result shows that the corresponding potential is 124V. Fig. 3 presents the temperature distribution in the plasma window which is result of the interaction of the high speed gas flow and the arc.

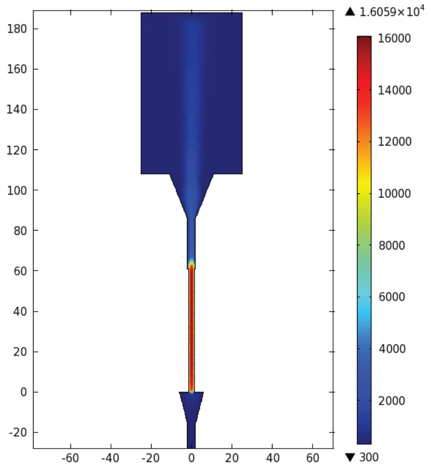

Figure 3: Temperature field of the domain for 40A and 124V DC arc.

All the temperature of the walls is fixed as 300K, but in real circumstances it is a complicated process of interaction of the high temperature gas flow with the wall cooled by the water cooling system. A higher and non-isothermal distribution is expected depending on the efficiency of cooling. The average temperature in the center of the plasma window is 11100K, and the highest temperature can reach 16100K.

Fig. 4 presents the pressure distribution along the axis with and without DC arc. The final outlet pressure is 319Pa, which is 35 times lower than the one attained without DC arc about 11245Pa. The Ar gas consumption at standard condition is 0.095SLM and 3.37SLM when run with and without DC arc separately. Besides it can be found that the pressure decreases little in the gas feed tube before arriving plasma. This shows that the plasma window has an apparent block effect for the gas flow. Along the axis, main pressure drop happens at the plasma section because of its smallest aperture, which is confirmed by Poiseulle's equation.

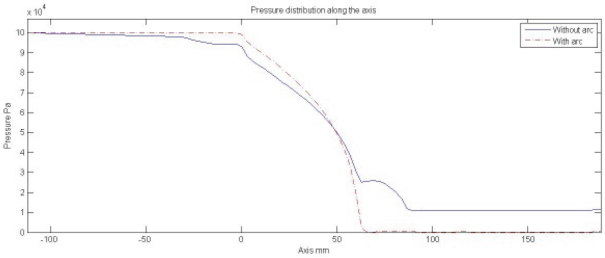

Figure 4: Pressure distribution along the axis with and without DC arc.

Because of such a high pressure gap, the velocity of the gas flow can reach several Mach. Fig. 5 presents velocity field in the domain without arc and with arc separately. As the arc heat the inlet gas to an average temperature of 1.1×10^4 K, partially ionized gas is accelerated and ejected into the buffer vessel. The average ejecting velocity is 1716m/s, which is about 1.6 times of which runs without arc heating, which is about 1.6 times of which runs without arc heating, which leads to further pressure drop.

CONCLUSIONS

The theory of plasma window is concluded into three effects, including viscosity block, thermal block and cooling effect. A neutral gas joule-heating and laminar flow model is constructed to simulate the plasma window to show that such a cascaded arc heating instrument working at high speed gas flow can provide a large pressure gap to connect atmosphere and vacuum.

From the simulation results, the temperature distribution in the domain shows an average temperature of 11000K in the domain can be attained at 40A and 124V. In the center of the plasma aperture, the highest temperature can reach 16000K. By comparing the outlet pressure of the plasma window working without and with arc, it shows that a 35 times lower pressure can be achieved, from 11245Pa to 319Pa. Besides, it can be found the pressure of the cathode cavity rises inversely from 9.4kPa to 10kPa, which verifies the thermal block directly. In future work, the simulating model of the plasma window should be improved by using a turbulent model and more accurate joule-heating model.

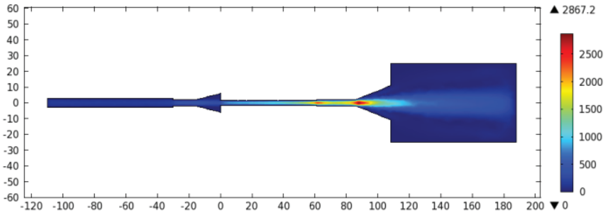

Figure 5(a) Velocity field in the domain at normal temperature 300K.

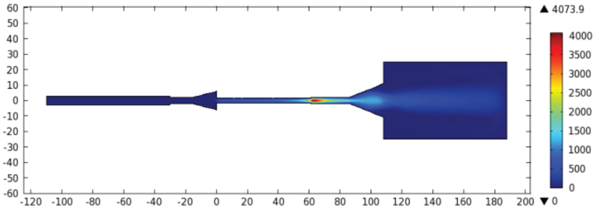

Figure 5(b): Velocity field in the domain with arc working at 40A and 124V.

REFERENCES

[1] A. Hershcovitch, "High-Pressure Arcs as Vacuum Atmosphere Interface and Plasma Lens for Nonvacuum Electron Beam Welding Machines", Journal of Applied Physics, (1995).

[2] L.D.Landau, E.M.Lifshitz, *Fluid Mechanics,* vol. 6 (1959).

[3] J.O. Hirschfelder, C.F. Curtiss, R.B. Bird, *Molecular Theory of Gases and Liquids*, Nueva York, EUA : Wiley, 1964, pp. 213-219.

[4] G.Z. Yuan, B.W. Hong, Z.G. Zhong, Journal of Engineering Thermophysics 6 (1985).

[5] H.K. C, "A Self-Consistent Model for the High Intensity Free-Burning Argon Arc" [Ph.D Thesis], (1982).