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Numerical simulation and experimental progress on plasma window

S. Z. Wang, K. Zhu(*), S. Huang, Y. R. Lu and B. L. Shi

State Key Laboratory of Nuclear Physics and Technology, Peking University
Beijing 100871, China

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Summary. — In this paper, a numerical 2D FLUENT-based magneto-hydrodynamic simulation on 3 mm plasma window using argon, taken as a windowless vacuum device, was developed. The gas inlet, arc creation and developing and plasma expansion segments are all contained in this model. In the axis-symmetry cathode structure, a set of parameters including pressure, temperature, velocity and current distribution were obtained and discussed. The fluid dynamics of plasma in cavities with different shapes was researched. Corresponding experiments was carried out and the result agrees well to the numerical simulation. The validity of sealing ability of plasma window has been verified. Relevant further research upon deuteron gas as neutron production target is to be continued, considering larger diameter plasma window experimentally and numerically.

1. – Introduction

The plasma window was first invented by Andy Hershcovitch [1] in 1995, a new device used for windowless vacuum seal. The cascaded arc discharge [2] inside is formed, then inducing high temperature plasma jet. With the high speed and temperature combined gas jet, atmosphere-vacuum interface could be maintained due to the viscosity of plasma flow. Furthermore, the magnetic field in the plasma flow produced by the current could make a centripetal force on injected charged particle beams, so making possible the non-vacuum electron welding [3] in electron gun and windowless deuteron gas target for neutron source [4, 5]. High vacuum plasma sealing effects as well as high compatibility with electrons, ions, and x rays transportation have been showed and verified by many experiments [6-8]. However, because of the complex interaction among high-speed electrons, sorts of ions and neutral atoms, few papers carrying on simulation works of

(*) E-mail: zhukun@pku.edu.cn

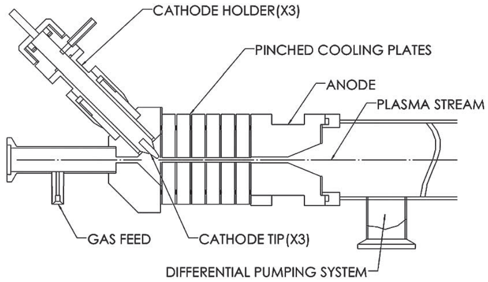

Fig. 1. – Diagram of plasma window.

plasma window were reported. We analysed the inner activities of axis-symmetry plasma flow and improved segments in diverse shapes were studied. The study work on plasma window is introduced in the following.

2. – Plasma window

A typical plasma window is mainly composed of cascaded arc apparatus and differential pumping system seen in fig. 1. The real experimental device is shown in fig. 2. We used three cathodes and one anode to create a constant current, which could be up to 80 A. The argon was led in through gas feed into aperture with 3 mm diameter. The arc is restrained by cascaded copper plates which are electrically insulated by boron nitride spacer plates. The pressure can drop from about 1 atm in the gas feed to nearly 100 Pa or even lower. As a result of differential pumping system, the pressure could be down to 10^{-4} Pa, which is the required vacuum degree for beam injection [6-9].

3. – Numerical simulation

We used FLUENT software to set appropriate boundary conditions and quadrilateral mesh to simulate our real plasma window design. In order to analyze effects of shape of plasma window on the its flows characteristics, different shapes of plasma section wall has been designed to see whether there exists an optimized point where we can realize the satisfactory plasma isolation function with lower argon gas waste. Table I shows simulated results of 3 mm plasma window with different shapes of plasma section

Fig. 2. – Physical device of plasma window.

TABLE I. – *Simulation of 3 mm plasma window with different shapes of plasma section wall.*

	Inlet/outlet pressure (kPa/Pa)	Current (A)	Cathode voltage (V)	Mass flow rate (kg/s)
Normal	52.5/60	50.2	121.0	4.8×10^{-5}
Arc	52.5/60	50.2	94.0	6.9×10^{-5}
Convex	52.5/60	50.3	103.0	5.4×10^{-5}
Concave	52.5/60	50.2	122.2	4.4×10^{-5}
Double concave	52.5/60	50.0	123.8	4.1×10^{-5}

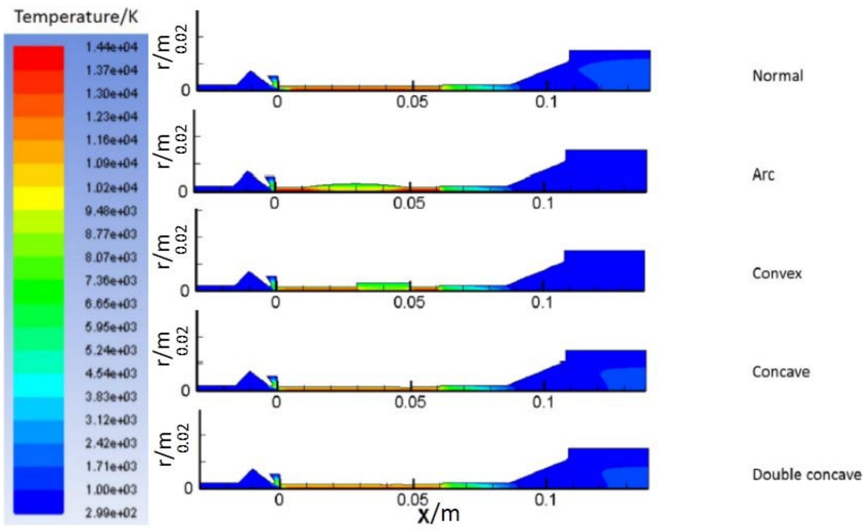

Fig. 3. – Temperature distribution of plasma window with different shape.

wall including normal, arc, convex, concave, and double-concave appearance. In the simulation, inlet pressure, outlet pressure and current were set the same while cathode voltage and mass flow rate differ from each other with the boundary condition that cathode and anode temperature is 7000 K and other walls with room temperature 300 K, all calculated in magneto-hydrodynamics model with standard k-epsilon model set as viscous model. The temperature distribution derived from simulation result is shown in fig. 3.

From table I, it can be concluded that power needed will go down when volume of plasma section increases. It could be explained by regarding plasma flow as electric current, the electric conductivity increases when the radius of plasma cylinder increases, so leading to the resistance decreasing. Thus with the same value of current, the arc shape and convex ones with obviously larger volume compared to the normal shape have lower voltage. While on the contrary, the concave and double-concave ones with smaller volume have higher voltage than the normal ones. In terms of gas consumption, it seems that smaller volume ones have smaller mass flow rate, which means narrower plasma gas passage will lead to less gas waste.

TABLE II. – *Comparison of plasma window between experiment and simulation.*

	Inlet/outlet pressure (kPa/Pa)	Current (A)	Cathode voltage (V)	Mass flow rate (kg/s)
Experiment	52.5/60	47	115	4.87×10^{-5}
Computed	52.5/60	47	140	5.12×10^{-5}
Error			17.8%	4.8%

4. – Experimental comparison

In table II, one type of simulation was conducted to compare with relevant experimental results. We verified by the fact that 3 mm diameter plasma windows experimental result almost matches simulation result in table I. While the voltages little difference could be explained by noting that theoretical Local Thermal Equilibrium (LTE) model is not precisely suitable for such situation where temperature of electrons is higher than that of ions. So experimentally it leads to larger electrical conductivity and lower voltage than simulated at the same current.

5. – Conclusion

We used fluent MHD 2D model to set up and simulated the real 3 mm plasma window and plasma properties including the influence of volume of plasma section and shapes have been studied. Finally it has been demonstrated by the fact that it could be used as a windowless plasma sealing device isolating high pressure from vacuum, verified by experiment result. Also we have conducted its simulation work and compared it with experimental result which has good consistence with computed outcome. That means we can use simulation to model our expected experiment using deuteron as neutron production target gas and predict the result for directing future research.

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