Development of a facility simulating fusion divertor plasmas at KAERI

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1. Introduction

Divertor is a device installed inside a fusion reactor to remove helium ashes produced by D–T fusion reaction during the plasma operation. The divertor concept is currently being used in several fusion reactors including KSTAR and will be used in ITER. In order to efficiently remove the helium ashes, strong magnetic fields intersect with the divertor plate (strike point). Thus, the divertor plate near the striking point experiences high heat and particle fluxes. In ITER, it is expected that the divertor plate will be hit by a heat flux of 10 MW/m^2 and a particle flux of 10^{24} /m^2/s in steady-state [1,2]. In the ELM phase, the peak heat flux can reach to 1 GW/m^2 [1,2].

In order to develop divertor cooling techniques that can handle ITER level (or higher) heat and particle fluxes, Center for Innovative Divertor (CID; center leader: Prof. MooHwan Kim at Postech) has been launched since last September. The CID consists of three teams – Postech, UNIST, and KAERI. The Postech team studies the divertor cooling tube design to improve the cooling capability. The UNIST team led by Prof. MinSup Hur will studies divertor structure design using simulation codes such as SOL-PS. The KAERI team has developed a divertor plasma simulating facility to test the divertor cooling techniques developed by the Postech team and to develop divertor plasma diagnostics including divertor Langmuir probe and optical emission spectroscopy. The developed diagnostics will be installed in KSTAR and the data obtained from KSTAR plasmas will be used to verify the simulation results of the UNIST team.

2. Divertor plasma simulating facility

The characteristics of ITER divertor plasmas are as follows [1,2]:

1) high plasma density: 10^{14}–10^{15} cm^{-3}
2) relatively low plasma temperature compared to core region: few eV to few tens of eV
3) strong magnetic field: few Tesla
4) neutral gas density is relatively high compared to core plasma: several mTorr

The Magnum PSI in the Netherlands is the most advanced divertor plasma simulating facility in the field [1]. A cascade arc jet which typically operates at tens of Torr is used as a plasma source in the Magnum PSI. Thus, the differential pumping is required to have a low neutral gas pressure similar to the actual divertor region in the target chamber. A 270 kW direct current (DC) power supply is used to plasma ignition and an external magnetic field of several Tesla is applied to focus the plasma beam. The typical heat and particle fluxes obtained in Magnum PSI are 12 MW/m^2 and 10^{24} /m^2/s at present [1].

In Korea, Chonbuk and Seoul National Universities [3,4] have arc plasma torches somewhat similar to the cascade arc jet in the Magnum PSI. However they only operate at high neutral gas pressure (few tens – hundreds of Torr) and magnetic fields cannot be applied.

Instead of using an arc plasma torch, we decided to use the applied-field magnetoplasmadynamic (AF–MPD) thruster as a plasma source for our divertor simulating facility because it can operate at low gas pressure with strong magnetic fields. Several types of AF-MPD thrusters have been reported thus far and the specifications of notable AF-MPD thrusters are shown in Table 1 [5,6]. As seen in the table, the DRL's X9 and Stuttgart's SX3 thrusters are promising to provide heat and particle fluxes similar to the fusion divertor region. The simple calculation below shows that 24 MW/m^2 heat flux (Q) is achievable if we use a 100 kW power supply and we assume the radius of the plasma beam to be 2 cm and the plasma converting efficiency to be 30%.

$$Q = 10^5 \text{ W} \times 30\% / \pi (2 \text{ cm})^2 = 24 \text{ MW/m}^2 \quad (1)$$

Table1. Specifications for several AF-MPD thrusters [5,6]. Particle and heat fluxes are calculated with assuming plasma beam radius $r = (r_{\text{anode}} + r_{\text{cathode}})/2$.

	DLR X9	**AF 100-kW**	**Mai 130-kW**	**Stuttgart SX3**
anode material	-	Cu	W	Cu
cathode material	W+2%ThO_2	W+2%ThO_2	W	W
anode radius (cm)	2	2.5-5	8	4.3
cathode radius (cm)	0.5	0.64	2.25	0.6
discharge current (A)	800-1200	1000	1700-2100	500-1000
discharge voltage (V)	30-80	22-98	54-58	100-200
external B-field (T)	< 0.262	0.03-0.16	0.09	0.1-0.4
flow rate (mg/s)	120	100	86	100-120
exhaust speed (km/s)	20.4	17.9	32.6	~30
heat flux (MW/m^2)	48	20	6	27.5
particle flux (/m^2/s)	> 10^{24}	> 10^{24}	< 10^{23}	~10^{24}

There are several important points to be considered when the AF-MPD source is designed.

1) ratio of anode size and cathode size must be between 4 and 8
2) better performance can be achieved when the gas is provided through both anode and cathode
3) cathode with the hollow shape is more robust for erosion.
4) in order to avoid anode erosion, the conical shaped anode is recommended

We think that since the anode radius of the X9 thruster is only 2 cm, it is difficult to put a water cooling system inside the anode. Therefore, we concluded that the SX3 thruster is more suitable for us. The tentative design of our plasma source is shown in Fig. 1; it consists of the Cu anode, W hollow cathode, and several insulators made of boron nitride, PEEK, and alumina. The insulators will be placed between the anode and cathode for electrical insulation and for centering of thruster components. A water cooling system will also be embedded in the anode and cathode to prevent the plasma source from overheating.

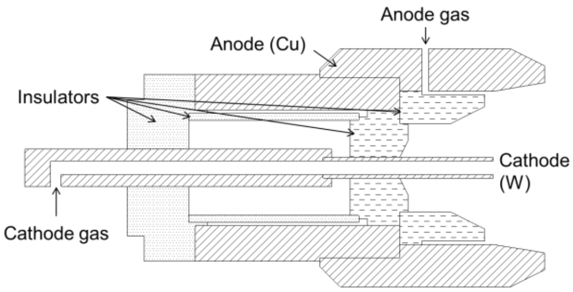

Figure 1. A sketch of our MPD thruster. It consists of Cu anode, W hollow cathode, and three insulating materials. The general concepts are adopted from Ref. [6].

Figures 2(a) and (b) show a drawing and a photo of the vacuum chamber of the KAERI divertor simulating facility. The cylindrical chamber made of stainless steel was manufactured by I.T.S Vacuum and installed at KAERI. The diameter and the length of the chamber are both 1.5 m and are large enough to accommodate the actual divertor cooling channel (~ 1 m).

Because AF-MPD thrusters typically operate at high inlet gas flow rates as high as several liters per minute (lpm), we need high performance vacuum pumps for low operation pressure. The calculation shown below indicates that we need vacuum pumps that have a pumping speed of 10,000 l/s to maintain the operation pressure of few mTorr at 3.3 lpm inlet flow rate.

$$
\begin{aligned}
p &= \text{leak rate / pumping speed} \\
&= (100\text{mg/s=3.3lpm=42Torr}\cdot l\text{/s}) / (10^4 l / s) \quad (2) \\
&= 4.2 \text{ mTorr}
\end{aligned}
$$

Two cryopumps (Genesis ICP-300L) having the pumping speed of 5,000 l/s are installed at present. Two additional pumps will be purchased if necessary.

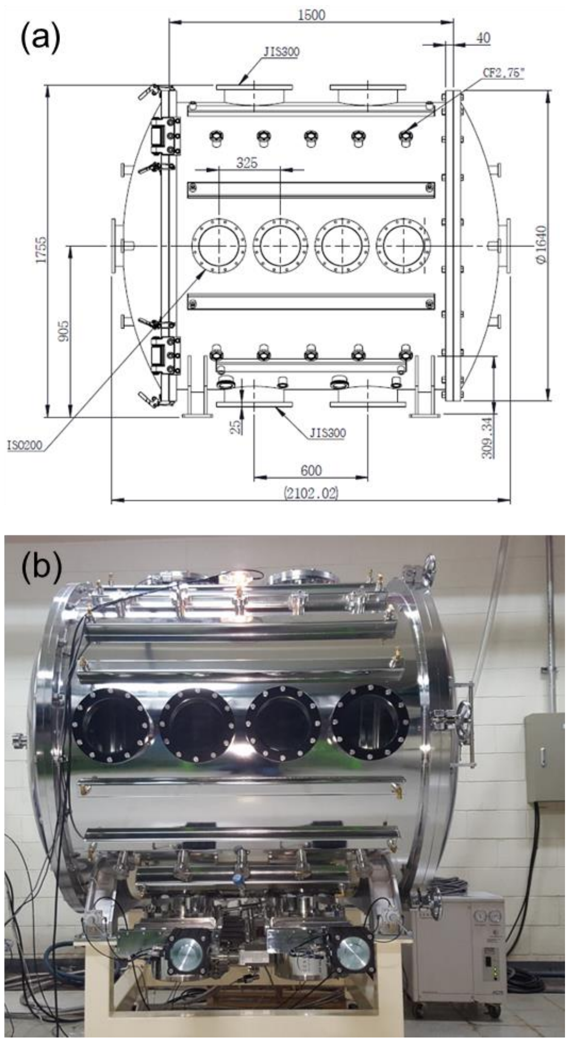

Figure 2. (a) CAD drawing of the vacuum chamber. Chamber is big enough to accommodate the divertor cooling channel mockup. (b) A photo of the vacuum chamber. Two cryopumps are installed at present to provide 5,000 l/s pumping speed.

3. Plasma diagnostics

In order to measure the heat flux provided by our divertor simulating facility, an infrared (IR) camera will be used. Details about the IR camera will be determined after the first plasma is achieved. For measuring the ion flux provided by our facility, Langmuir probe array will be utilized. We will carefully design the Langmuir probe array that can be used in both our experiment and the KSTAR. This project will be conducted in the collaboration with National Fusion Research Instutite. The optical emission spectroscopy based on a collisional–radiative (CR) model can measure the electron temperature and density of our plasma. Currently, an Ar CR model was successfully developed and it is under verification phase.

4. Concluding remarks

KSTAR divertor upgrade is scheduled for 2021. One of the goals of the CID is to provide meaningful data that can be used when the KSTAR divertor is upgraded. Examples include the design of divertor cooling channels, in-situ divertor plasma diagnostics, and innovative divertor structures.

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REFERENCES

[1] G. De Temmerman et al., Fusion Engineering and Design 88, 483 (2013).
[2] R. A. Pitts, *Tokamak edge physics and plasma-wall interactions*, French Fusion Masters, CEA/RFM (2012).
[3] B. G. Hong, M. H. Kim, and J. H. Seo, Transactions of Fusion Sci. Tech. 63, 213 (2013).
[4] H.-S. Kim et al., J. Nucl. Mater. 463, 215 (2015).
[5] A. D. Kodys and E. Y. Choueiri, *A critical review of the state-of-the-art in the performance of applied-field magnetoplasmadynamic thrusters*, in 41th AIAA/ASME/ SAE/ASEE Joint Propulsion Conference, number AIAA-2005-4247, Tucson, AZ, USA (2005).
[6] A. Boxberger and G. Herdrich, *Integral measurements of 100 kW class steady state AF-MPD thruster SX3 and perspectives of AF-MPD technology*, 35th International Electric Propulsion Conference, number IEPC-2017-339, Atlanta, GA USA (2017).