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Nuclear fusion one-side Joule heating system on subcooled flow boiling

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1. Introduction

Nuclear fusion energy is one of promising future energy sources. The fusion energy is created by using deuterium (D_2) and tritrium (T_3) as main source as plasma. The plasma is kept in the tokamak in nuclear fusion reactor and the path of the plasma is controlled by the magnetic field. This magnetic field drives the plasma to the bottom of the tokamak, where the divertor is located. The divertor is heated by plasma only on the top side, resulting in one-side heating. The amount of heat flux applied on the divertor is about 10 MW/m^2 in steady-state or 20 MW/m^2 in slow transient state in 10 s duration time [1].

The role of the divertor is to remove the impurities such as helium ash created by the plasma reaction. The main function is to remove the heat flux by plasma, therefore thermal-hydraulic analysis of the cooling channel inside divertor is essential.

For reproducing the one-side heating for divertor researches, currently Ion or electron beam is used. While using Ion or electron beam is more physically similar to nuclear fusion operating condition, it is difficulty to be applied to develop engineering system involving various design evaluations due to the price of the equipment and difficulty of system preparation. The Joule heating using electrical energy is controllable so it could be used to set up the facility. However, the current one-side Joule heating system is limited up to only 2.5 MW/m^2 [2]. Since it is too low to test on nuclear fusion system, it is necessary to develop one-side Joule heating system. In this paper, designing the one-side Joule heating system and development will be discussed. Finally, the Joule heating system will be used to compare with CFD (COMSOL multi-physics v 5.4 simulation) and subcooled flow boiling experiments.

2. Methods and Results

Joule heating system design includes three main steps;

(1) Decision of target heat flux and area
(2) Material selection and connection of the component layers
(3) Thermal resistance heat flux test

2.1 Decision of target heat flux and area

The target heat flux to describe the divertor situation in the operation is about 10 MW/m^2 in steady state. The actual hitting area of plasma on the divertor is about 23 x 40 mm^2. Considering the worse scenario, 23 x 100 mm^2 has been decided for heated area with 10 MW/m^2 target heat flux.

2.2 Material selection and connection of the component layers

The most important task for designing one-side Joule heating system is decision of the heater. The heater selection is based on the material properties such as electrical resistance (ρ), melting point (T_{melt}), thermal expansion coefficient (α), thermal conductivity (k), and manufacturing feasibility. Among those properties, electrical resistance, melting point, and thermal expansion coefficient are significant. Conventionally available metal and metal alloy are evaluated as heater materials. The metal candidates are Molybdenum (Mo), Platinum (Pt), and Silver (Ag). For alloys, FeCrAl (Iron-Chromium-Aluminum) and NiCr (Nickel-Chromium) are best nominees. The alloys have high electrical resistance with low thermal conductivities. In contrasts, pure metal has 10^3 lower electrical resistance compared to metal alloys with high thermal conductivity. In this one-side Joule heating system, to produce high heat flux we chose to use metal alloys having high electrical resistance and melting point with low thermal expansion coefficient. Between two metal alloy candidates, FeCrAl (Cr 22% Al 5.8% Fe 72.2%) have been chosen because of higher electrical resistance and melting point with lower thermal expansion coefficient.

Table I: Metal and Metal alloys properties

Material	ρ (Ω/m)	T_{melt} (°C)	α (10^{-6}/K)	k (W/m-K)
Pt	105 x 10^{-9}	1768	8.8	71.6
Ag	15.9 x 10^{-9}	962	18.9	429
FeCrAl	1.45 x 10^{-6}	1500	14	13
NiCr	1.09 x 10^{-6}	1400	16	15

With the chosen material, proper thickness of the material for 10 MW/m^2 is determined. The heater thickness is decided to reach the target heat flux but without material melting. The amount of heat flux produced in Electrical Joule heating method is calculated with material's resistance. The electrical resistance is decided by the electrical resistance (ρ), material length (L), and the cross area (A) where current flows. Since the material length and electrical resistance are given, material thickness will determine the producible heat flux amount. Based on the equation (1) and equation (2) below, the minimum and maximum thickness are decided:

$$Q = I \cdot V\ [W] = I^2 \cdot R = \frac{V^2}{R} \quad (1)$$

$$R = \rho \cdot \frac{L}{A} \quad (2)$$

The thickness range was from 33 ~ 2800 um from the calculation.

The final step is to calculate the temperature of the each layer of heating system as thickness changes in order to avoid melting point. Our heating system layer is composed of Heater - Electrical insulator - Cooling channel, and top of the heater is insulated as shown in Fig 1. When heat flux is applied, T_4 has the highest temperature, and sequentially the temperature decreases towards cooling channel. Therefore, for heater, T_4 calculation is most important depending on the heater thickness.

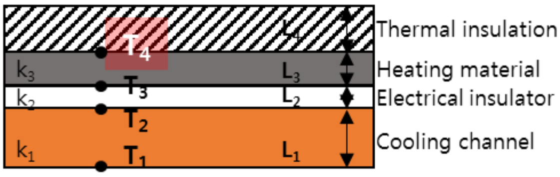

Fig. 1. One-side Joule heating system layer

286 ^{o}C value was used for T_1 from the pre-liminary experiment for 10 MW/m^2 (v = 8 m/s, P = 2 MPa, T_{in} = 15 ^{o}C). T_2, T_3, and T_4 are calculated from Fourier's heat conduction equation. When the heater thickness is 2800 um, T_4 is 1490^{o}C, which is almost melting point of the heater (FeCrAl, 1490 ^{o}C). Since in this calculation unpredictable contact resistance between each layer is not accounted in the temperature calculation, we reduce further the heating material thickness to secure more temperature margin from melting temperature. On the other hand, thin layer is difficult to be fabricated with reliable material robustness. So 400 um thickness (T_4 = 567 ^{o}C) was finally chosen as heating layer thickness.

$$q'' = k \cdot \frac{T_2 - T_1}{x_2 - x_1} \quad (3)$$

$$R_{total} = R_1 + R_2 \quad (4)$$

2.3 Thermal resistance test

To reduce the thermal resistance between the heater and electrical insulator layer, thermal paste was used. The main properties considered choosing thermal paste were viscosity, maximum temperature, and thermal conductivity. The different types of pastes tested are provided in Table II.

Table II: Thermal paste properties and accomplished heat flux

Paste	k (W/m-K)	T_{max} (^{o}C)	Max. Heat flux (MW/m^2)
#1	8.5	400	11.5
#2	3	1200	4.4
#3	2.7	450	7.8
#4	14.3	300	8.1
#5	13.8	380	11

Maximum heat flux test was conducted using one-side Joule heating system described above section and the heat flux was applied by the SCR (silicon controlled rectifier), which provides up to 66 V and 3200 A. Thermal paste was painted between heater and electrical insulator layer, where area is 23 x 100 mm^2. The data was taken for 3 minutes when the flow rate and pressure become steady for each data point after increasing heat flux.

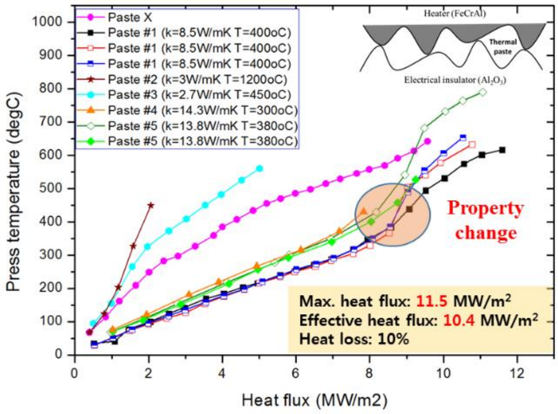

Fig. 2. Thermal resistance pre-test result

The reference result was the Paste X case, which does not use paste. Since the heater had very thin thickness, the heater temperature was predicted by measuring the press (thermal insulator, L_4 in Fig 1.) temperature just 1 mm above the heater. The first of all, the viscosity was the priority property for application of thermal paste, because applied area is wide. If the viscosity of thermal paste is high, it is difficult to uniformly apply it on the area. Therefore, paste #2 was not useful. Paste #3 has very low thermal conductivity, therefore the heat transfer from the heater to the cooling channel was inefficient. Lastly, the Paste #1, #4, and #5 were comparable. The paste #4 and #5 had high thermal conductivity and temperature, but compared to paste #1 the temperature of the thermal paste was lower, resulting thermal paste's property quickly changes or evaporation once it exceeds temperature limit. Therefore, paste #1 was used for the maximum heat flux test, and the maximum heat flux was 11.5 MW/m^2. The effective heat flux was 10.4 MW/m^2, considering 10% heat loss which was calculated from the subtraction between the applied heat flux (Q = I*V) and fluid heat balance ($Q = \dot{m} * C_p * (T_{out} - T_{in})$).

There is a debate where at the 9 MW/m^2 around 400°C, the slope of the graph is steep. Two possible reasons for this outcome are suggested. First, since the temperature is above 400°C, the thermal paste had exceeded the limit temperature that resulted in change in property or it underwent evaporation. Secondly, the thermal expansion caused the physical gap between the heater and electrical insulator layer since the thermal expansion coefficients are different, as shown in Fig 3.

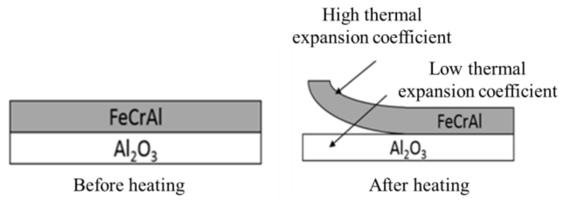

Fig 3. The gap between two layers before/after heating

2.4 Comparison between pre-liminary experimental result and simulation

Comparison between the pre-liminary experimental result and the simulation by COMSOL multiphysics v5.4 of the heater system is done. The experiment was run under T_{in} = 140 °C, P = 10 bar (T_{sat} = 180 °C), and V = 2 m/s. The simple 2D simulation was conducted. The unique characteristic of the one-side heating is the non-uniform heat transfer distribution along the cooling channel boundary [3]. Therefore, the heat transfer coefficient has to be changed along the angle changes at boundary of cooling channel. Dittus-Boelter correlation was applied for single phase, and Araki et al. correlation [3] was applied for subcooled boiling regime. The air convection of h = 10 W/(m^2-K) was used for outside channel boundary.

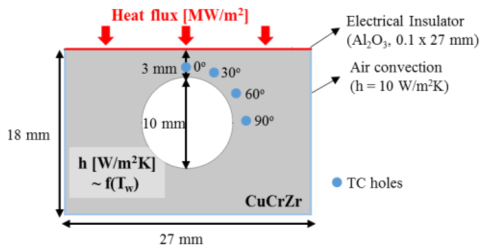

Fig. 4. Simulation boundary condition

The experimental results are shown in dots, and simulation results are shown in lines. The temperatures were compared along the cooling channel boundary (0°, 30°, 60°, 90°) 1 mm away from the wall.

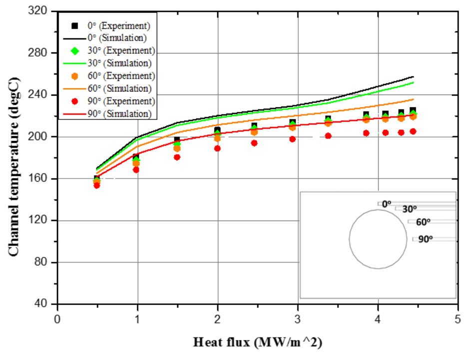

Fig. 5. Comparison between experiment and simulation result

The averaged simulation error percentage is shown in Table III. The error is relatively low in single phase compared to that of two phase regime. Correlations for single phase regime predict very well in one-side heating situation [3][4]. However, the temperature prediction using existing uniform heating correlation for subcooled boiling regime cannot predict the temperature distribution in one-side heating case [3][4]. Additionally, Araki et al. correlation [3] experimental range is different from our experimental condition. The simulation result shows decent agreement with experimental result. Further one-side heating correlation must be developed for our experimental condition.

Table III: Simulation error percentage

Angle (°)	0	30	60	90
Error (%)	8.62	8.69	6.13	6.68

3. Conclusions

One-side Joule heating system was developed based on material properties and applied heat flux condition for thermal-hydraulic test under divertor condition of nuclear fusion. The most common method of one-side heating in current experiments is ion or electron beam, but it is very difficult to develop the system and expensive in cost. Joule heating system also has advantage of heat flux application during an experiment. Detailed heating system dimension and property analysis was conducted and 10.4 MW/m^2 effective heat flux was achievable. Using the heating system, preliminary experiment and numerical simulation are compared. Result comparison showed good agreement between 6 – 8% differences. In future, for better prediction, heating system to reach higher heat flux and the one-side heating correlation representing well two-phase area would be developed for nuclear fusion application

REFERENCES

[1] Gunn, J. P., et al. "Surface heat loads on the ITER divertor vertical targets." *Nuclear Fusion* 57.4 (2017): 046025.

[2] Boyd, Ronald D., and Hongtao Zhang. "Conjugate heat transfer measurements with single-phase and water flow boiling in a single-side heated monoblock flow channel." *International journal of heat and mass transfer* 49.7-8 (2006): 1320-1328..
[3] Araki, Masanori, et al. "Experiments on heat transfer of smooth and swirl tubes under one-sided heating conditions." *International journal of heat and mass transfer* 39.14 (1996): 3045-3055.
[4] Zhu, Ge, et al. "Experimental study of subcooled flow boiling heat transfer of water in a circular channel under one-side heating conditions." *International Journal of Heat and Mass Transfer* 119 (2018): 484-495.