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Graphite Heater Design for the High Heat Flux Test Facility KoHLT-1

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1. Introduction

We are developing the ITER (International Thermonuclear Experimental Reactor) blanket first wall (FW) which consists of Be tiles bonded to a CuCrZr heat sink and a SS316L block [1]. Thus it is essential to develop a HIP (hot isostatic pressing) joining technology to bond different metals, i.e., Be-to-CuCrZr and CuCrZr-to-SS316L. In order to verify the integrity of a HIP bonded first wall, we constructed a heat load test facility using a graphite heating panel in 2008, which is similar to the BESTH [2]. The facility is called KoHLT-1 (Korea Heat Load Test facility-1) and is currently in operation for thermal cycle tests of various first wall mockups at a high heat flux. Its schematic diagram is shown in Fig. 1. The KoHLT-1 consists of a graphite heating panel placed between two mockups, a box-type test chamber with water-cooling jackets, an electrical power supply, a water-cooling system, an evacuation system, an He gas system, and some diagnostics, which are equipped in an authorized laboratory with a special ventilation system for the Be treatment.

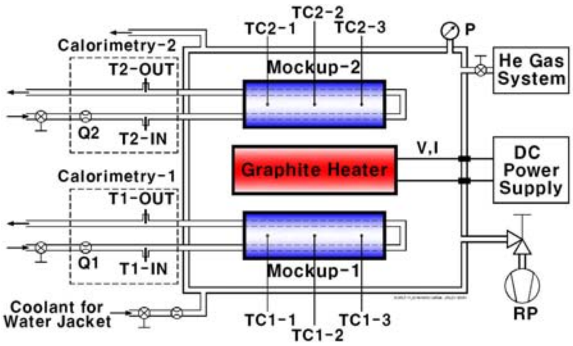

Fig. 1. Schematic diagram of the KoHLT-1 facility.

We have carried out the thermal cycle tests of various Be mockups, including two large mockups with three Be-tiles of 80×80 mm^2, which are identical to the FWQM (First Wall Qualification Mockup) [3], six small mockups with three Be-tiles of 35 × 35 mm^2 bonded to a CuCrZr block, and six single tile mockups with an identical cross-section to the FWQM. Prior to the main test, we performed a pre-test to adjust the required heat flux, in which we changed the electrical current shot by shot. Nominal heat flux was 0.63 MW/m^2 or 1.5 MW/m^2 depending on the mockup sizes. Some Be tiles were detached during a thermal cycle test at the heat-up or cool-down phases, but others survived up to 5200 cycles at 0.63 MW/m^2 or 1100 cycles 1.5 MW/m^2.

2. Graphite heater design

We designed and fabricated several graphite heating panels to have various heating areas depending on the tested mockups, and to have an electrical resistance of 0.2-0.5 ohms during a high temperature operation. Figure 2 shows three fabricated graphite heaters. The heater is connected to an electrical DC power supply of 100 V/400 A. The heat flux is easily controlled by the pre-programmed control system which consists of a personal computer and a multi function module. The graphite heater provides the heat load by radiation. So the heating power is directly dependent on the temperature of the heating element. We calculated the radiation heat power from the graphite heater for various electrical currents using the following power balance equation;

$$P_e(t) = I^2(t)R = C_g M_g \frac{dT_g(t)}{dt} + A\varepsilon\sigma T_g{}^4(t), \quad (1)$$

where I is the electrical current, R is the resistance, C_g is the specific heat, M_g is the mass, $T_g(t)$ is the time dependent temperature, A is the surface area, ε is emissivity, of the graphite heating panel, and σ is the Stefan-Boltzmann constant. In this calculation, we assumed that the conduction heat loss is negligible. Graphite has unique temperature dependency of the electrical resistance. As temperature rises, the electrical resistance decreases in a range of 0-900 ^{o}C, but it increases in a higher temperature range. We determined the resistance from the voltage and current values during a high temperature operation. The first term of the right-hand side of eq. (1) corresponds to the heat required to increase the temperature of the graphite heater itself. The last term corresponds to the irradiation power, from which we can obtain the absorbed power by multiplying a heat transfer efficiency. The heat transfer efficiency is mainly determined by a radiation shape factor, which is defined as a fraction of energy leaving a surface which reaches other surface. Most of the radiating power is absorbed by the adjacent mockups, but a part of that is lost to heat-up the chamber wall and other structure material. We can increase the efficiency by decreasing the gap distance between the graphite heater and the mockups. However the gap distance is limited by an arcing problem. In the KoHLT-1, the gap distance was adjusted to 2-3 mm. The heat transfer efficiency was experimentally determined from an absorbed power measured by a calorimetric method and the applied electrical power, and it was normally e=0.7-0.85.

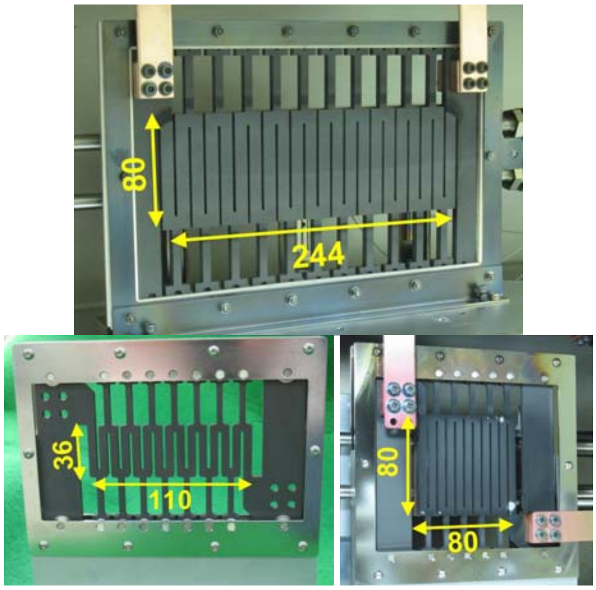

Fig. 2. Fabricated graphite heaters with various effective heating areas.

Figure 3 shows the calculated response curves of the graphite heater having a effective heating area of 244×80 mm^2, R=0.24 ohms, and e=0.8, for various currents. In this calculation, we used the current profile of a 30-s heating-up, a 180-s holding, a 30-s cool-down, and a 60-s power-off, which is the test condition of a normal operation determined by the ITER IO (International Organization) [4]. As shown in the figure, it takes tens of seconds to reach the saturated heat flux. The higher the electrical current is, the shorter the rising time is. Figure 4 shows the absorbed heat flux, the graphite temperature, and the rising time calculated for a given graphite heater of R=0.24 ohms. As shown in the figure, we need an electrical current of 357 A to obtain a heat flux higher than 0.625 MW/m^2 which is the heat load value for the testing of the ITER FWQM. In that case, it takes 58 sec to obtain the 90 % of the full heat flux. If we need a higher heat flux, we can get it by increasing the current. But it is limited by the maximum output current and voltage of the DC power supply, and by the allowable graphite temperature. In the case of the FWQM, the available heat flux is below 0.8 MW/m^2 which is limited by the maximum output current of the power supply.

For the smaller graphite heaters, we performed similar calculations. In the case of the 35×35×3 mockups, we designed and fabricated a graphite heater which has an effective heating area of 110×36 mm^2, and an electrical resistance of 0.20 ohms. By using this heater, we can get the required heat flux of 1.5 MW/m^2 with a current of 288 A. In the case of the 80×80×1 mockups, the heater has the effective heating area of 80×80 mm^2, and the electrical resistance of 0.32 ohms. By using this heater, we can get the required heat flux of 1.5 MW/m^2 with a current of 262 A.

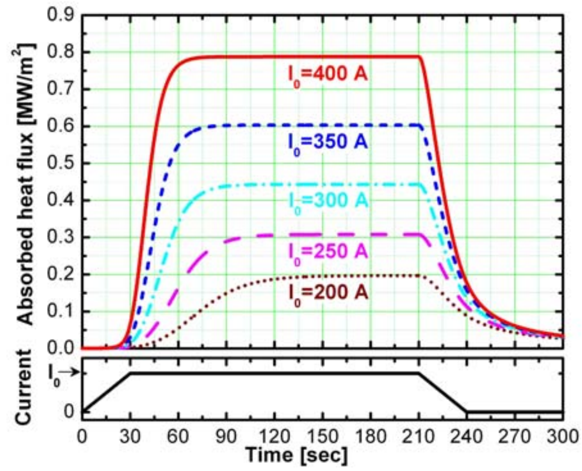

Fig. 3. Temperature response of a graphite heater for various currents in the case of the FWQM.

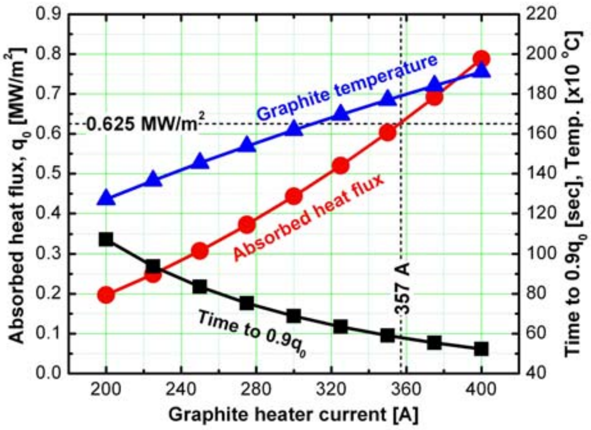

Fig. 4. Absorbed heat flux, graphite temperature, and rising time of the heat flux calculated for a given graphite heater with an electrical resistance of 0.24 ohms.

Using the fabricated graphite heaters, we performed thermal cycle tests of various Be mockups. The required heat fluxes were easily obtained by controlling the graphite heater currents, and those agreed well with the expected values.

REFERENCES

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