Testing of Thermal Protection Systems for Nuclear-Powered Space Systems Under Re-Entry Conditions Using a 0.4MW Plasma Jet Facility

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1. Introduction

Nuclear-powered thermoelectric generators (RTGs) provide a stable power supply in space by utilizing the decay heat of radioactive fuel. These generators are essential for long-duration missions, including deep-space exploration. However, in the event of a launch failure or accidental re-entry, the containment system must endure extreme aerothermal conditions to prevent the release of radioactive material.

Carbon-based thermal protection systems (TPS), such as carbon-carbon (C/C) composites, are widely used for shielding re-entry vehicles due to their excellent thermal resistance and ablation properties. During re-entry, heat fluxes can reach 3.4 MW/m² [1]. To evaluate the performance of C/C composites under these conditions, ground-based testing is essential.

This study investigates the thermal response and ablation characteristics of C/C composite containment systems for nuclear batteries using a 0.4 MW plasma jet facility at Jeonbuk National University. The facility replicates high-temperature and high-enthalpy environments similar to re-entry conditions. Experimental tests were performed to assess material performance under a heat flux of 7.59 MW/m² and a recovery enthalpy of 13.9 MJ/kg. The results contribute to the development of reliable TPS designs for space nuclear applications.

2. Experimental Setup

The tests were conducted at the 0.4 MW arc-heated test facility (Fig. 1) , which includes a segmented arc plasma torch, a vacuum test chamber, and high-speed diagnostic tools. The facility operates at a maximum power of 0.4 MW with a maximum current of 250 A. A supersonic Mach 2 plasma flow was generated using a mixed gas of air (95%) and argon (5%).

A carbon-carbon hemispherical sample (20 mm in diameter) was used for testing. The sample was exposed to the plasma jet for 120 seconds under controlled conditions (Fig. 2). Surface temperature measurements were obtained using a pyrometer, and a Gardon gauge was used to determine heat flux. High-speed cameras captured real-time ablation behavior with a frame rate of up to 150,000 fps.

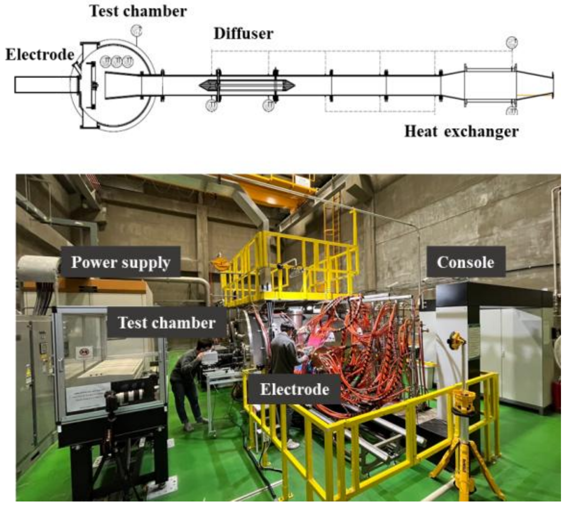

Fig. 1. Schematic illustration and photograph of the 0.4 MW arc-heated test facility at Jeonbuk National University, Korea.

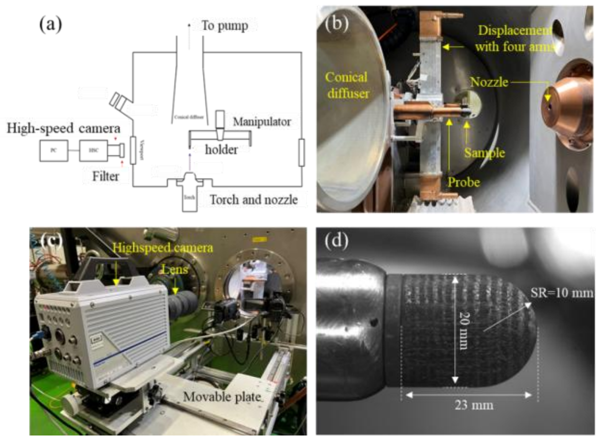

Fig. 2. (a) Schematic illustration of the test chamber; (b) a photograph of the chamber interior and (c) the high-speed camera installed outside the chamber; (d) photograph of the C/C composite sample taken by the high-speed camera.

The test conditions were designed to exceed typical re-entry heat flux and enthalpy values to simulate worst-case scenarios. High-temperature plasma flow conditions implemented within the 0.4 MW-AHWT are summarized in Table 1. The Mach number, as measured with a laboratory-made wedge probe, was 2 [2].

Table 1. Experimental conditions within the 0.4MW arc-heated test facility

Parameter	**Condition**
Mach number	2
Power (kW)	86.22
Mass flow rate (g/s)	4.02
Nozzle-to-sample distance (mm)	200
Torch pressure (bar)	1
Chamber pressure (mbar)	60
Exposure time (s)	120

3. Results and Discussion

Fig. 3(a) displays an image of the plasma flame produced in the 0.4 MW arc-heated test facility under the operating conditions outlined in Table 1. To maintain a Mach 2 supersonic flow, the torch pressure and chamber pressure were set at 1 bar and 60 mbar, respectively, as indicated in Fig. 3(b). As depicted in Fig. 3(c), the discharge current and voltage were stabilized at 70 A per electrode (totaling 140 A) and 580 V. Prior to inserting the test sample, the heat flux was recorded using a Gardon gauge positioned 200 mm from the nozzle at the intended sample placement location. As shown in Fig. 3(d), the gauge was exposed to the plasma flame for 30 seconds. Once thermal equilibrium was achieved, the average heat flux on a flat surface was determined to be 5.06 MW/m². This value, when adjusted for the stagnation point of the hemispherical sample, corresponds to a heat flux of 7.59 MW/m².

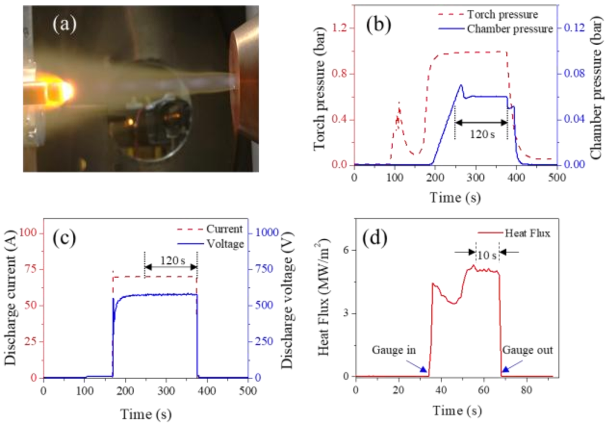

Fig. 3. (a) Photograph of the plasma flame generated in the 0.4 MW arc-heated wind tunnel; (b) torch pressure and chamber pressure; (c) discharge current and voltage during the plasma operation; (d) heat flux during the ablation test.

Experimental results indicated that the C/C composite sample experienced significant ablation and thermal response under high heat flux conditions:

- The surface temperature peaked at 1940°C within 30 seconds before stabilizing at approximately 1810°C due to mass loss through ablation.(Fig. 4)
- The sample experienced a total mass loss of 27.1%, decreasing from 9.52 g to 6.94 g. (Fig. 5)
- The material recession rate was measured at 0.04 mm/s, with a total surface recession of 4.94 mm over 120 seconds.

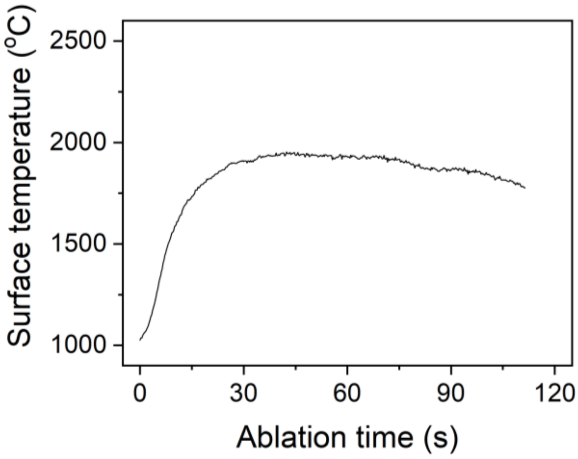

Fig. 4. History of surface temperature for a carbon-carbon sample during the ablation test

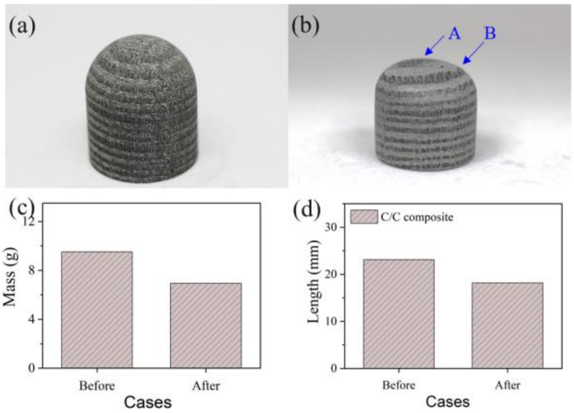

Fig. 5. The carbon-carbon composite (a) before and (b) after the ablation test; the samples' changes in (c) mass and (d) length before and after the ablation test.

The recession was most significant at the apex of the hemispherical sample due to stagnation point heating.

In summary, the carbon-carbon composite demonstrated specific surface temperature, recession, and mass loss characteristics under the given heat flux and air enthalpy conditions, as detailed in Table 2. These results provide essential data for the future design and evaluation of C/C-based thermal protection systems for nuclear batteries (Table 3). Utilizing this experimental data, researchers can refine TPS configurations to improve durability and reliability in extreme aerothermal environments, thereby ensuring the secure deployment and operation of nuclear-powered thermoelectric generators in space missions.

Table 2. Surface temperature, mass loss, and recession of carbon-carbon composite under the following arc-jet test condition for 120 seconds.

Heat Flux	Air Enthalpy	Surface Temperature	Mass loss	Recession
7.59 MW/m^2	13.9 MJ/kg	1800 – 1940 ºC	2.58 g	4.94 mm

Table 3. Maximum heat flux and air enthalpy applied to a nuclear battery under specific re-entry condition [1]

Heat Flux	Heating period
3.4 MW/m^2	200 sec

4. Conclusions

This study examined the thermal response and ablation behavior of carbon-carbon composites under reentry-relevant aerothermal conditions using a 0.4 MW plasma jet facility. Experimental results indicated that, at a heat flux of 7.59 MW/m^2 and a recovery enthalpy of 13.9 MJ/kg, the carbon-carbon samples reached a peak surface temperature of approximately 1940°C, experienced a mass loss of 27.1%, and exhibited a recession rate of 0.04 mm/s over a 120-second exposure. These findings provide essential data for validating and optimizing thermal protection systems (TPS) designed for nuclear battery containment, ensuring structural integrity during atmospheric reentry. The insights from this study will aid in the development of more resilient TPS configurations, enhancing the safety and reliability of nuclear-powered thermoelectric generators in future space missions.

REFERENCES

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