Evaluation by Rocket Combustor of C/C Composite Cooled Structure for Combined-cycle Engine

**Masao Takegoshi, *Fumiei Ono, *Shuichi Ueda, *Toshihito Saito, and **Osamu Hayasaka*
**Japan Aerospace Exploration Agency (JAXA)*
1 Koganezawa, Kimigaya, Kakuda, Miyagi, 981-1525, Japan
***Foundation for Promotion of Japanese Aerospace Technology (JAST)*
1-16-6 Izumi-chuoh, Izumi, Sendai, Miyagi, 981-3133, Japan
takegoshi.masao@jaxa.jp

Keywords: C/C composite, cooled structure, metallic cooling tubes, combined-cycle engine

Abstract

In this study, the cooling performance of a C/C composite material structure with metallic cooling tubes fixed by elastic force without chemical bonding was evaluated experimentally using combustion gas in a rocket combustor. The C/C composite chamber was covered by a stainless steel outer shell to maintain its airtightness. Gaseous hydrogen as a fuel and gaseous oxygen as an oxidizer were used for the heating test. The surface of these C/C composites was maintained below 1500 K when the combustion gas temperature was about 2900 K and heat flux to the combustion chamber wall was about 9 MW/m^2. No thermal damage was observed on the stainless steel tubes which were in contact with the C/C composite materials. Results of the heating test showed that such a metallic-tube-cooled C/C composite structure is able to control the surface temperature as a cooling structure (also as a heat exchanger), as well as indicating the possibility of reducing the amount of the coolant even if the thermal load to the engine is high. Thus, application of the metallic-tube-cooled C/C composite structure to reusable engines such as a rocket-ramjet combined cycle engine is expected.

Introduction

Carbon/Carbon (C/C) composite is a candidate material for the engine walls of airbreathing engines such as the rocket-ramjet combined-cycle engine, the extendible nozzle of a rocket engine and the turbine blades for a more highly efficient gas turbine generator because it has a superior specific strength under conditions of high temperature. Especially, it is important to use materials with high specific strength under high temperature conditions for the rocket-ramjet combined-cycle engine shown in Fig.1 because the engine is so large. However, since the C/C composites are actively oxidized in high temperature air, an oxidation-resistant layer on the surface is required for their use in the high temperature air. C/C composites are usually coated with silicon-carbide (SiC) by chemical vapor deposition (CVD) to protect the surface. However, as the heat-resistant temperature of silicon-carbide (SiC) coating for the oxidation-resistance of C/C composite is about 1800 K in practical use in an oxidative environment, a cooled structure is considered to be necessary for the C/C composite when it is applied to an engine wall exposed to combustion gas with a temperature of around 3000 K.

Although the cooling structure of the C/C composite has been studied in some cases, details of the cooled structure and its performance have not been reported[1) – 4)]. In the present study, the authors examined the structure of C/C composite cooled by metallic tubes as the coolant path. These tubes were fixed by the elastic force of the materials to the C/C composite without any chemical bonding. In a previous study, sufficient cooling performance of such a structure was reported in the case of small specimens[5)]. Numerical analysis indicated that it is possible to cool the surface of the C/C composite to below 2000 K under conditions of a heat flux of 6 MW/m^2 and an environmental temperature of 3000 K.

In this study, the cooling characteristics and the performance of the metallic-tube-cooled structure of C/C composite was clarified by exposure to a combustion gas temperature from 1900 K to 3000 K in the rocket combustor.

Experimental apparatus and experimental procedure

Rocket combustor for heating test and metallic-tube-cooled structure of C/C composite

A rocket combustor was used for evaluation of the cooling characteristics of the metallic-tube-cooled structure of C/C composite in this study (Fig. 2). Paquette et al. performed a test of a cooled CMC structure exposed to exhaust gases from a rocket

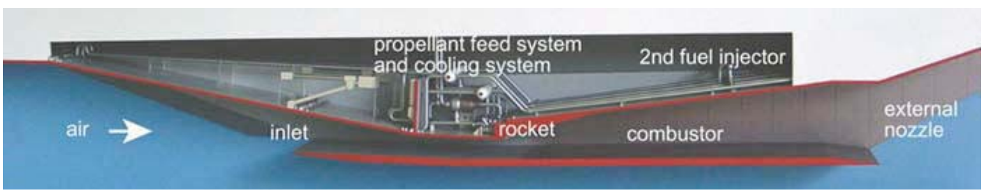

Figure 1 Rocket-ramjet combined-cycle engine.
Rocket engines are embedded in the airflow path of a ramjet engine.

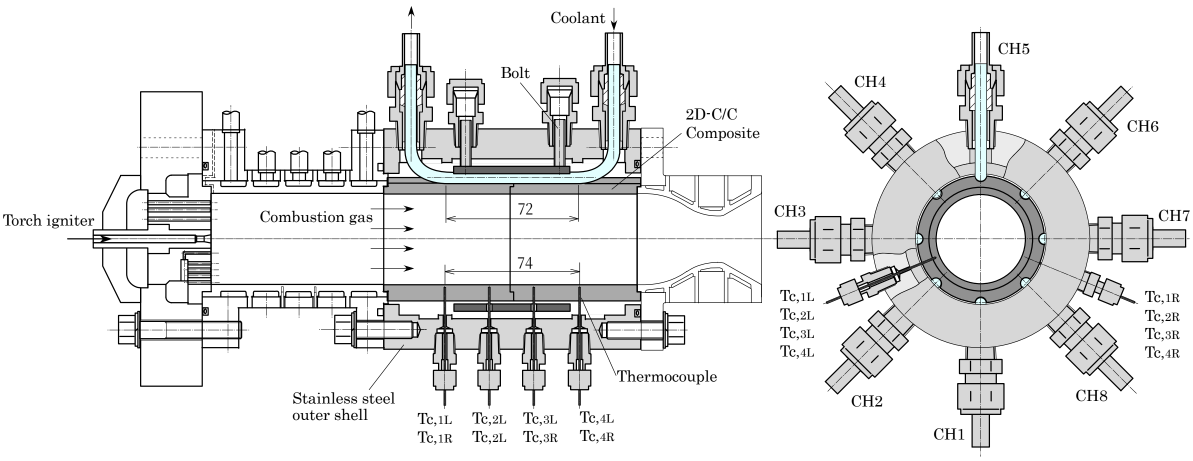

Figure 2 Heating apparatus of rocket combustor with a metallic-tube-cooled C/C composite structure.

combustor nozzle. Although their exposure test simulated the actual flow in the scramjet engine model, the heating apparatus and cooled structure tend to enlarge in such a case. In our case, however, the cooled structure of C/C composite was contained in the rocket combustor because our objective was to obtain its cooling characteristics. The temperature of combustion gas in the rocket chamber can be estimated by ODE (one-dimensional equilibrium) calculation and C* efficiency.

The heating apparatus consists of an injector, a water-cooled copper alloy combustor, a cooled C/C composite, and a water-cooled nozzle throat. Inner shell of the combustor and the nozzle throat were made of copper alloy, and the outer shell was stainless steel. The water coolant flows around the circumference of the chamber. A shower head-type injector was adopted. Gaseous hydrogen and gaseous oxygen were used. The fuel / oxidizer mixture ratio was controlled from 2 to 8.

The cooling structure of the C/C composite has two inner shells of C/C composite and 8 stainless steel cooling tubes surrounding the C/C composite. The stainless tubes were pressed by bolts against the C/C composite inner shell.

Figure 3 shows a test piece of the C/C composite inner shell. Laminate type 2D-C/C composite material was used. Table 1 shows the mechanical properties and thermal properties of the C/C composite. The inner shell of the C/C composite has 8 hemicircular grooves which encase the stainless steel cooling tubes. The U-shaped stainless tube was 6.35 mm in diameter

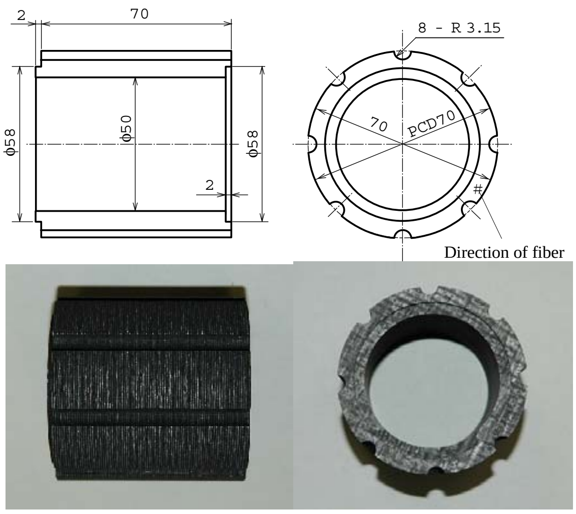

Figure 3 Test piece of C/C composite inner shell.

and 0.5 mm in thickness. The length of the tube in contact with the C/C composite was 72 mm. The stainless outer shell around the C/C composite was used to maintain airtightness as the C/C composite is not airtight. The temperature of the C/C composite was measured by thermocouples.

The cooling structure of C/C composite can be exchanged with a water-cooled copper alloy chamber of the same length. Figure 4 shows a general view of the combustor with a copper alloy chamber instead of the cooling structure of C/C composite. The distribution of heat flux to this copper alloy chamber can be measured in the same region as that in the case

Table 1 Mechanical properties and thermal properties of 2D-C/C composite.

Density	1700 kg/m^3
Modulus of Elasticity in Tension	50 GPa
Tensile Strength	120 MPa
Thermal Expansion Coefficeint	1x10^{-6} in the fiber direction, 8x10^{-6} in the layer direction
Thermal Conductivity	26 W/m/K in the fiber direction, 13 W/m/K in the layer direction
Specific heat	710 J/Kg/K

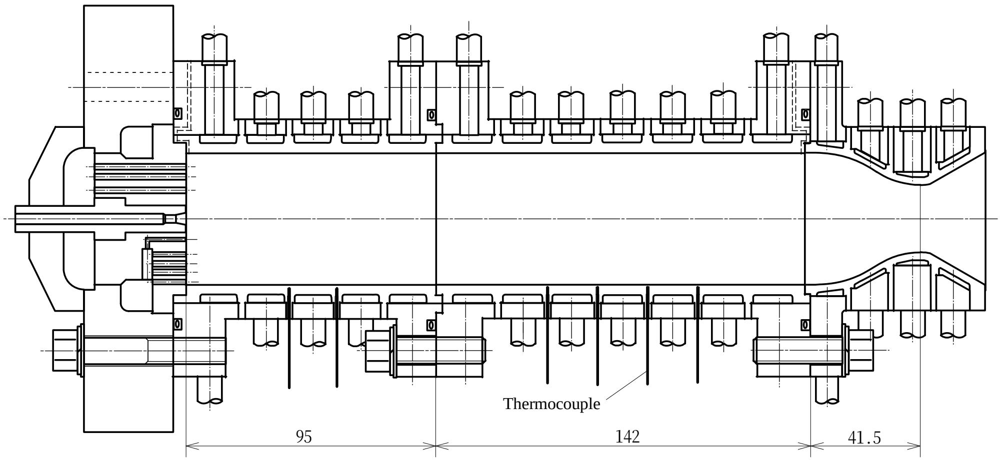

Figure 4 Water-cooled copper alloy chambers for measurement of heat flux distribution.

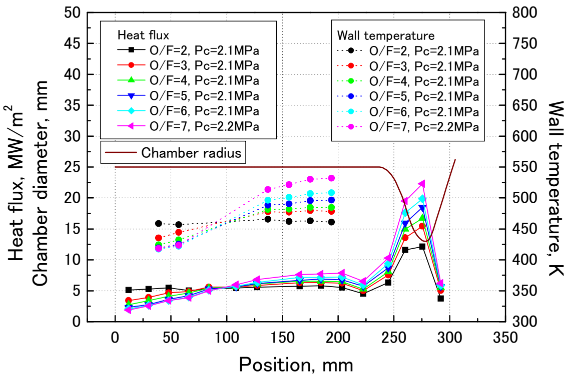

Figure 5 Heat flux distribution and temperature distribution obtained by water-cooled copper alloy chambers.

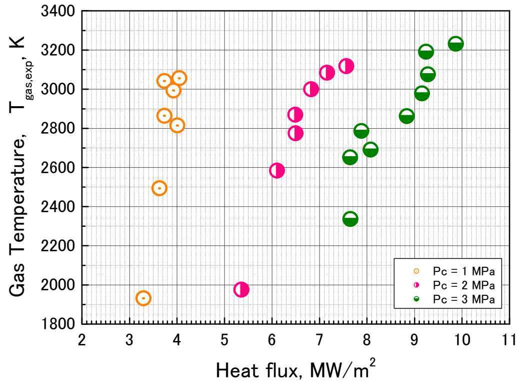

Figure 6 Heating conditions that can be achieved by this combustor.

of the C/C composite chamber. The heat flux was calculated based on the temperature rise of the water coolant. The wall temperature of copper alloy chamber was measured at 1.5 mm from the internal surface by thermocouples.

Measurement of heat flux as a test condition

The temperature of the combustion gas and the distribution of the heat flux to the chamber wall depend on the mixture ratio of fuel/oxidizer, the chamber pressure and the combustion efficiency of the rocket combustor. Therefore, test conditions of the rocket combustor were investigated before the heating test. The copper alloy combustor shown in Fig.4 was used to investigate the heat flux distribution in the same region as where the C/C composite cooling structure was installed. The effect of mixture ratio and chamber pressure on heat flux distribution was clarified with copper alloy chamber.

Figure 5 shows the heat flux distribution obtained by the copper alloy chamber as an example. The test condition was from 2 to 7 of the mixture ratio at about 2.0 MPa of chamber pressure. The heat flux near the injector faceplate increased with distance from the faceplate. The heat flux where the cooling structure of the C/C composite was installed (the position from 95 mm to 237 mm from faceplate) was almost constant. The wall temperature distribution obtained under the same conditions is also shown in Fig. 5. Although the temperature slightly increased toward the throat of the chamber under high mixture ratio conditions, the temperature distribution in the region where the cooling structure for the C/C composite was installed was almost as constant as the heat flux distribution. This result shows that the C/C composite inner cylinder can be heated uniformly by combustion gases.

The real temperature of combustion gas $T_{gas,exp}$ is estimated by the next equation (1) with C* efficiency (ηC^*), initial gas temperature T_i , and theoretical temperature of combustion gas $T_{gas,th}$.

$$T_{gas,\exp} = (\eta C^*)^2 (T_{gas,th} - T_i) + T_i \qquad (1)$$

Figure 6 shows the heating conditions obtained by using the copper alloy combustion chamber. It was clarified that the C/C composite can be exposed to high temperature gas from 1900 K to 3200 K and heat flux from 3 MW/m^2 to 10 MW/m^2 by changing the mixture ratio of the fuel/oxidizer and chamber pressure.

(a) Before test (b) During test (c) After test

Figure 7 Heating test of the cooling structure of C/C composite installed in the rocket combustor.

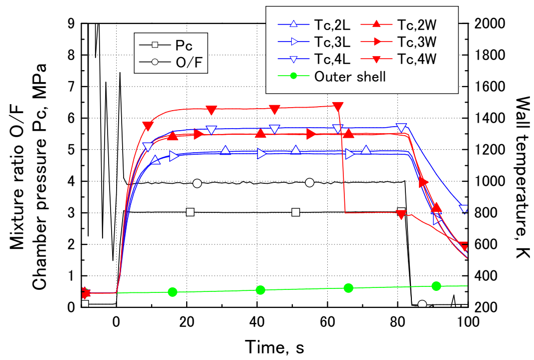

Figure 8 Time histories of chamber pressure and mixture ratio during heating test. ***The wall temperature was measured at 3 mm from the surface.***

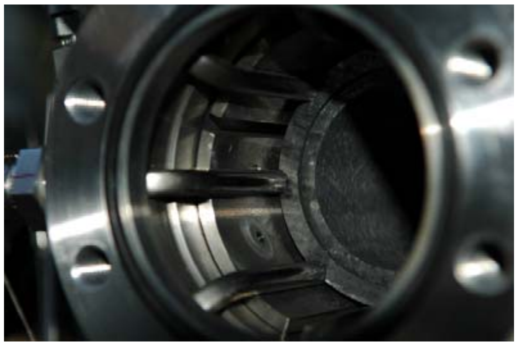

Figure 9 Cooling tubes and C/C composite inner shell test piece in the cooling structure after the heating test.

Test conditions for the evaluation test of the metallic-tube-cooled C/C composite structure

Heating tests for evaluation were performed under conditions of an O/F of 2 to 4 and a P_c of 1 to 3 MPa. These conditions correspond to heat fluxes to the copper alloy chamber of about 3.2 MW/m^2 and 8.7 MW/m^2 and combustion gas temperature of 1950 to 2900 K. Testing time was 80 seconds in expectation of the wall temperature becoming steady state. The flow rate of the water coolant for the cooling structure of the C/C composite was 0.15 L/s.

Experimental results

Heating test

Figures 7 (a), (b), (c) show overviews of the cooled chamber before, during and after the heating test, respectively. From Fig. 7 (c), the C/C composite inside the chamber is seen to be red hot; indicating that its surface temperature was very high.

Figure 8 shows the time histories of the chamber pressure and the mixture ratio under conditions of P_c = 3 MPa and O/F = 4 as an example. The combustion was steady state during the heating tests, and the chamber pressure and mixture ratio were almost constant. The C* efficiency was 0.94 in this case. The combustion gas temperature was estimated at about 2750 K in the combustion chamber. Figure 8 also shows the temperature histories of the C/C composite inner shell during the heating test. The temperature measured by thermocouples at $T_{c,2L}$, $T_{c,3L}$, $T_{c,2R}$ and $T_{c,3R}$ inserted into the C/C composite in the contact region of the cooling tubes reached steady state. The temperature at $T_{c,2L}$, $T_{c,3L}$ and that at $T_{c,2R}$, $T_{c,3R}$ are shown in Fig. 8. The region of contact of the cooling tubes with the C/C composite as well as the inserted position of the thermocouples is shown in Fig. 2. The length of contact of the cooling tubes with the C/C composite was 72 mm. The temperature of the C/C composite was measured by thermocouples over the whole length of the tubes in the contact region. The C/C composite at the positions of $T_{c,1L}$, $T_{c,4L}$, $T_{c,1R}$ and $T_{c,4R}$ was not cooled sufficiently by cooling tubes because the temperatures at the positions of $T_{c,4L}$, $T_{c,4R}$ were higher than that at the positions of $T_{c,3L}$, $T_{c,3R}$. However, the condition was close to the steady state because the temperature rise was very small. It is thought that both ends of the C/C composite were cooled by the copper alloy combustion chambers.

By the way, Fig. 8 also shows that the temperature at position of $T_{c,4R}$ dropped suddenly. Since the wall of C/C composite inner shell was partially oxidized tremendously and wall was thinned, the tip of the thermocouple melted by combustion gas.

Figure 9 shows the cooling tubes and the test piece of the C/C composite inner shell in the cooling structure after the heating test. No thermal damage, no discoloration and no deformation were observed on the tube surfaces.

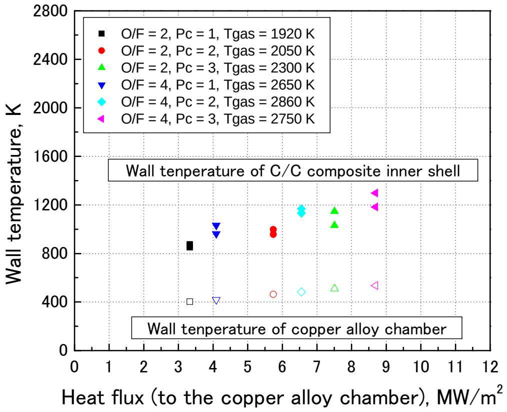

Figure 10 Wall temperature of C/C composite inner shell

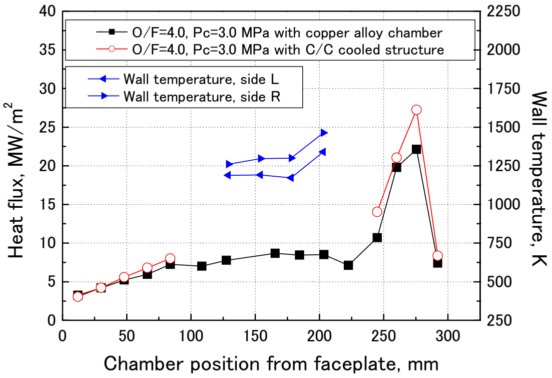

Figure 11. Heat flux distributions of the copper alloy chamber obtained by heating test with the cooling structure of C/C composite under the condition of a chamber pressure of 3 MPa and mixture ratio of 4.

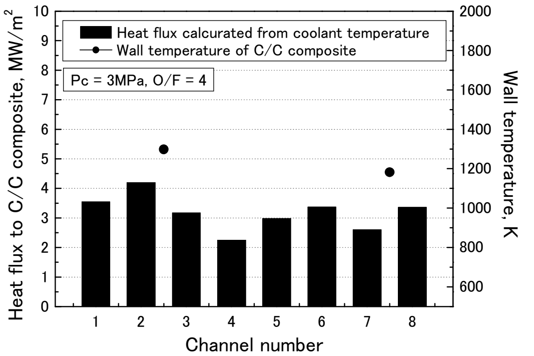

Figure 12 Heat flux to the C/C composite inner shell

Wall temperature

Figure 10 shows the wall temperature of C/C composite inner shell measured at 3 mm from the surface. Horizontal axis is the value of the heat flux to the copper alloy chamber cooled by water coolant. Although the temperature of the combustion gas was various at each test condition, the effect of the gas temperature on the temperature of the wall of the C/C composite was small. On the other hand, the wall temperature of the C/C composite increased depending on the heat flux.

Figure 10 also shows the wall temperature of the copper alloy chamber obtained under the same test conditions. In case of the water coolant, the wall temperature on the cooling passage side is determined by the pressure of the water coolant, because the water boils on the wall surface. Therefore, the temperature rise of the wall was proportional to the heat flux. In the case of the C/C composite chamber, the similar result was obtained like as the temperature rise of the wall was proportional to the heat flux. Thus, it is thought that the inner wall temperature of the cooling tubes was a certain constant temperature that depended on the pressure of the coolant water when the combustion chamber was C/C composite.

Distribution of heat flux

Figure 11 shows the heat flux distributions of the copper alloy combustion chamber and the nozzle throat chamber obtained in the heating test. The heat flux distributions of the copper alloy chamber obtained before the heating tests for purposes of comparison are also shown in Fig. 11. Figure 11 shows that the heat flux increased in the regions of 50 mm to 90 mm and 240 mm to 275 mm. Heat flow from test pieces of C/C composite to both the cooling tubes and the upstream and downstream chamber walls of the copper alloy combustor is thought to have occurred because the temperature of C/C composite inner shells was elevated in the heating test. It was estimated that the heat flow to the upstream chamber wall was about 3840 W/s and that that to the chamber wall of the nozzle throat was about 18000 W/s.

Figure 12 shows the heat flux to the C/C composite calculated by the flow rate and temperature rise of the water coolant. Total heat received by the water coolant of the eight cooling tubes was 57800 W/s. As the quantity of heat to the copper alloy chamber was 21840 W/s, 28% of the heat of C/C composite test pieces was cooled by copper alloy chambers and the other 72% was cooled by metallic tubes. Figure 12 also shows that the quantity of heat in each channel was various. It is thought that the nonuniform combustion in the chamber or the nonuniform contact pressure between each cooling tube and the C/C composite inner shell caused the difference.

The mean heat flux from combustion gas to the C/C composite inner shell was 2.59 MW/m^2 as calculated from the experimental results. The heat flux to the C/C composite inner shell from the combustion gas was less than half that to the copper alloy chamber. Because the surface temperature of the C/C composite inner shell was higher than that of the copper alloy chamber, the heat flux decreased.

The heat flux to the C/C composite combustor was compared with that to the copper alloy chamber under the same conditions as in Fig. 13.

This result shows that the flow rate of the coolant in the engine can be decreased though it becomes disadvantageous for the heat exchanger. In the case of hypersonic vehicles such as an aerospace plane, surplus coolant can be used to cool the airframe and the leading edge.

In addition, the most important things is that the heat flux distributions for the engine model of the C/C composite can be estimated if the heat flux distribution of a copper engine model is obtained.

Summary

In this study, the cooling performance of a metallic-tube-cooled C/C composite structure with tubes fixed by elastic force without chemical bonding in a rocket combustor was evaluated experimentally using combustion gas. The following conclusions were obtained:

1. This structure was shown to be able to cool the surface of the C/C composite sufficiently by water-cooled metallic tubes fixed by elastic force under an estimated gas temperature of 2800 K and a heat flux corresponding to that of 8.7 MW/m^2 to a copper alloy chamber.
2. In the case of the cooling structure of the C/C composite, the possibility that the heat flux from combustion gas to the C/C composite can be estimated by that to the copper alloy chamber was indicated.
3. No damage and no discoloration on the surface of the stainless steel cooling tubes were observed after the heating test.

References

1) Bouchez, M and Beyer, S.," PATH-SOCAR Fuel-cooled Composite Material Structure for Dual-Mode Ramjet and Liquid Rocket Engine – 2006 status," 14th AIAA/AHI Space Planes and Hypersonic Systems and Technologies Conference, 2006, AIAA-2006-8072.

2) Paquette, E.," Cooled CMC Structures for Scramjet Engine Flowpath Components," AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies, AIAA2005-3432.

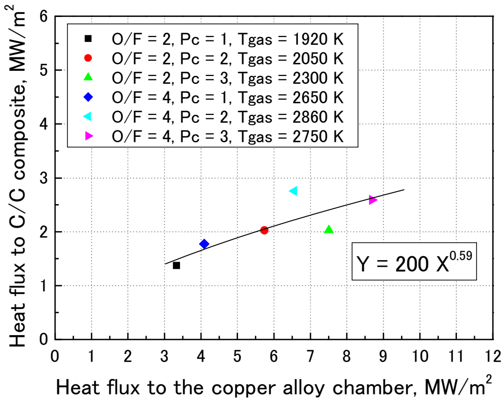

Figure 13 Comparison between the heat flux to the water-cooled copper alloy chamber and that to the water-cooled C/C composite chamber

3) Bouquet, C., Roger Fischer, R., Luc-Bouhali, A., Dessornes, O., Thebault, Jacques., and Soyris, P.," Fully Ceramic Composite Heat Exchanger Qualification For Advanced Combustion Chambers.," AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies, AIAA2005-3433.

4) Hatta, H., Goto, K., Sato, T. and Tanatsugu, N.," Applications of Carbon-Carbon Composites to an Engine for a Future Space Vehicle," Adv. Composite Mater. 12, (2003), pp.237-259.

5) Takegoshi, M. and Ueda, S.," Fundamental Study on Cooling Structure of C/C Composite Material with a Metallic Tube," Proceedings of the 25th International Symposium on Space Technology and Science, ISTS-2006-c-04.

Nomenclature

C^*	=	characteristic velocity
ηC^*	=	C* efficiency
T_i	=	initial temperature of fuel and oxidizer
$T_{gas,th}$	=	theoretical temperature of combustion gas
$T_{gas,ex}$	=	estimated temperature of combustion gas
O/F	=	mixture ratio of fuel and oxidizer
P_c	=	chamber pressure
$T_{c,1L}$	=	temperature measured by thermocouple at position 1L