K. Nishio

K.-I. Igashira

K. Take

Research Institute of
Advanced Material Gas-Generator,
Tokyo, Japan

T. Suemitsu

Material Research Department of
Akashi Technical Institute,
Kawasaki Heavy Industries Limited,
Hyogo, Japan

Development of a Combustor Liner Composed of Ceramic Matrix Composite (CMC)

The Research Institute of Advanced Materials Gas-Generator (AMG), which is a joint effort by the Japan Key Technology Center and 14 firms in Japan, has, since fiscal year 1992, been conducting technological studies on an innovative gas generator that will use 20 percent less fuel, weigh 50 percent less, and emit 70 percent less NOx than the conventional gas generator through the use of advanced materials. Within this project, there is an R&D program for applying ceramic matrix composite (CMC) liners to the combustor, which is a major component of the gas generator. In the course of R&D, continuous SiC fiber-reinforced SiC composite (SiC^F/SiC) was selected as the most suitable CMC for the combustor liner because of its thermal stability and formability. An evaluation of the applicability of the SiC^F/SiC composite to the combustor liner on the basis of an evaluation of its mechanical properties and stress analysis of a SiC^F/SiC combustor liner was carried out, and trial SiC^F/SiC combustor liners, the largest of which was 500-mm in diameter, were fabricated by the filament winding and PIP (polymer impregnation and pyrolysis) method. Using a SiC^F/SiC liner built to the actual dimensions, a noncooling combustion test was carried out and even when the gas temperature was raised to 1873K at outlet of the liner, no damage was observed after the test. Through our studies we have confirmed the applicability of the selected SiC^F/SiC composite as a combustor liner. In this paper, we describe the present state of the R&D of a CMC combustor liner.

Introduction

In the process of developing more efficient industrial gas turbines and turbine engines for airplanes to travel at supersonic speeds, much effort has been directed at raising the combustor outlet (turbine inlet) temperature, as is shown in the chart of the increase in gas turbine inlet temperature in Fig. 1 [1]. This has created the need to develop new materials that can withstand these ultra-high temperatures. In response to that need, as is shown in Fig. 2, such new metallic materials as DS (directionally solidified) superalloys and SC (single crystal) superalloys have already reached the stage of practical application and the development of intermetallic compounds, oxide dispersed superalloys, and other metallic materials is under way [2]. In response to the drive to achieve combustion at temperatures that exceed the limits of durability of metallic materials, CMC materials that can be applied as materials with greater heat resistance than metallic materials are being developed.

The Research Institute of AMG is conducting research and development to apply these composite materials as parts for gas generators that operate at ultra-high temperatures. The research period is nine years and one month, from March 1993 to March 2002, as shown in Fig. 3. The total research budget amounts to 10 billion yen (about $100 million). The fourteen participating domestic companies are three gas turbine manufactures, five materials companies, four mechanical components manufactures, and two control systems companies [3].

In the AMG program, we are engaged in the R&D of application technology and processing technology for CMC parts with the aim of applying CMC materials to gas generator static parts.

In this paper, we describe the results of our evaluation of CMC's applicability as a combustor liner based on an analysis of thermal stress and evaluation of a CMC liner model, and an evaluation of an actual CMC liner assembled in a combustor and subjected to a combustion test.

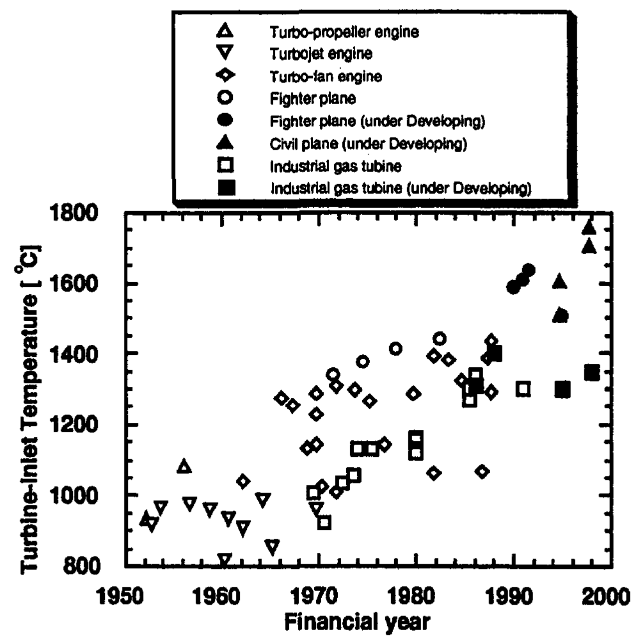


Fig. 1 Turbine inlet temperature in gas turbines

Concept of Advanced Materials Application to the AMG Combustor

In the AMG combustor, the plan is to apply CMC to the combustor liner and TiAl to the combustion gas swirl introduction swirler. Silicon carbide fiber-reinforced silicon carbide (SiC^F/SiC), which features superb resistance to high tempera-

Contributed by the International Gas Turbine Institute and presented at the International Gas Turbine and Aeroengine Congress and Exhibition, Stockholm, Sweden, June 2–5, 1998. Manuscript received by the ASME Headquarters April 1, 1998. Paper No. 98-GT-104. Associate Technical Editor: R. Kielb.

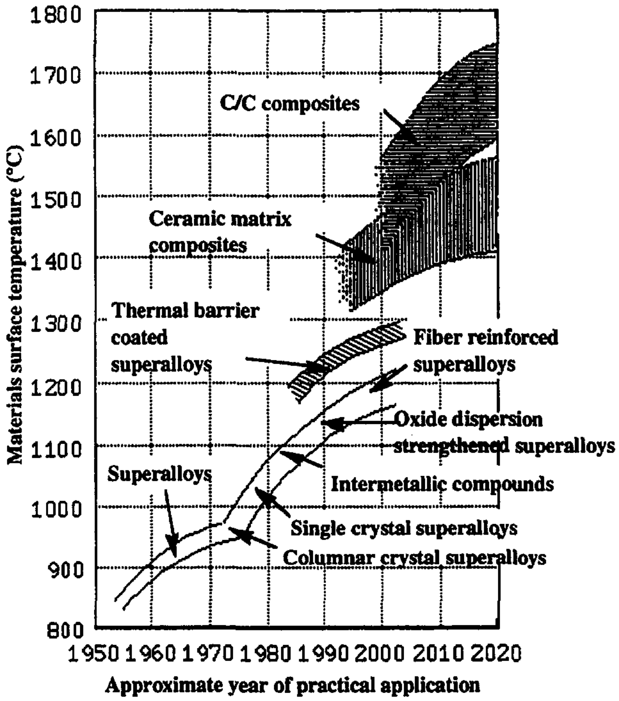


Fig. 2 Development trends of heat-resistant materials

tures and oxidation, was selected as the candidate CMC material for the AMG combustor liner. The conceptual configuration of the combustor is shown in Fig. 4.

To produce the combustor liner we selected the filament winding (FW) method, which makes it easy to adjust the fiber orientation angle and makes it easy to form a near net shape over a wide range, from small to large parts, by replacing the mold.

Material Characteristics of CMC [4]

As the test piece for evaluating the material characteristics of the CMC combustor liner, a fiber-oriented pre-preg sheet was laminated by deflecting at a specified angle and this fiber-laminated material was composited by the polymer impregnation and pyrolysis (PIP) method to obtain a sheet of CMC, from which the test piece was taken. The fiber used was Si-Ti-C-O fiber (Tyranno Lox M-S5 from Ube Industries Ltd.). The fiber has a carbon surface layer that becomes the fiber/matrix interface layer during compositing. Polycarbosilane (PCS) was used as the matrix precursor polymer. A tensile strength test at room temperature was used as the characteristics evaluation test and the relationship between tensile characteristics and fiber orientation angle was found. The fiber orientation angle of the test piece was set at seven values, in the range of 0° to ±82.5°, which included ±22.5°, which is equivalent to the combustor liner forming angle. The relationship between tensile strength and fiber orientation angle is shown in Fig. 5. Tensile strength decreased as the orientation angle increased and tensile strength approached zero when the fiber orientation angle exceeded 75 deg. Regarding the material strength of the combustor liner, the tensile strength at an angle (about 20 deg) equivalent to the fiber orientation angle of the combustor liner is believed to be about 250 MPa. When we subjected the experimental material to a separate frexural strength test we found virtually no difference in strength between RT (room temperature) and 1473K. Based on this, we concluded that the results at RT discussed in this paper also apply at 1473K, which is in the liner's operating temperature range.

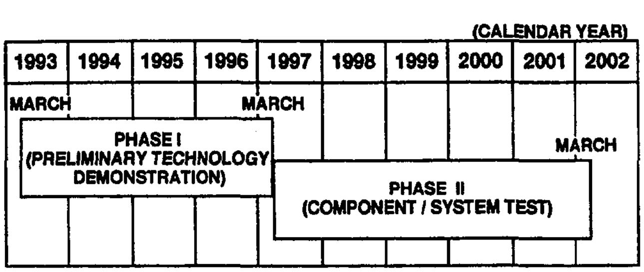


Fig. 3 AMG research and development schedule

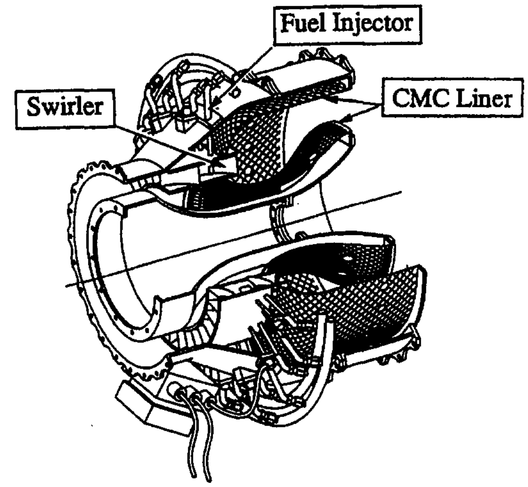


Fig. 4 Conceptual configuration of the AMG combustor

Thermal Stress Analyses in CMC Combustor Liner

The thermal stress generated when a combustor fitted with a CMC combustor liner is operated was estimated by numerical analysis using representative characteristic values of the trial-produced composite materials, aiming at clarifying the question of strength in the application of the composite material in a combustor liner.

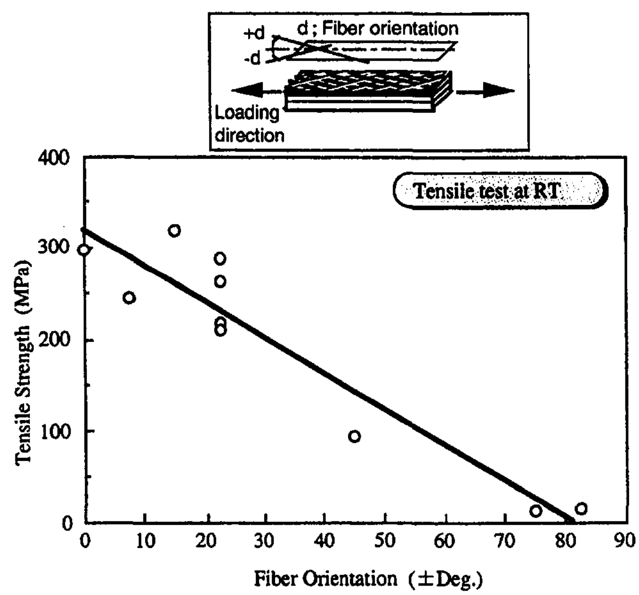


Fig. 5 Relationship between tensile strength and fiber orientation of trial-produced composite material

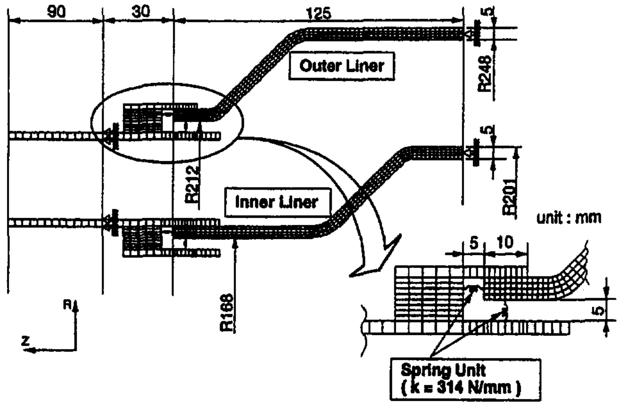


Fig. 6 Thermal stress analysis model of CMC combustor liner

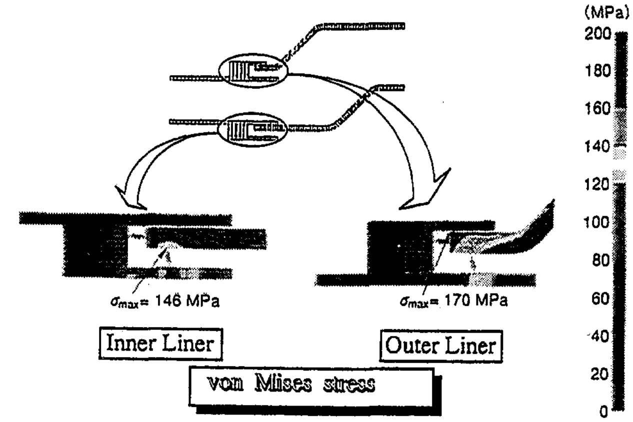


Fig. 7 Results of steady state thermal stress analysis of CMC liner for AMG combustor

The thermal stress analysis model and analysis method were studied in accordance with the basic design specifications of the CMC combustor liner. As the combustor liner, to be the subject of analysis, a model was created using axis symmetric solid elements. For the tie-in part between the liner and the swirler, a spring-type fitting structure was used with the aim of relieving the thermal stress arising from the difference in the thermal expansion rates of SiC^F/SiC and TiAl, and a model was produced using linear spring elements. The model used for analysis is shown in Fig. 6.

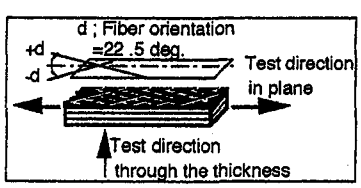
The temperature distribution in the liner's axial direction and the liner's thickness direction was found by means of heat transfer analysis using heat boundary conditions that were estimated based on the results of combustion tests of a metal liner. The swirler temperature was assumed to be constant at 973K.

The analysis of heat transfer thermal stress was made using ABAQUS analysis software, based on the material data obtained from the characteristics test of the trial produced materials. The material characteristics data used for the analysis are shown in Table 1.

1 Results of Thermal Stress Analysis at Steady-State Conditions and Discussion [4]. The results of thermal stress analysis at steady-state conditions of the CMC liner are shown in Fig. 7. The maximum thermal stress occurred on the liner side in the vicinity of the liner and swirler tie-in part. The peak thermal stress did not exceed the 200 MPa set as a preliminary criterion for the application of SiC^F/SiC and was not considered excessive stress when compared with the tensile strength (about 250 MPa) obtained through the characteristics evaluation of the trial-produced composite material. The value of the maximum thermal stress was 170 MPa for the outer liner and 146 MPa for the inner liner at the respective material temperatures of approximately 1350K and 1300K. The maximum main stress direction was in the circumferential direction and the liner's thermal stress was believed to be mainly hoop stress. Therefore, applying SiC^F/SiC in the combustor liner should present no problem.

Table 1 Material characteristics data used for analysis

Materials		SiC^F/SiC			TiAl	
Properties	Units	Temperature	Orientation: In Plane	Orientation: Through the thickness	Temperature	
Tensile Young's Modulus	GPa	1273K	100	50	973K	150
Tensile Poisson's Ratio	—	1273K	0.16	—	973K	0.3
Thermal Expansion Coefficient	$x10^{-6}/K$	1273K	4.3	6.9	973K	11.5
		1573K	4.2	5.0		
Thermal Conductivity	W/mK	1273K	—	1.59		—
		1573K	—	2.34		
Specific Heat	J/kgK	1273K	1.47			—
		1573K	1.62			
Application Parts		Combustor Liner			Swirler	



In this analysis, a spring constant equivalent to that of a practical material was used and it would be possible to reduce thermal stress caused by replacing the spring with one with a lower spring constant.

Through thermal stress analysis during steady combustion of a model in which the material was applied as the combustor liner, the thermal stress generated was found to be less than the material strength. These results suggest the suitability of using SiC^F/SiC as the combustor liner.

2 Results of Thermal Stress Analysis at Transient Conditions and Discussion. As thermal stress analysis while simulating the combustor in operation, we analyzed heat transfer thermal stress under transient conditions when the combustion state shifted from idle combustion to design point combustion and from design point combustion to idle combustion. For the analysis, the heat boundary conditions were varied in stages by assuming that the shift in combustion state between idle combustion and design point combustion would be immediate.

The results of analyzing heat transfer and thermal stress were collated by focusing on the center point of the region where the

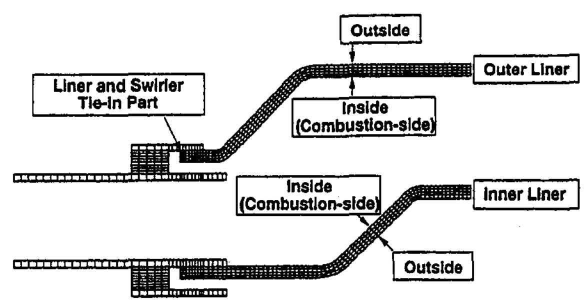


Fig. 8 Focal points of temperature and stress

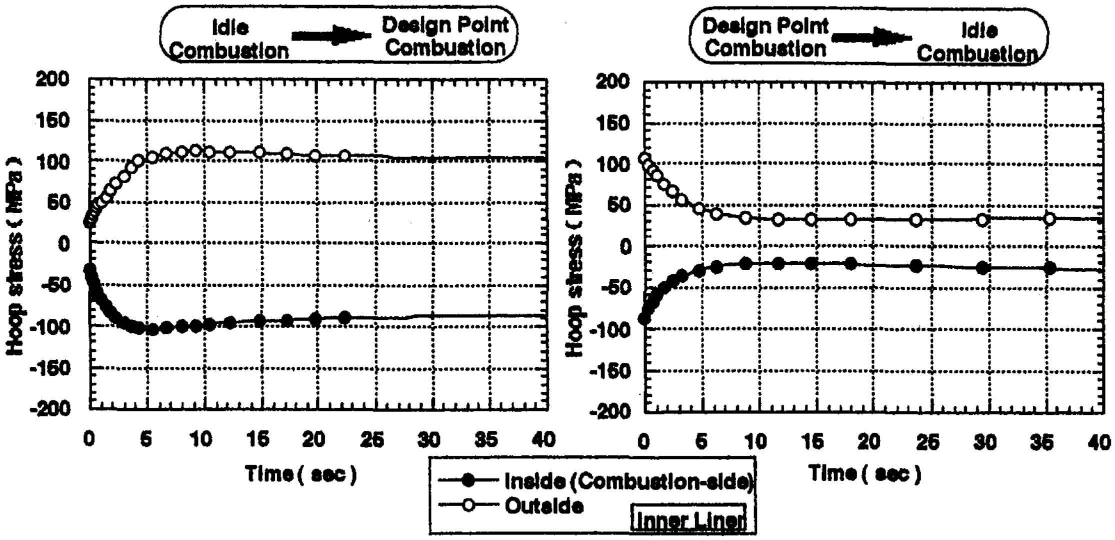


Fig. 9 Results of transient thermal stress analysis of CMC liner for AMG combustor

combustion gas temperature is assumed to reach the highest point and the tie-in point between the liner and the swirler. The location of these focal points are shown in Fig. 8. The heat transfer analysis confirmed that the liner temperature reached the highest level at the focal point (the center of the region where the combustion gas temperature reaches the highest level).

The analysis of thermal stress under transient conditions as the combustion state varied between idle combustion and design point combustion revealed that, due to the difference in the change of temperature between the liner surface and the inside of the liner's wall, the peak thermal stress appears several seconds after the combustion state shifts in the combustion side of both the inner and outer liner. The peak thermal stress did not exceed the maximum thermal stress in the steady-state analysis. Therefore, applying SiC^F/SiC in the combustor liner should present no problem. Changes in thermal stress over the passage of time at the focal point of the inner liner is shown in Fig. 9 as examples of the analysis of thermal stress under transient conditions.

Evaluation of CMC Combustor Liner in Combustion Test

1 Method for Producing the Liner. The liner was produced by filament winding molding and the polymer impregnation and pyrolysis (PIP) method using a low-oxygen silicon carbide fiber (product name: Tyranno LoxE) from Ube Industries Ltd. as the reinforcement fiber and polycarbosilane (product name: Nipushi) from Nippon Carbon Co. Ltd. as the matrix precursor polymer. The fiber orientation of the liner was about ± 20 deg as shown in Fig. 10. Neither a fiber coating nor seal coat for oxidation resistance was applied to the prototype liner. We are currently testing a fiber coating and seal coat applied using a process developed by Kawasaki Heavy Industries Ltd. for durability and other properties.

2 Method for Evaluating the Combustion Test. To evaluate the applicability of the prototype combustor liner made of composite material, we produced a CMC combustor liner, subjected it to a combustion test, and looked for changes in its basic characteristics after the combustion test by observing external appearance and measuring the dimensions and weight of the prototype composite liner before and after the test. Restrictions on liner shape and dimensions made it impossible for us to use NDE such as X-ray CT scanning. Neither a strength test nor structure examination, in which the liner needs to be cut to take samples, was conducted because a combustion test was to be performed following the damage assessment.

The prototype liner made of composite material was assembled to the combustor body and a combustion test was conducted. A diagram and view of the assembled combustor are shown in Fig. 11 and Fig. 12. The combustion test consisted

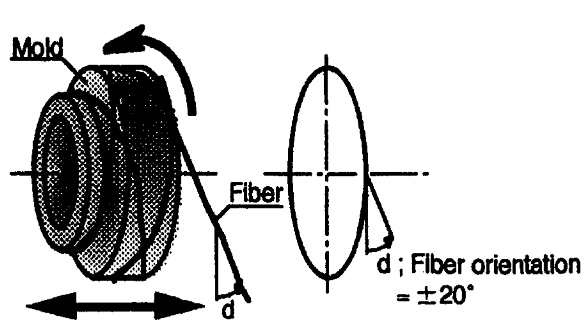


Fig. 10 Fiber orientation of CMC liner for AMG combustor

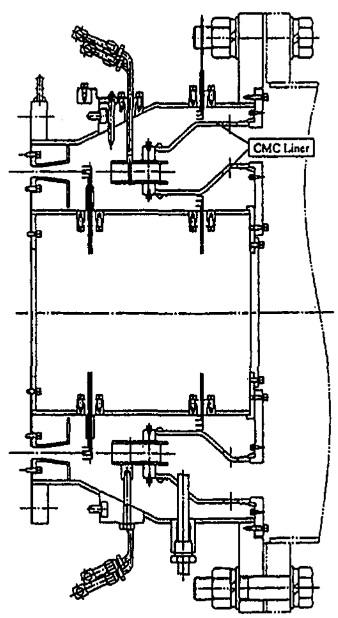


Fig. 11 Schematic view of combustion test equipment

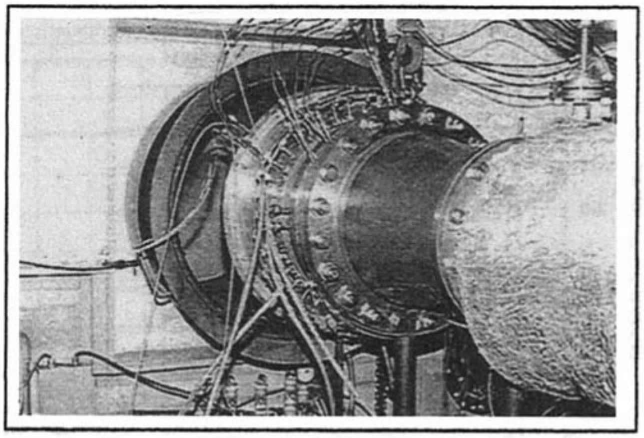


Fig. 12 External view of combustion test equipment

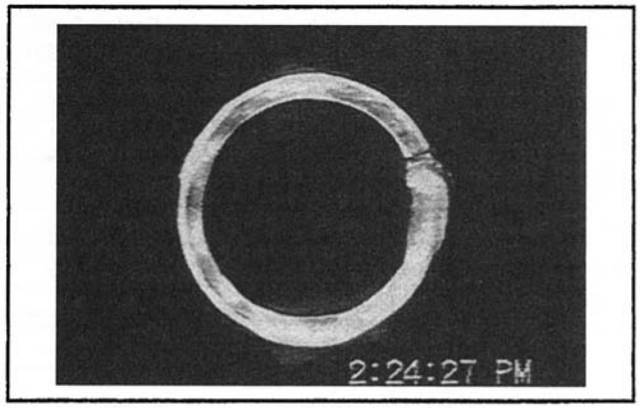


Fig. 14 State of combustion viewed from behind the combustor outer

of methane combustion under such combustion conditions that the combustor outlet gas temperature would reach the AMG target temperature of 1873K. The test conditions are shown in Fig. 13.

Combustion was repeated at ten-minutes intervals because the fuel cylinder had to be replaced after each combustion. The cycle of combustion and pause was repeated 18 times and the high-temperature retention time was about three hours. The state of combustion viewed from behind the combustor outlet is shown in Fig. 14. The temperature of the liner during the combustion test was measured with a thermocouple fitted near the dilution hole on the inner surface (combustion gas side) of the outer liner.

3 Results of Combustion Test and Discussion. Upon completion of the test, the external appearance was observed and the liner's dimensions and weight were measured to analyze changes from the pre-test condition.

The changes in external appearance are shown in Fig. 15. The inspection of external appearance revealed that no abnormalities like cracking or lamination had occurred but the surface on the combustion gas side had turned blue due to the formation of an oxide layer.

Regarding dimensions, we measured the liner's inlet and outlet diameter, thickness, and overall length at eight points in the circumferential direction and compared the values before and after the test. The changes in dimensions are shown in Fig. 16. A fairly large degree of change was seen at each measuring point. However, we believe this was due to undulations caused by the reinforcement fiber flux appearing on the surface, producing changes in the circumferential direction. The measuring points in the circumferential direction were not especially uniform before and after the test and the effect of the undulations

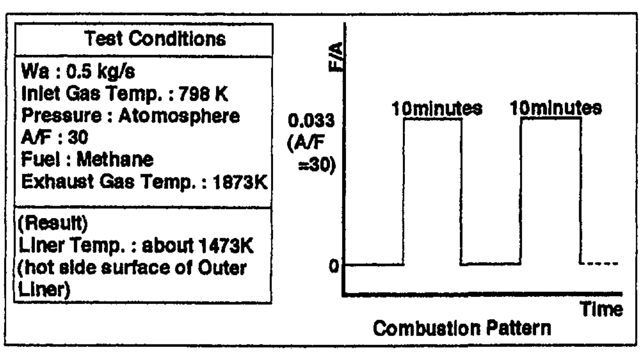


Fig. 13 Combustion test conditions

in the surface must be taken into account regarding the changes in dimensions.

Due to those undulations, the measuring precision is believed to be ±1 mm and the measuring precision in comparing the dimensions before and after the test is believed to be about double that figure, ±2 mm. When the results of measuring the dimensions are compared by taking into account measuring precision, the amount of change before and after the test falls within the measurement tolerance range, so it can be said that there was no deformation during the combustion test.

The changes in weight are shown in Fig. 17. Although there was a slight (10 g) change in weight, we believe the true weight changed very little during the combustion test, after taking into account the change in weight caused by coating of the thermopaint and the change in weight due to the sample being weighed when in a dry state. Apart from the combustion test, a hot-rig test simulating a combustion test was conducted using a cylindrical model test piece to perform microstructural and powder X-ray analyses. In the test, no SiO2 was detected. From this result, we concluded that there was no increase in weight due to SiC oxidation in the short-time combustion test.

In the combustion test, although the combustion period was brief, the SiC^F/SiC liner suffered no changes in characteristics during combustion using gas fuel. Therefore, we believe the applicability of SiC^F/SiC in the combustor liner was confirmed. This was a first phase, short-time combustion test using methane conducted to gauge the performance of the prototype combustor. Preparations are being made for second-phase combustion tests using kerosene.

Conclusions

To evaluate the applicability of CMC in the combustor liner, we evaluated the material characteristics of SiC^F/SiC as a candidate CMC material of the combustor liner, we estimated the amount of stress generated in a model SiC^F/SiC combustor liner by analyzing thermal stress during combustion and we subjected an actual SiC^F/SiC combustor liner to a combustion test. The followings is a summary of the results.

1 In the evaluation of the material characteristics of the CMC combustor liner, the tensile strength of the trial-produced SiC^F/SiC for the combustor liner declined as the fiber orientation angle increased. At the fiber orientation angle for liner formation, it had a tensile strength of about 250 MPa at RT. Based on other test results, we concluded that the results at RT also apply at the liner's operating temperature range.

2 In the analysis of heat transfer thermal stress under steady-state conditions, the thermal stress generated during steady combustion of the SiC^F/SiC combustor liner generated a maximum hoop stress in the vicinity of the swirler tie-in part. The peak thermal stress did not exceed the material's strength and did

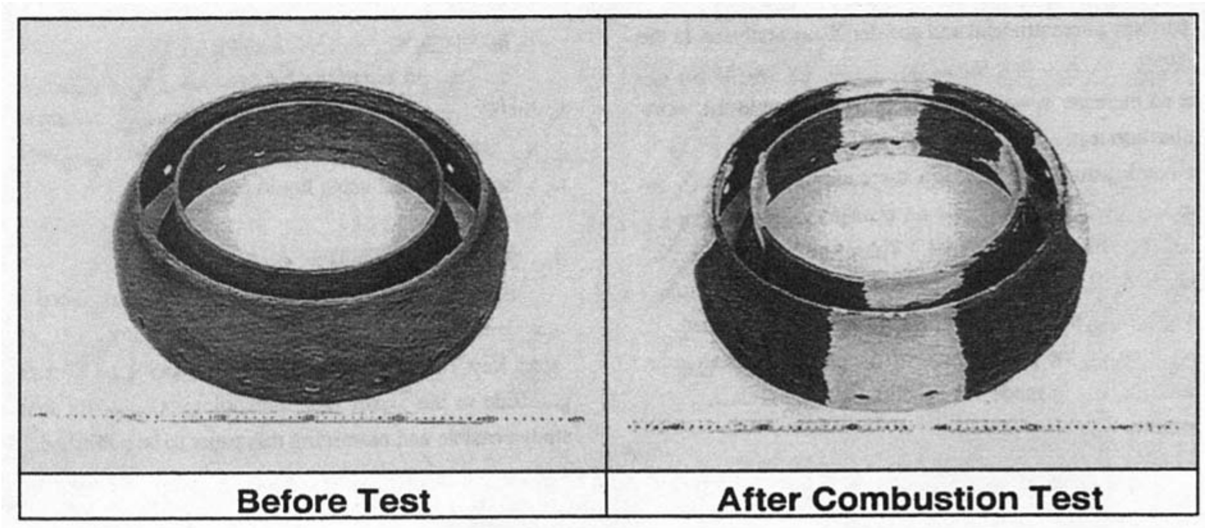


Fig. 15 Results of combustion test (external appearance)

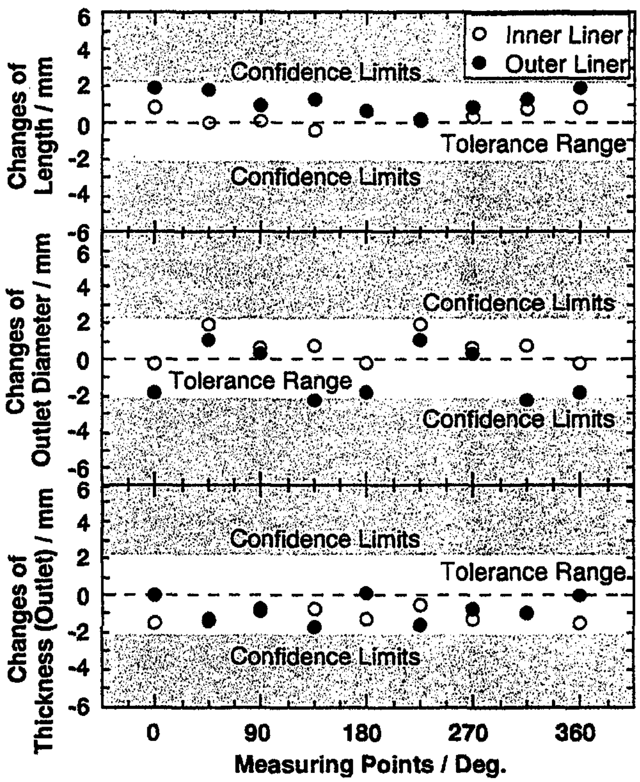


Fig. 16 Results of combustion test (measurement of dimensions)

not exceed the stress set as a preliminary criterion for application. The value was 170 MPa on the outer liner and 146 MPa on the inner liner.

3 In the analysis of heat transfer thermal stress under transient conditions, the peak thermal stress in the SiC^F/SiC composite material generated during the transition between idle combustion and design point combustion did not exceed the maximum thermal stress in the steady-state analysis.

4 In the combustion test lasting for about three hours with the combustor outlet gas temperature at 1873K, the SiC^F/SiC composite material liner suffered no changes in characteristics.

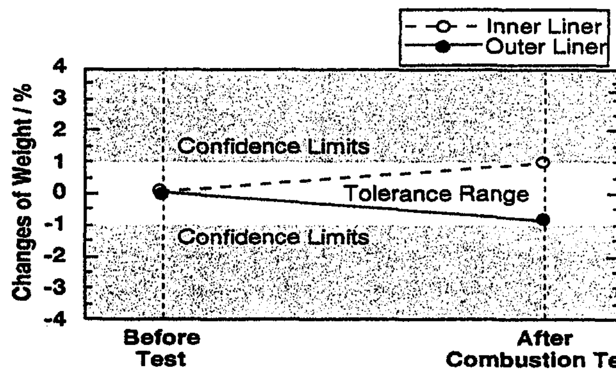


Fig. 17 Results of combustion test (measurement of weight)

Based on these results, we have confirmed the applicability of SiC^F/SiC composite material to the combustor liner for the AMG project.

In the future, we intend to develop a CMC combustor liner with superior strength reliability by evaluating the durability of SiC^F/SiC, improving the process to increase strength, and improving the structure to reduce thermal stress, and to subject the prototype liner to a combustion test using liquid fuel.

Acknowledgments

This study is being carried out under the Advanced Materials Gas-Generator R&D program with a joint investment from the Japan Key Technology Center. The authors wish to express their gratitude to the Japan Key Technology Center for making this study possible and permitting this paper to be published.

References

1 Yoshida, T., 1993, "The Progress and Future of Cooling Technology of High Temperature Gas Turbines," *Journal of the Japan Gas Turbine Society,* Vol. 20, No. 80, p. 4.

2 Petrasek, D. W., McDaniels, D. L., Westfall, L. J., and Stephens, J. R., 1986, "Fiber-Reinforced Superalloy Composites Provide an Added Performance Edge," *Metal Progress,* Vol. 130, No. 2, p. 27.

3 Hiromatsu, M., Yamamura, T., Chikata, T., Sekido, T., Ohama, S., Miyagawa, H., Murakami, I., and Seki, S., 1995, "Research and Development Status of Advanced Material Gas-Generator (AMG) Project," ASME95-GT-287.

4 Nishio, K., Igashira, K., Take, K., Suemitsu, T., 1997, "Development of Combustor Liner Composed of Ceramic Matrix Composite (CMC)," *Journal of the Japan Gas Turbine Society,* Vol. 25. No. 98, p. 94.