Technology Research on Gas Turbine Combustor Utilizing Melt-Growth Composite Ceramics

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Keywords: Advanced Material, Combustor, Cooling Structure, Fuel Nozzle

Abstract

"Research and Development of Melt-Growth Composite (MGC) Ultra High Efficiency Gas Turbine System Technology" program has been started in JFY2001. The main objective of the program is to establish basic component technologies to apply MGC material to an efficient gas turbine system successfully. It is known that MGC material maintains its mechanical strength at room temperature up to about 2000 K, which is ideal for the high temperature gas turbine. The purposes of the present study are to develop the cooling structure of the gas turbine combustor liner where MGC material is applied as the heat shield panel, also to develop the low NOx combustion system for a 1970 K (1700 deg.C) class gas turbine combustor. To start with, basic heat transfer characteristics were investigated by one-dimensional calculation and heat transfer experiment for the cooling structure. Axially staged configuration and fuel preparation were investigated by CFD calculation and experiments for the low NOx combustor.

INTRODUCTION

Improving gas turbine efficiency is strongly required to protect the global environment. Increasing turbine inlet temperature has been conducted for the improvement by applying heat-resistant superalloys to hot sections, such as combustor liners or turbine blades. In order to avoid deterioration, a lot of cooling air is required to cover the hot side of them. However, further improvement using conventional superalloys will be difficult because the amount of cooling air cannot be decreased from its present level. Innovative heat-resistant material is needed to endure under higher temperature condition.

"Research and Development of Melt-Growth Composite (MGC) Ultra High Efficiency Gas Turbine System Technology" has been started in JFY2001 (Fujiwara et al., 2003). The objective of the program is to establish basic component technologies to apply MGC material successfully to combustor liners and to turbine nozzles, and to realize 1970 K class highly efficient MGC gas turbine system.

Melt-Growth Composite (MGC) is a new ceramic material, which has eutectic composition of single crystal Al_2O_3 and single crystal $Y_3Al_5O_{12}$ or $GdAlO_3$ made by unidirectional solidification (Waku et al., 1997). This material maintains its mechanical strength at room temperature up to near its melting point of about 2000 K. Such characteristic is quite attractive as the substitute for the heat-resistant superalloys. Figure 1 gives an example of the combustor where MGC material is applied. MGC material is installed as the heat shield panel inside the liner, which prevents the metal component from being exposed to high temperature flames. Panels can be fastened to the liner using studs or by bonding each other. Axially multi-staged combustion system with rapid fuel mixing technology is adopted for the combustor.

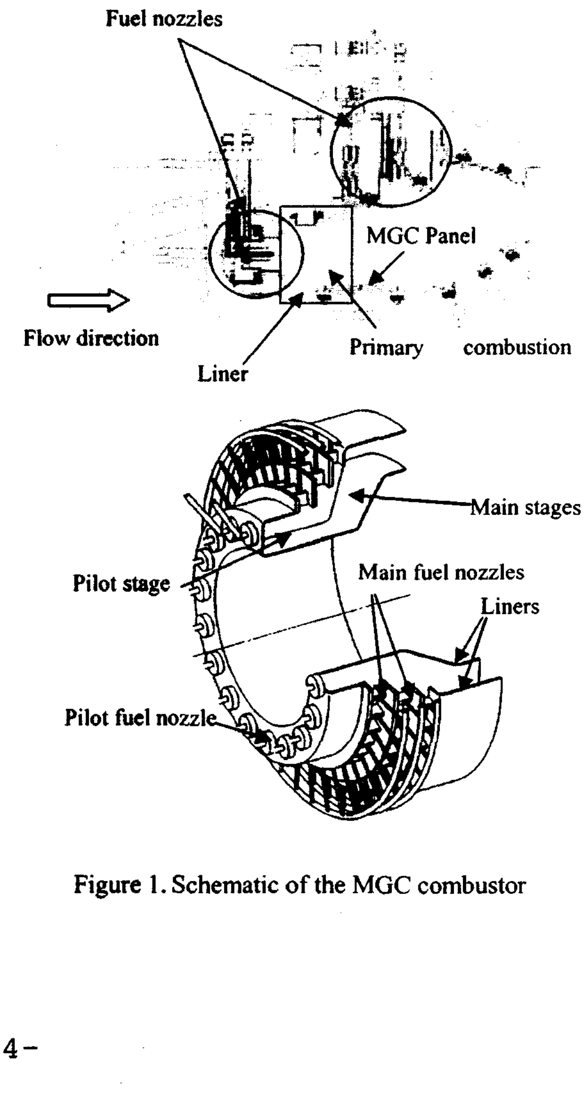


Figure 1. Schematic of the MGC combustor

In order to achieve such cooling structure scheme, several problems should be considered. First one is the cooling structure of the metal liner. Although the liner is protected from the combustion gas with MGC panel, it will be heated by strong radiation from the panel. On the other hand, minimizing the amount of cooling air is needed for the higher temperature operation. Hence, it is necessary to search a mutually acceptable compromise. Another problem is the reduction of thermal stress occurred in MGC panel, because this material is brittle compared to the metal. Choosing the panel configuration with less temperature gradient inside the panel is important. Fuel nozzle configurations and staging combustor configuration should be also considered to minimize NOx emissions at design point of 1970 K operation.

The purpose of the present study is to develop the cooling structure and low NOx combustion system of the 1970 K class gas turbine combustor applying the MGC material. In this paper, temperature level of MGC panel and metal liner in the combustor is estimated by means of one-dimensional calculation. Experimental results of heat transfer test for MGC sample panels are shown and the convectional cooling effectiveness is investigated. CFD calculation results on flow field of a staging combustor, and experimental results of fuel preparation test are also shown.

MGC Material

Melt-Growth Composite (MGC) material is a ceramic composite with a different kind of microstructure, made by unidirectional solidification of Al_2O_3 and $Y_3Al_5O_{12}$(YAG) or $GdAlO_3$(GAP) eutectic mixture. These composites have microstructures in which continuous networks of single-crystal Al_2O_3 and single-crystal YAG or GAP interpenetrate without grain boundaries. Figure 2 shows an SEM micrograph that illustrates the three-dimensional configuration of the single-crystal GAP in the unidirectionally solidified eutectic composite (Al_2O_3 phases are removed for clarity). Rather than brittle fracture, the materials show plastic deformation at 1873K owing to dislocation motion as observed in metals.

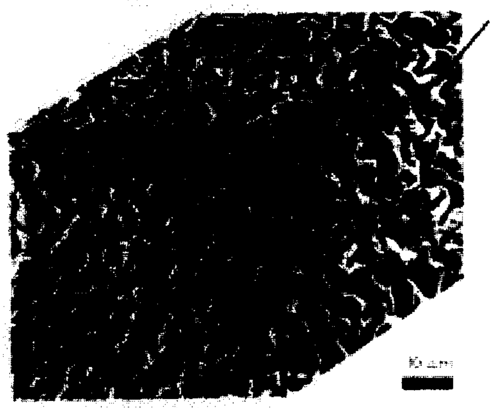


Figure 2 Microstructure of MGC material (Al_2O_3 phase is removed)

The microstructure is stable even when exposed at high temperature in air, and the flexural strength at room temperature can be maintained almost up to its melting point, that is, 2100K. Temperature dependence of flexural strength of the MGC material is compared to those of a superalloy and a sintered ceramics in figure 3. One can see that flexural strength of the MGC material is almost constant, while other materials show degradation in the flexural strength above certain temperature.

Photographs in figure 4 are examples of the MGC panel, which were fabricated in the preliminary study. Dimension of these panels are 70mm x 35mm x 1mm. A hole is made at the center of both panels to fasten on the liner with a bolt or a stud.

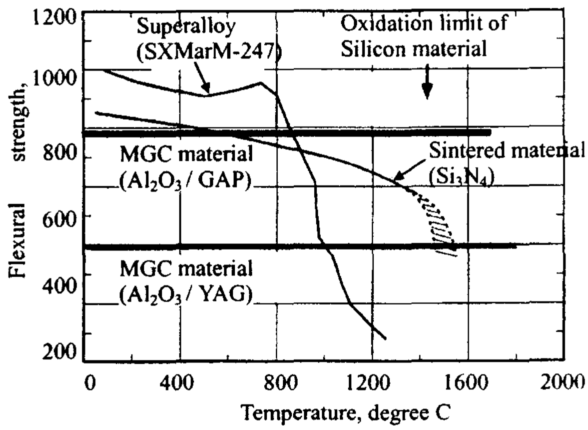


Figure 3 Temperature dependence of flexural strength

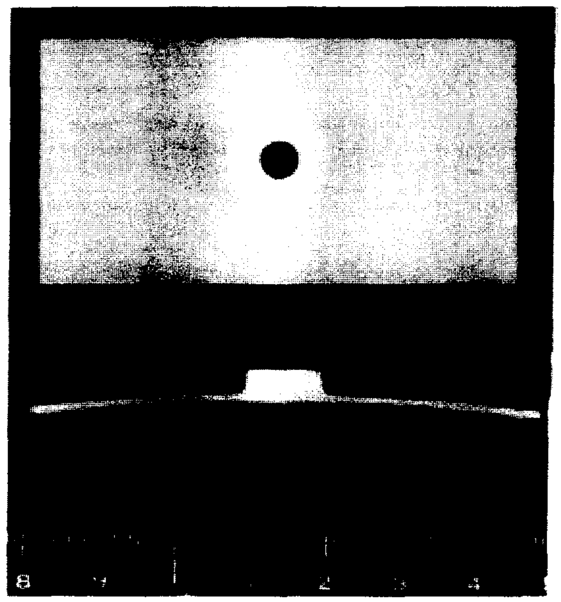


Figure 4 Examples of the MGC panel
(Curved panel with flat surface)

Cooling Structure Study

In order to design the basic cooling structure with MGC material, surface temperatures of MGC panel are estimated for some configurations through one-dimensional calculation, which accounts for heat balance between convection, radiation and conduction of the combustor liner in a gas turbine.

Figure 5 shows the configuration for calculation. There are three channels of combustion gas (mainstream), cooling air between MGC panel and the liner and annulus air. MGC panel and the liner are 2mm thick and cooling air is supplied between the panel and the liner with 2mm gap.

Flow conditions are listed in table 1, which assumes those of primary combustion zone. Thermal conductivity of MGC panel and metal components are set at 5.6W/(m·K) and 26W/(m·K), respectively. Emissivities of them are set at 0.46 and 0.7, respectively. Temperature dependencies of these properties are considered for MGC panel.

Surface temperature distribution against the ratio of coolant velocity to combustion gas velocity is shown in figure 6. Solid lines indicate the upper limit of wall temperature for each component, that is, 1973K for MGC panel and 1173K for liner. All surface temperatures increase as coolant velocity decreases, but they are lower than their limit values. It is expected that fair amount of cooling air will be reduced by applying MGC panel inside the liner.

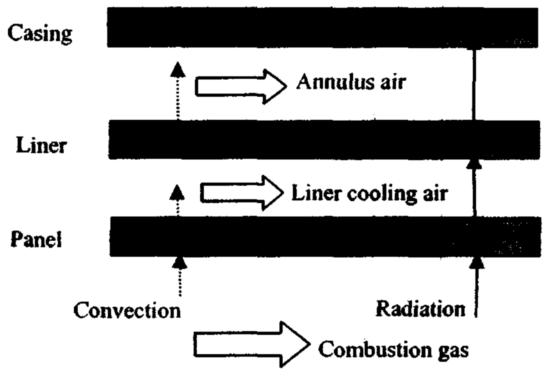


Figure 5. Basic cooling structures

Table 1 Flow conditions for the cooling structure

	Mainstream	Coolant channel	Annulus
Pressure [MPa]	2.85	2.89	2.91
Temperature [K]	2200	835	835
Velocity [m/s]	50	0~40	43
Channel height [m]	0.068	0.002	0.075

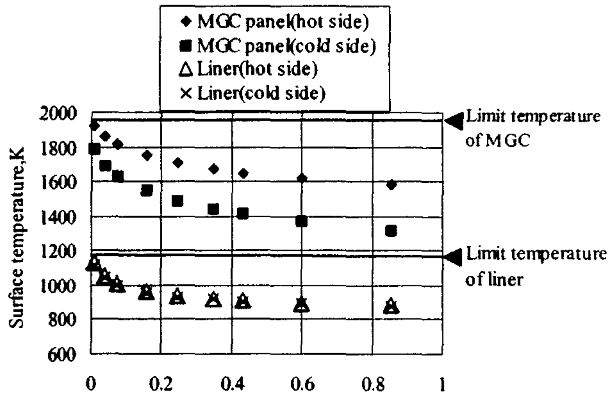


Figure 6. Panel temperature and velocity ratio of coolant (Uc) to mainstream gas (Um)

The problem in this case is the steep temperature gradient occurred in MGC panel. Surface temperature of cold side of MGC panel decreases almost 200K from the hot side temperature for the present condition. Considering that the MGC material has brittle feature, it is important to reduce the temperature gradient in MGC panel.

There could be several approaches to reduce the temperature gradient; one is to reduce the gas temperature near the wall, which reduces heat input from the combustion gas. For the present combustor, slot-cooling method can be considered, as illustrated in figure 7. Some portion of the coolant between the panel and the liner is discharged to the hot side of the next panel, which prevents the panel from being exposed to the flame.

The effect of the slot cooling is investigated by adding the film cooling effectiveness to the above 1D calculation. Film cooling effectiveness is defined as

$$\eta_f = \frac{T_m - T_{w,ad}}{T_m - T_c} \quad (1)$$

where $T_{w,ad}$ is the adiabatic wall temperature, or the gas temperature near the wall. Temperature difference between hot and cold sides of the MGC panel is compared for various film cooling effectiveness in figure 8.

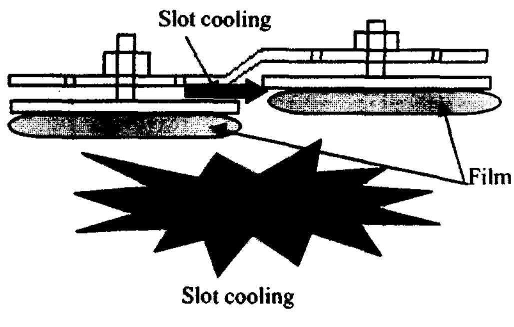


Figure 7. Approaches to reduce temperature gradient

One can see that slot-cooling decreases at least 10% of the temperature gradient occurred in the case without slot cooling. To decrease the temperature gradient of the panel with high combustion gas temperature, cooling the hot side slightly with small amount of air could be favorable.

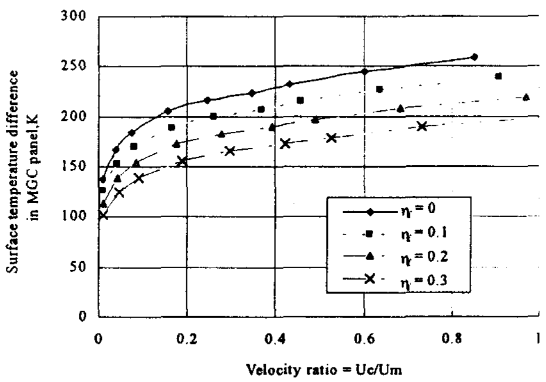


Figure 8. Temperature difference between hot and cold side of MGC panel for various η_f

Heat Transfer Test

Heat transfer tests are conducted to know the basic convective heat transfer characteristics of MGC panel.

Test Facility

Figure 9 shows the schematic of the heat transfer test section. Convective cooling characteristic is evaluated by exposing the sides of MGC panel to hot air and cooling air.

Static pressure, total pressure and temperature are measured at both channels by inserting probes as shown in figure 9. K-type thermocouples and an infrared radiation thermometer (NEC SAN-EI Thermo Tracer TH7102MX, spectral range : 8-14μm) are used to measure the surface temperature of MGC panel. IR thermometer is used for the measurement of temperature distribution of hot side surface. ZnSe windows with 7mm thickness are equipped at the mainstream duct and the plenum chamber to observe the panel surface with the IR thermometer.

Test Pieces

Three MGC panels with different thickness are fabricated for the present test. These panels are 1mm, 1.5mm and 2mm thick, respectively. One of the fabricated panels is shown in figure 10. All panels have flat shapes with the same dimension shown in this figure. Surface roughness of the panels are nominally 0.4μm, hence the surface of the panels are smooth enough to treat as hydraulically smooth surface.

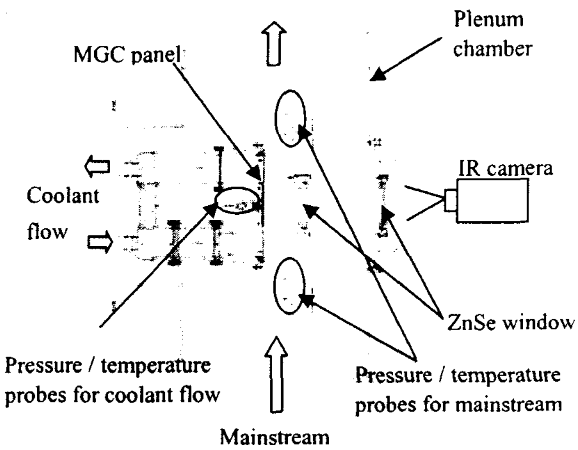


Figure 9. Schematic of the heat transfer test facility

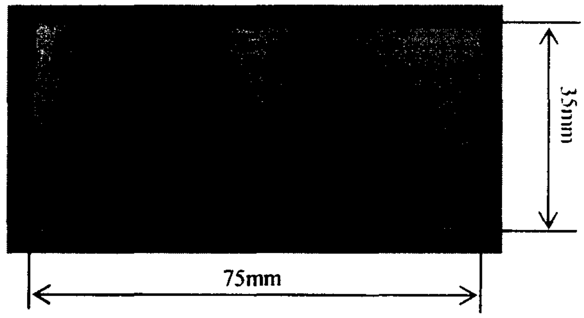


Figure 10. MGC panel for the heat transfer test

Test Conditions

Flow conditions for the present heat transfer test are listed in table 2. In order to know the basic characteristics of MGC panel, effects of density ratio and the amount of coolant to cooling effectiveness are investigated in the present study.

Tests are conducted at atmospheric pressure condition. Density ratio of coolant to mainstream (DR) is varied from 1 to 2.2, which is similar to that for the combustor. Coolant bulk velocity is varied from zero to 32m/s Basic flow condition is DR=2.2 and u_c=18m/s in the present test. Reynolds numbers of mainstream and cooling air flow, based on each hydraulic diameter, are approximately 9.4×10^4, 1.7×10^4, respectively. These values are similar to those of the present combustor.

Table 2 Test conditions

	Main	Coolant
Pressure [MPa]	0.10	0.10
Temperature [K]	RT – 623	RT
Mass flow rate [kg/s]	0.28	0 – 0.01
Cross sectional area [m^2]	1.0×10^{-2}	3.76×10^{-4}

Results and Discussions

Figure 11 compares the cooling effectiveness of MGC panel as a function of density ratio of coolant to mainstream for experimental results of the three panels and one-dimensional calculation data. In this case, coolant velocity is 18m/s. Cooling effectiveness is determined in Eq.(2) in the present study,

$$\eta = \frac{T_m - T_p}{T_m - T_c} \quad (2)$$

where T_p is the averaged temperature value between hot side and cold side of the panel.

Little difference is seen between the experimental results, which have different thickness. In the present experimental condition, thermal conductivity of MGC material is relatively high, which is estimated at 9.35W/(m·K). Therefore, it is considered that the panel thickness has little effect on cooling effectiveness.

One-dimensional calculation is conducted for the panel thickness of 2mm. In this calculation, thermal conductivity of MGC material is 9.35 W/(m·K). The effect of radiation is omitted, because it can be considered that the temperature level is low enough to neglect that. Calculated results agree well with the experimental results. Therefore, one can confirm that the present one-dimensional calculation appropriately reproduces the effectiveness of convectional cooling obtained by the present experiment.

Cooling effectiveness slightly decreases with increase in density ratio for all results. Under the constant mass flow rate condition, heat transfer rate can be evaluated as the function of temperature, which is described as approximately $h \propto T^{0.3}$. In this test, mainstream temperature is raised at higher density ratio condition, which makes hot side heat transfer rate increase. Therefore, cooling effectiveness decreases at higher density ratio. This figure shows that the effect of density ratio to the cooling effectiveness is relatively small.

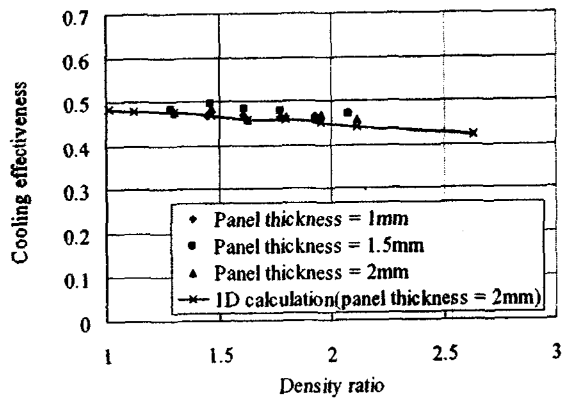


Figure 11. Relations between cooling effectiveness and density ratio of coolant to mainstream (coolant velocity = 18m/s)

Distribution of cooling effectiveness for various ratios of coolant velocity to mainstream velocity is shown in figure 12, in which density ratio is 2.2. Cooling effectiveness increases with increase in coolant mass flow rate for all results, because higher coolant velocity increases heat transfer rate for cold side surface.

It is observed that the experimental result is 5-15% higher than the calculated result for lower velocity ratio. This may be caused by the higher heat transfer rate for the coolant side in the experiment. It is considered that the cooling air flow cannot be fully developed in the channel, while the calculation assumes the fully developed turbulent flow. Heat transfer rate for the developing turbulent flow is higher than that for the developed flow, hence that could be the reason for the above discrepancy.

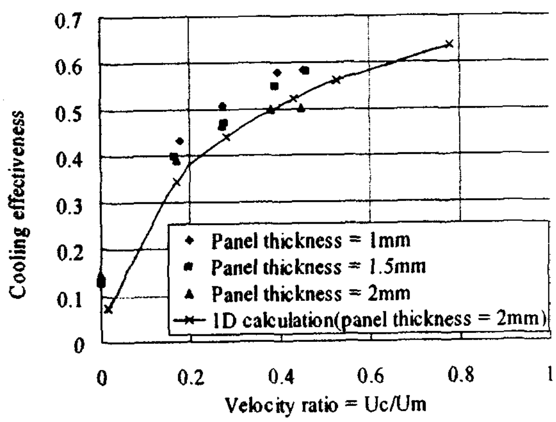


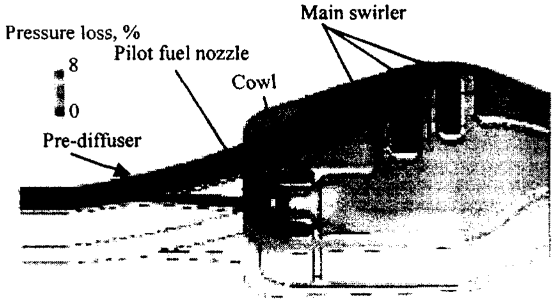
Figure 12. Relations between cooling effectivenes and velocity ratio of coolant to mainstream (density ratio = 2.2)

Low NOx Combustion System Study

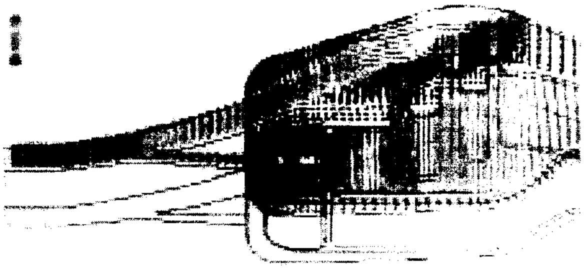
Multi-Staged Combustor

The MGC combustor uses axially multi-staged combustion system with rapid fuel mixing injection to decrease NOx generation at 1700 deg. C operation. This axially multi-staged configuration is very complex and it is important to understand flow fields accurately for each stage in the combustor. CFD calculations were conducted on several combinations of configuration between pre-diffuser and staged liner to predict air flow rate ratios of each stage and total pressure loss ratio.

CFD calculation results showed the combination of double path pre-diffuser and three-main stage liner is suitable. Figure 13 shows total pressure loss contours and an air velocity vector of the combustor. It presents that smooth air flow into each stage, especially pilot stage , first main stage and second main stage, is well established. Total pressure loss is also concerned to achieve high thermal efficiency of an engine, and low pressure loss was achieved by this configuration.



(a) Pressure loss contour



(b) Air velocity vector

Figure 13 CFD calculation results on flow filed of double path and three-main stage configuration

Fuel Preparation

Fuel preparation is the major concern for low NOx combustors, especially highest TIT combustor like this. Pilot fuel nozzle and main fuel nozzles are being investigated, and progresses of the pilot fuel nozzle research are shown below.

Figure 14 shows a schematic of the pilot fuel nozzle. It has combination of a primary injector inside and a secondary injector outside, and those injectors were designed based on rapid fuel mixing technology.

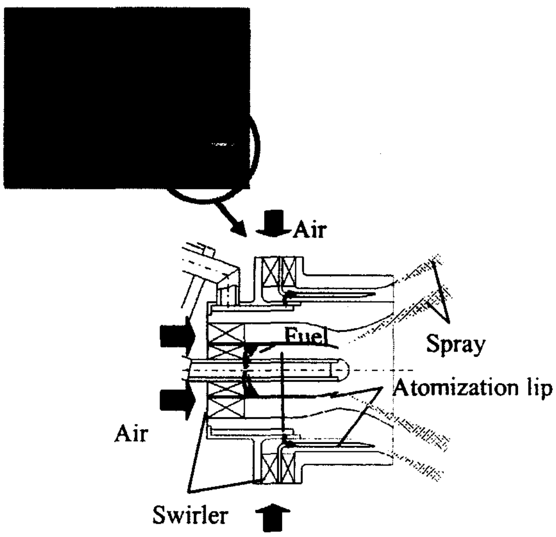
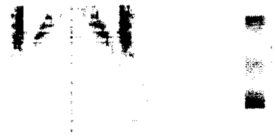
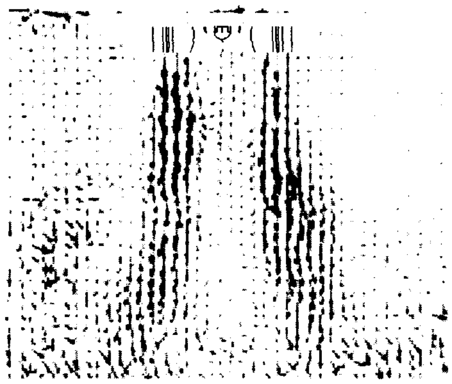


Figure 14. Schematic of pilot fuel nozzle



(a) Air velocity vector from primary injector (CFD calculation result)



(b) Air velocity vector from primary injector (PIV measurement)

(c) Droplets distribution image by LIF

Figure 15. Fuel preparation results of pilot fuel nozzle

Figure 15 shows fuel preparation of the pilot fuel nozzle. Picture (a) is an air velocity vector from the primary injector predicted by CFD calculation. Diffusive of air into outside is weak, but a strong recirculating flow is produced downstream of the exit. Picture (b) is an air velocity vector obtained by PIV measurement. Prediction and measurement are well correspondent Picture (c) is an image of fuel droplets obtained by LIF measurement, and it shows a favorable fuel distribution.

CONCLUSION

A high temperature and low NOx combustor have been investigating. In order to apply MGC material to the high temperature combustor as the heat shield panel, heat transfer characteristic of the basic cooling configuration with MGC panel is investigated by one-dimensional calculation and heat transfer experiment. Following results are obtained in the present study:

1. One-dimensional calculation shows that the temperature level of MGC panel is sufficiently low, but that the temperature gradient should be decreased. Slot cooling can be effective to achieve that; however, the amount of cooling air should be minimized to keep high temperature in the combustor liner.
2. Experimental study on basic convective heat transfer characteristic is conducted. Results of the experiment are approximately consistent with the calculated result. Cooling effectiveness obtained in the experiment is slightly higher than that in the calculation, which may be caused by higher heat transfer rate in the cooling channel. In order to investigate such characteristic precisely, measurement of heat transfer rate would be needed.
3. Low NOx combustion system study is also executed. Multi-staging combustor concepts with rapid fuel mixing system are investigated, and CFD calculation and laser measurements are conducted to design the combustor.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to the New Energy and Industrial Technology Development Organization (NEDO) and Ministry of Economy, Trade and Industry (METI), who gave them the opportunity to conduct "Research and Development of MGC Ultra High Efficiency Gas Turbine System Technology".

NOMENCLATURE

DR : Density ratio = ρ_c / ρ_m
GAP : Gadolinium Aluminum Perovskite
MGC : Melt-Growth Composite
RT : Room temperature, K
t : Thickness, mm
T : Temperature, K
$T_{w,ad}$: Adiabatic wall temperature, K
w : Mass flow rate per area, kg/(s.m^2)
YAG : Yttrium Aluminum Garnet

Greek

η : Cooling effectiveness
ρ : Density, kg / m^3

Subscripts

c : Coolant
ins : Insulation
m : Mainstream, or mean
p : Panel
f : Film

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