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PERFORMANCE EVALUATION OF MULTI-STAGE SOFC AND GAS TURBINE COMBINED SYSTEMS

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ABSTRACT

Solid oxide fuel cell (SOFC) and gas turbine hybrid power generation systems have gained more and more attention with regard to the development of the high performance distributed energy systems. The SOFC can be combined with a gas turbine because the SOFC operating temperature of about 1000°C matches the turbine inlet temperature. In this study, we proposed the multi-stage type SOFC/GT combined system and compared the system performance of it with that of other combined systems using the thermal efficiency and exergy evaluation. It is noted that the thermal efficiency of the 3-stage type SOFC/GT combined system can reach more than 70% (HHV) at low pressure ratio.

NOMENCLATURE

SOFC	Solid Oxide Fuel Cell
FC	Fuel Cell
C	Compressor
GT	Gas Turbine
HE	Heat Exchanger
AB	After Burner
HRSG	Heat Recovery Steam Generator
ST	Steam Turbine
HHV	Higher Heating Value
TIT	Turbine Inlet Temperature
S/C Ratio	Steam/Carbon Mole Ratio

INTRODUCTION

In recent years, concern has been raised about developing a distributed energy system using the micro gas turbine and fuel cells. The SOFC has the advantage of generating power at high thermal efficiency and has small irreversible losses compared with other fuel cells. It is effective that the SOFC operated at a high temperature of 1000°C is combined with a gas turbine because the operating temperature of SOFC matches the turbine inlet temperature and the exhaust heat of the fuel cell is transformed to the electric power by the gas turbine.

The system analysis of the SOFC and gas turbine hybrid systems has been carried out and several system configurations are proposed until now. The anode and cathode gas recycling systems are effective to raise the turbine inlet temperature (Mori et al., 2000). The fuel cell system with the air preheating can reduce the inlet air flow for cooling the cell because the inlet air flow is preheated by the heat generated in the fuel cell up to the operating temperature of SOFC (Campanari, 2000). The SOFC can be combined with the intercooled reheat gas turbine system (Johansson et al., 1998). They investigated the reheated and intercooled gas turbine system with two SOFC units where the second unit replaces the reheat burner. Furthermore, the humid air turbine (HAT) cycle is incorporated in the SOFC and intercooled reheat gas turbine combined systems (Rao et al., 2001). They showed that the thermal efficiency of the single SOFC-HAT hybrid system and the dual SOFC-HAT hybrid system are 69.05% and 75.98% of LHV, respectively. The efficiency of the SOFC/GT/ST combined system is higher (over 70%) than the efficiency of the advanced combined cycle plant (Massardo et al., 2000).

In this paper, we proposed the multi-stage type SOFC/GT combined system which has a high efficiency, and compared the performance of the multi-stage type combined system with that of other combined systems. First, the effects of the pressure ratio of the compressor and the turbine inlet temperature on the thermal efficiency of each combined system are analyzed and the optimum conditions are shown. A low pressure ratio achieves the high system efficiency and the additional fuel supply for increasing the TIT decreases the system efficiency. Secondly, the exergy losses of components in each system are evaluated using exergy analysis and the effects of the improvements of the system configuration on the performance are clarified. Importance is noted to reduce the exergy loss of the after burner in order to improve the system efficiency. It is shown the efficiency of the 3-stage type SOFC/GT combined system can reach 70% (HHV) at low pressure ratio.

SYSTEM CONFIGURATION AND ASSUMPTIONS

We analyzed three SOFC and gas turbine combined systems of the standard type (Fig.1), internal heat recovery types (Fig.4, 5) and multi-stage types (Fig.7, 9). The computation was made by use of the software "HYSYS". The assumptions used for the analysis of the SOFC/GT combined systems are described below.

The performance and operating conditions of SOFC are shown in Table 1. Methane (CH_4) is reformed to hydrogen and carbon monoxide by the internal reforming in the SOFC. The electric generation efficiency of the fuel cell is assumed to be 48% as a fixed value. The efficiency of the fuel cell is defined as the fraction of the direct current (DC) output to the CH_4 HHV of the inlet flow, and estimated from the cell temperature 1000°C, cell voltage 0.7V and fuel utilization ratio 80%. We didn't consider the influence of the operating pressure of the fuel cell and the compositions of anode and cathode gases on the fuel cell efficiency. The fuel utilization ratio 80% is defined as the ratio of the fuel flow utilized for the reaction to the inlet fuel flow at the anode. The inlet and outlet temperatures of the fuel cell are 950°C and 1050°C, respectively. The method of the fuel reforming is the steam reforming, and the S/C mole ratio is assumed to be 3.0 in order to prevent from the accumulation of the carbon in the cell. These assumptions are given in Fuel Cells Handbook (Rev. 3) of DOE (Hirschenhofer et al., 1994).

In Table 2, the conditions of gas turbine system are shown. The heat loss and pressure loss in each component were neglected and the steady state system operation is considered.

Table 1 Performance and Operating Condition of SOFC

Type	Solid Oxide Fuel Cell (Internal Reforming)
Fuel	CH_4
Electric Generation Efficiency	48% (HHV) $\left(\dfrac{\text{DC output}}{\text{inlet CH}_4\text{ HHV}} = 0.48\right)$
Fuel Utilization Ratio	80%
Operating Temperature	950°C (Inlet) / 1050°C (Outlet)
Fuel Reforming	Steam Reforming S/C Ratio = 3.0

Table 2 Conditions of Gas Turbine System

Atmospheric Temperature	25°C
Atmospheric Pressure	101.3 kPa
Adiabatic Efficiency of Compressor and Turbine	80%
Temperature Effectiveness of Heat Exchanger	Under 90%

STANDARD TYPE SOFC/GT COMBINED SYSTEM

Figure 1 shows the flow scheme of the standard type SOFC/GT combined system formed by the simple combination of the SOFC and gas turbine. Pressurized fuel, air and steam for reforming the fuel are preheated up to about 800°C by the exhaust heat from the gas turbine in the heat exchanger (HE). They are preheated up to 950°C of the temperature for reforming the fuel and operating the SOFC by the high temperature combustion gas in the after burner (AB). Since the temperature difference of 100°C between the inlet and outlet of the cell is small, the large air ratio of 5.85 in the fuel cell is needed for cooling the cell. The exhaust heat from the gas

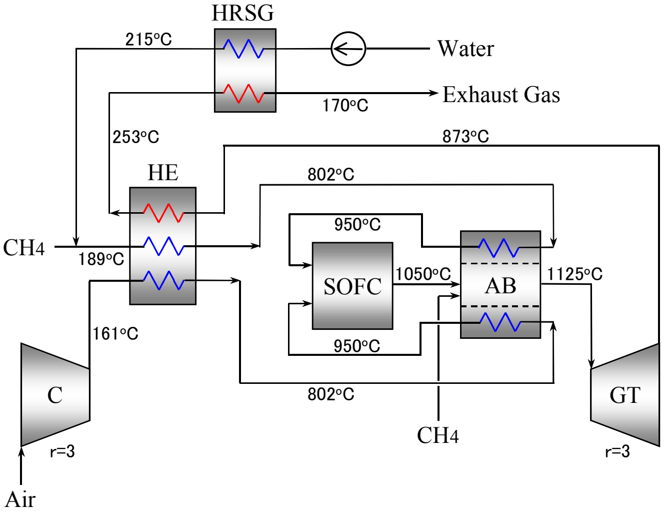


Fig.1 Standard Type SOFC/GT Combined System

Table 3 Optimum Conditions and Performances of Standard Type SOFC/GT Combined System

Pressure Ratio		3.0
Turbine Inlet Temperature		1125°C
Fuel Flow Ratio	for FC	0.70
	for AB	0.30
Air Ratio	FC	5.85
	System	4.11
Power Ratio	FC	0.58
	GT	0.42
System Efficiency (HHV)		58.6%

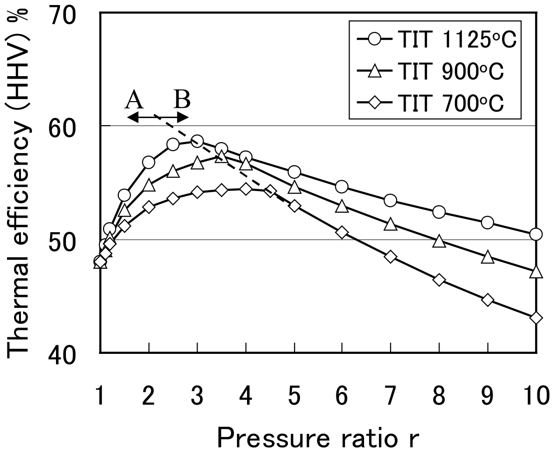


Fig.2 Thermal Efficiency of Standard Type (under 1125°C TIT)

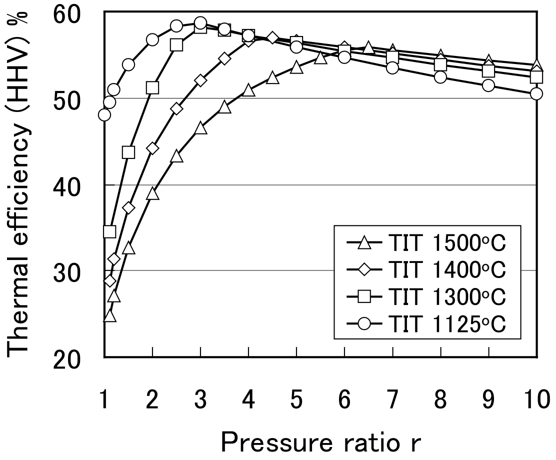


Fig.3 Thermal Efficiency of Standard Type (over 1125°C TIT)

turbine is used for preheating the fuel and air and generating steam. If the energy for preheating and generating steam is defected, fuel must be directly supplied to the after burner and the heat generated in the after burner must be used for preheating the fuel and air. Steam for reforming the fuel is generated by the exhaust heat from the heat exchanger at the heat recovery steam generator (HRSG). A fuel gas compressor is omitted in all figures, but the calculation of the system efficiency takes the work of the fuel gas compressor into consideration.

In Fig.2 and Fig.3, the effects of the pressure ratio and TIT on the thermal efficiency of the standard type are shown. The temperature of exhaust gas from the cell increases up to 1125°C when the fuel not oxidized in the anode is completely burned in the after burner. Figure 2 shows the relation between the pressure ratio and the thermal efficiency when the TIT is less than 1125°C, and Figure 3 shows the relation between them when the TIT is more than 1125°C.

When the TIT is less than 1125°C, the characteristics of the thermal efficiency are different between the A region which is shown in the left side of the broken line, and the B region which is shown in the right side. In the B region, the fuel for the after burner is minimized and the system efficiency is optimized under the condition of 90% constant temperature effectiveness of the heat exchanger when the conditions of the pressure ratio and turbine inlet temperature are given. The fuel flow for the after burner and the heat which is exchanged at the after burner must be increased with increasing the pressure ratio because the heat which is recovered at the heat exchanger decreases at high pressure ratio. In the A region, the HRSG has the pinch point if the fuel flow for the after burner is decided under the conditions of B region. So, more fuel must be added to the after burner in order to prevent the pinch point of HRSG. The temperature effectiveness is less than 90% when the pinch point is avoided.

When the TIT is more than 1125°C, much fuel needs to be supplied to the after burner in order to increase the TIT, and the thermal efficiency falls.

The optimum efficiency of 58.6% of the standard type is gained at low pressure ratio of 3.0 when the fuel which is supplied to the after burner is 30% of total fuel and the temperature effectiveness of heat exchanger is high (90%). The supply of the fuel for increasing the TIT reduces the system efficiency.

INTERNAL HEAT RECOVERY TYPE SOFC/GT COMBINED SYSTEM

In the internal heat recovery type SOFC/GT combined system, fuel and air are preheated by the heat generated in the fuel cell. The air for cooling the fuel cell is reduced and the air

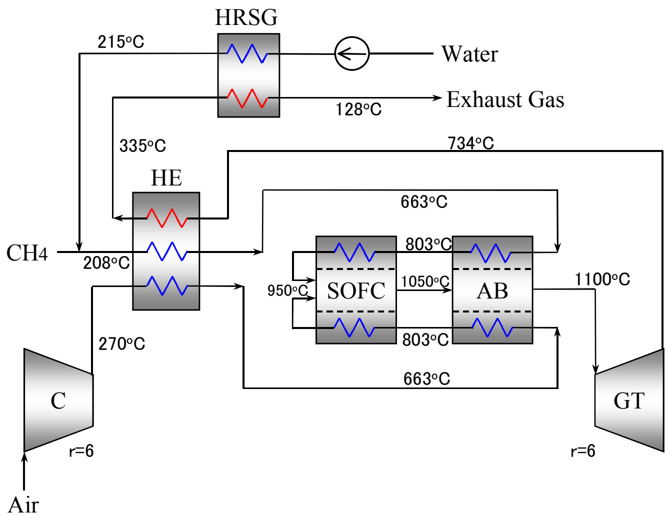


Fig.4 Internal Heat Recovery Type SOFC/GT Combined System (Steam Addition Layout)

Table 4 Optimum Conditions and Performances of Internal Heat Recovery Type (Steam Addition Layout)

Pressure Ratio		6.0
Turbine Inlet Temperature		1100°C
Fuel Utilization Ratio		0.8
Air Ratio		2.01
Power Ratio	FC	0.72
	GT	0.28
System Efficiency (HHV)		66.7%

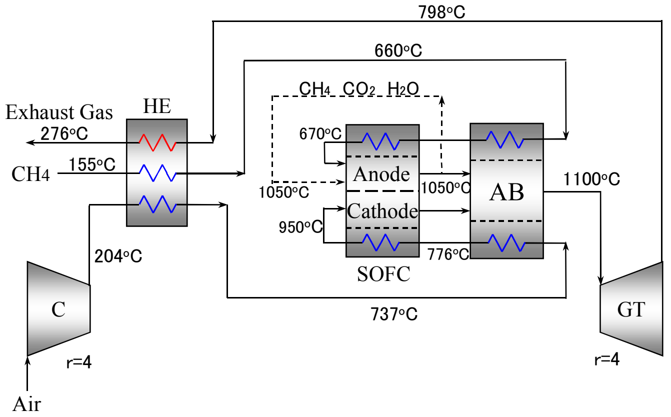


Fig.5 Internal Heat Recovery Type SOFC/GT Combined System (Steam Circulation Layout)

Table 5 Optimum Conditions and Performances of Internal Heat Recovery Type (Steam Circulation Layout)

Pressure Ratio		4.0	
Turbine Inlet Temperature		1100°C	
Anode Gas Recycle Ratio		60%	
Fuel Flow Ratio (Anode Inlet)	supplied	0.88	anode inlet =1.0
	circulated	0.12	
Fuel Utilization Ratio		0.8 $\left(\dfrac{\text{utilized fuel}}{\text{supplied fuel}} = 0.91\right)$	
Air Ratio		2.39	
Power Ratio	FC	0.79	
	GT	0.21	
System Efficiency (HHV)		69.5%	

ratio becomes small because of the heat circulation within the fuel cell. In this paper, we analyzed the performances of two systems of the steam addition layout and the steam circulation layout.

Figure 4 shows the flow diagram of the internal heat recovery type SOFC/GT combined systems of steam addition layout. The inlet temperature of the SOFC unit can be lowered to about 800°C as compared with that of the standard type of 950°C by preheating the fuel and air in the cell. Since the exhaust heat from the gas turbine is large enough to preheat the fuel, air and steam in the heat exchanger and HRSG, the fuel need not be supplied for the after burner.

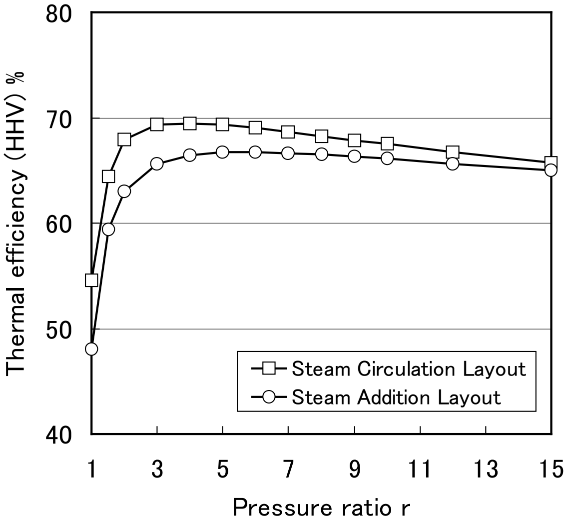


Fig.6 Thermal Efficiency of Internal Heat Recovery Type

Figure 5 shows the flow diagram of the steam circulation layout. Methane fuel is reformed by the steam included in the circulation gas. It is assumed that 60% of the exhaust gas from the anode is recovered at the anode outlet and injected into the anode inlet. The temperature of the supplied fuel from the preheater in the fuel cell is much lower (670°C) than the operating temperature of SOFC (950°C) because of the addition of the high temperature circulation gas of 1050°C. The exhaust gas temperature of this layout is higher (276°C) than that of the steam addition layout. This system has the advantages of the omission of the HRSG installation and the increase of the fuel utilization ratio. The latent heat loss of exhaust gas is reduced by no steam generation in the HRSG. The inlet fuel flow at the anode is the sum of the supplied fuel of 670°C from the preheater in the fuel cell and the circulated fuel of 1050°C from the anode outlet. The rate of supplied fuel to circulated fuel is 0.88 to 0.12. Therefore, 91% of the supplied fuel can be utilized in the fuel cell when the fuel utilization ratio is assumed to be 80%.

The effect of the pressure ratio on the thermal efficiency of two internal heat recovery types is shown in Fig.6. The TIT is set at 1100°C. The temperature effectiveness of the heat exchanger in the steam addition layout is set as 85% or less in order to supply the sufficient exhaust heat to the HRSG. Since the air ratio in the fuel cell is reduced by a decrease in the air for cooling the cell, the system efficiency of internal heat recovery types is higher than that of the standard type. The latent heat in the exhaust gas of the steam circulation layout is smaller than that of the steam addition layout because of the omission of the HRSG installation. This is the reason why the system efficiency of the steam circulation layout becomes high 69.5%(HHV). The optimum pressure ratio of this type is relatively low.

MULTI-STAGE TYPE SOFC/GT COMBINED SYSTEM

If much air for cooling the fuel cell must be injected to the cathode, the air ratio in the fuel cell becomes very large and much air isn't utilized for the cell reaction. In the multi-stage type SOFC/GT combined systems, the air that is supplied to the second cell and third cell, need not be preheated up to the operating temperature of SOFC of 950°C by using the exhaust heat from the gas turbine. Furthermore, the air utilization ratio becomes high. Since the part of the fuel which isn't reacted in the first cell, is utilized in the downstream cells, the total fuel utilization ratio of all stages is higher than that of one fuel cell of 80%. In this paper, we evaluated the system performance of 2-stage type and 3-stage type SOFC/GT combined systems.

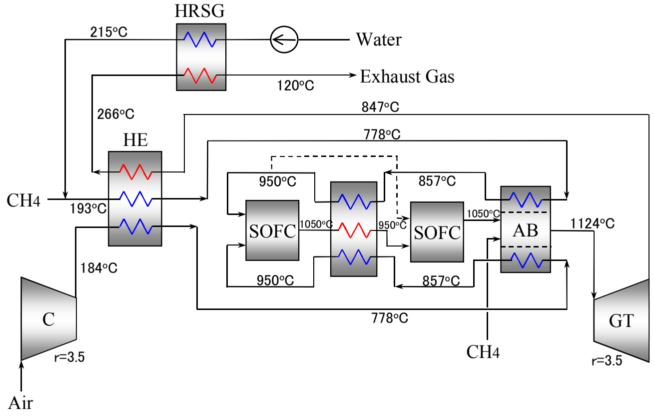


Fig.7 Multi-Stage Type SOFC/GT Combined System (2-Stage Type)

Table 6 Optimum Conditions and Performances of Multi-Stage Type (2-Stage Type)

Pressure Ratio		3.5
Turbine Inlet Temperature		1124°C
Fuel Flow Ratio	for 1st FC	0.47
	for 2nd FC	0.42
	for AB	0.11
Fuel Utilization Ratio	0.8 $\left(\frac{\text{utilized fuel (all stages)}}{\text{supplied fuel (all stages)}} = 0.885\right)$	
Air Ratio	FC	3.10
	System	2.75
Power Ratio	for 1st FC	0.34
	for 2nd FC	0.37
	GT	0.30
System Efficiency (HHV)		66.9%

2-Stage Type SOFC/GT Combined System

Figure 7 shows the flow scheme of the 2-stage type SOFC/GT combined system. The heat exchanger is installed between the first and second cells, and the exhaust gas from the first cell of 1050°C is cooled to the inlet temperature of the second cell of 950°C. The fuel flow rate for the after burner is much smaller than that of standard type because the part of exhaust heat from the first cell is used for preheating the fuel and air and the air ratio of multi-stage type becomes small.

The effects of the pressure ratio and TIT on the thermal efficiency of 2-stage type are shown in Fig.8. The exhaust gas temperature from the second cell is raised up to 1124°C when the fuel which is not reacted in the anode, is completely burned in the after burner. Under the pressure ratio and TIT conditions of the reheat area which is shown in the right side of the broken line, it becomes difficult to keep the temperature effectiveness of the heat exchanger 90% with preventing the pinch point of HRSG. Therefore, the fuel for preheating the fuel and air must be supplied to the after burner. Under the conditions of the non-reheat area which is shown in the left side of the broken line, the fuel for the after burner need not be supplied because the high temperature exhaust gas from the gas turbine can preheat the fuel and air and generate the steam for reforming the fuel. The characteristics of the thermal efficiency within the reheat area are different between the A region which is shown in the left side of the dotted line, and the B region which is shown in the right side. The difference of characteristics between the A region and B region of the multi-stage type is the same as that of the standard type.

The multi-stage type combined system has the advantage of the high performance operation over the standard type. The

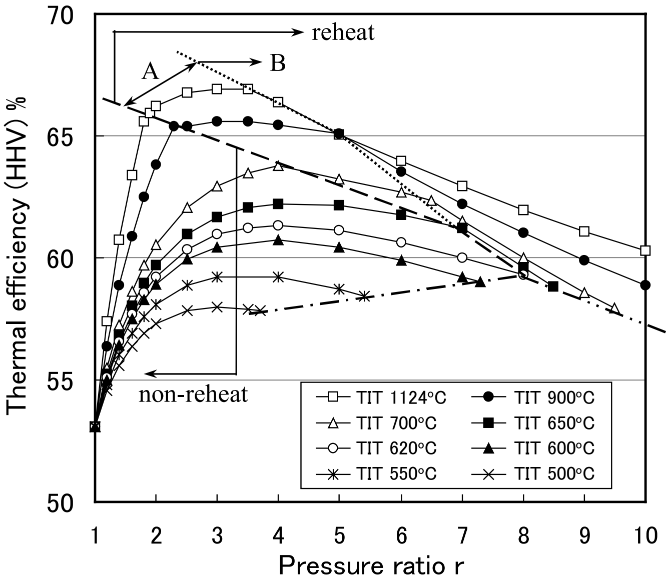


Fig.8 Thermal Efficiency of Multi-Stage Type (2-Stage Type)

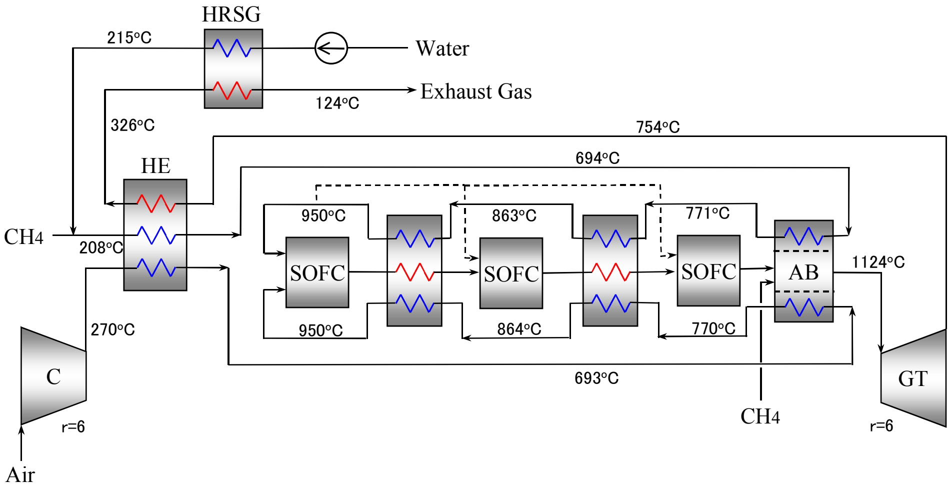


Fig.9 Multi-Stage Type SOFC/GT Combined System (3-Stage Type)

Table 7 Optimum Conditions and Performances of 3-Stage Type (All Cells Steam Addition Layout)

Pressure Ratio		6.0
Turbine Inlet Temperature		1124°C
Fuel Flow Ratio	for 1st FC	0.32
	for 2nd FC	0.29
	for 3rd FC	0.31
	for AB	0.08
Fuel Utilization Ratio	0.8 $\left(\frac{\text{utilized fuel (all stages)}}{\text{supplied fuel (all stages)}} = 0.917\right)$	
Air Ratio	FC	2.05
	System	1.89
Power Ratio	for 1st FC	0.23
	for 2nd FC	0.24
	for 3rd FC	0.27
	GT	0.26
System Efficiency (HHV)		68.8%

Table 8 Optimum Conditions and Performances of 3-Stage Type (1st Cell Steam Addition Layout)

Pressure Ratio		4.0
Turbine Inlet Temperature		1124°C
Fuel Flow Ratio	for 1st FC	0.37
	for 2nd FC	0.31
	for 3rd FC	0.32
	for AB	0.00
Fuel Utilization Ratio	0.8 $\left(\frac{\text{utilized fuel (all stages)}}{\text{supplied fuel (all stages)}} = 0.921\right)$	
Air Ratio	FC	2.18
	System	2.18
Power Ratio	for 1st FC	0.25
	for 2nd FC	0.26
	for 3rd FC	0.27
	GT	0.22
System Efficiency (HHV)		70.9%

fuel flow rate supplied to the after burner becomes small. In the multi-stage type, the exhaust heat per unit fuel flow becomes small because the air for cooling the fuel cell is cut down. The total fuel utilization ratio of all stages is much larger than that of one fuel cell of 80%. These are the reason why the multi-stage type efficiency is much larger than the standard type efficiency. The 2-stage type efficiency of 66.9% is obtained at low pressure ratio and the TIT of 1124°C.

3-Stage Type SOFC/GT Combined System

The flow diagram of the 3-stage type is shown in Fig.9. The fuel and air utilization ratio is more improved by multiplying the fuel cell. Two heat exchangers are installed between the first, second and third cells and the exhaust gas from the first and second cell cooled to the inlet temperature of the second and third cell. Since the heat recovered in the two heat exchangers between three fuel cells becomes large, the fuel flow rate for the after burner of the 3-stage type is less than that of the 2-stage type.

Steam contained in the exhaust gas from the first cell can be utilized for reforming the fuel at the second and third cells, and steam for the second and third cells need not be supplied from the HRSG. In this paper, we evaluated the performance of the 3-stage types of the all cells steam addition layout and the first cell steam addition layout. In the all cells steam addition layout, steam generated in the HRSG for reforming the fuel is supplied to all fuel cells. In the first cell steam addition layout, steam from the HRSG is supplied to the first cell only and

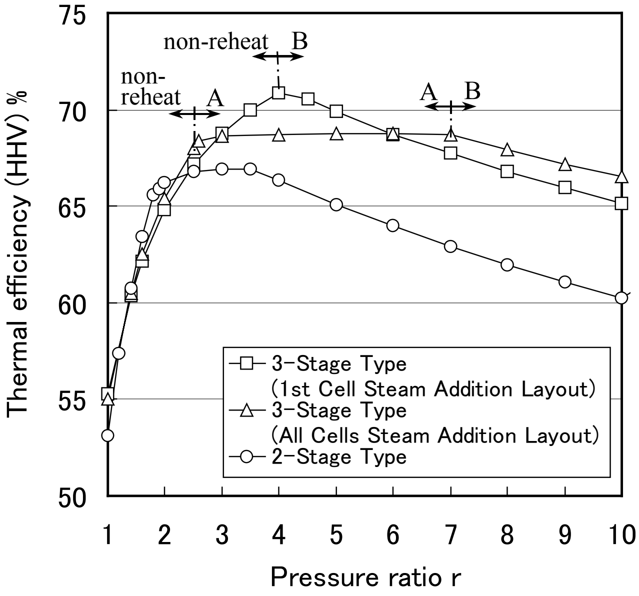


Fig.10 Thermal Efficiency of 3-Stage Type (1st Cell Steam Addition Layout and All Cells Steam Addition Layout)

steam generated at the anode in the first cell is utilized for reforming the fuel at the second and third fuel cells. The first cell steam addition layout has the advantage of the reduction of steam which is generated in the HRSG.

Figure 10 shows the effect of the pressure ratio on the thermal efficiency of 2-stage type and 3-stage types of two layouts. The characteristics of the non-reheat area, A region and B region which are shown in Fig.10, are the same as those of 2-stage type. The thermal efficiency of the 3-stage type is higher than that of 2-stage type.

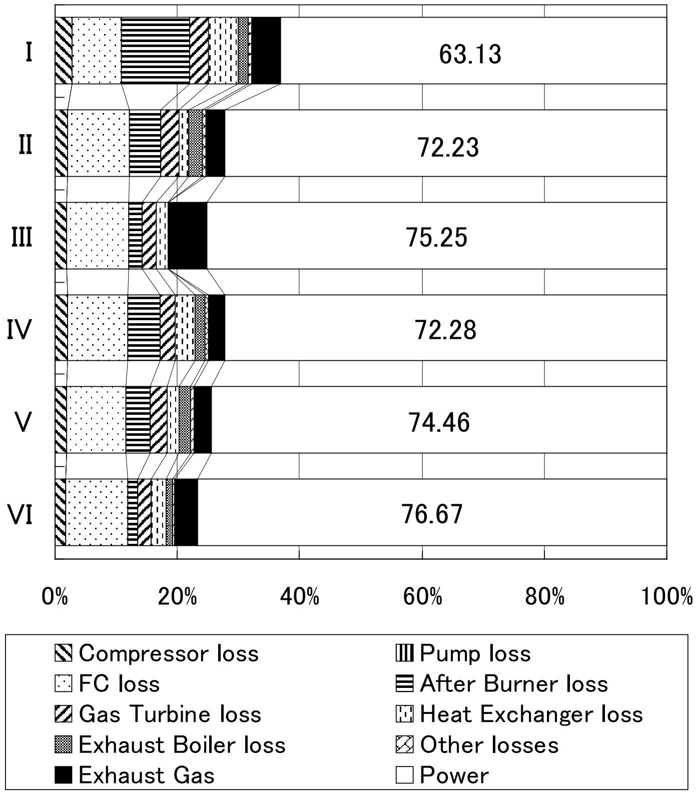
In the first cell steam addition layout, steam generated in the HRSG per unit fuel flow becomes small and the latent heat in the exhaust gas from the system becomes little. The HRSG doesn't have the pinch point even if fuel isn't supplied to the after burner. The system efficiency of all cells steam addition layout isn't increased with increasing the pressure ratio in the A region because the fuel flow supplied to the after burner is increased to prevent the pinch point of HRSG.

The 3-stage type of the first cell steam addition layout has the advantage of operating at high efficiency compared with the internal heat recovery type of steam circulation layout shown in Fig.5 because the exhaust gas temperature is lowered by the heat recovery in the HRSG. The high efficiency of 70.9% of the first cell steam addition layout is due to high fuel utilization ratio of 92%, low air ratio of 2.18 and no fuel supplied for the after burner. The optimum pressure ratio of the 3-stage type becomes low.

EXERGY EVALUATION OF SOFC/GT COMBINED SYSTEMS

Figure 11 shows the exergy evaluation of six SOFC/GT combined systems. The ratio of the exergy loss in each component against the exergy of the fuel supplied for the system is shown in percentage. The optimum pressure ratio and TIT of each system are used for the exergy analysis.

The main reactor of SOFC/GT combined systems is the fuel cell, and the exergy loss of it is about 10%. The exergy loss of a combustor in gas turbine systems is about 25~30% and the largest of all losses (Nishida et al., 2000). The efficiency of SOFC/GT combined systems is much higher than that of gas



I : Standard Type
II : Internal Heat Recovery Type
(Steam Addition Layout)
III : Internal Heat Recovery Type
(Steam Circulation Layout)
IV : 2-Stage Type
V : 3-Stage Type
(All Cells Steam Addition Layout)
VI : 3-Stage Type
(1st Cell Steam Addition Layout)

Fig.11 Exergy Evaluation of SOFC/GT Combined Systems turbine systems because of smaller irreversible loss in the reactor.

In the standard type, the exergy loss in the after burner becomes large because 30% of total fuel is injected to the after burner and the rate of fuel burned in the after burner is large. The air ratio is very excessive and the exhaust heat per unit fuel flow is large. These are the reason why the exergy loss of standard type becomes large. In the internal heat recovery type and multi-stage type, the fuel burned in the after burner is reduced by an increase in the fuel utilization ratio and a decrease in the ratio of fuel flow for the after burner. The air ratio is decreased by preheating the fuel and air in the fuel cell or by connecting fuel cells. The exergy losses in the after burner and the exhaust gas are smaller than that of the standard type, and the system efficiency becomes higher. The exergy loss in the exhaust gas of the steam circulation layout of the internal heat recovery type becomes large because the HRSG isn't installed and the exhaust gas temperature is high.

CONCLUSION

In this paper, we proposed the multi-stage type SOFC/GT combined system in order to achieve the high performance operation, and compared the characteristics of each combined system. The main results are as follows.

1. The thermal efficiency of each combined system becomes high at low pressure ratio. In the standard type and multi-stage type, the fuel supplied to the after burner is used for preheating the fuel and air in order to keep the temperature effectiveness of the heat exchanger 90% with preventing the pinch point of the HRSG. The optimum efficiency is obtained when the fuel supplied to the after burner is minimized. The supply of the fuel for increasing the TIT reduces the system efficiency.
2. The main reactor of SOFC/GT combined systems is the fuel cell. The exergy loss of the fuel cell is less than that of the combustor in gas turbine systems. SOFC/GT combined systems have the small irreversible loss reactor of the fuel cell and the efficiency becomes much higher.
3. The standard type efficiency is lower than other types efficiency because the exergy loss in the after burner is large. The internal heat recovery type and multi-stage type can achieve lower exergy loss in the after burner and higher system efficiency by an increase in the fuel utilization ratio and a decrease in the fuel flow for the after burner.
4. The thermal efficiency of 3-stage type with the first cell steam addition layout is higher than that of the internal heat recovery type, and can reach 70% of HHV.

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REFERENCES

Campanari, S., 2000, "Full Load and Part-Load Performance Prediction for Integrated SOFC and Microturbine Systems", ASME Journal of Engineering for Gas Turbines and Power, Vol.122, pp.239-246.

Hirschenhofer, J.H., Stauffer D.B. and Engleman R.R., 1994, "Fuel Cells A Handbook (Rev.3)", Gilbert/Commonwealth Inc. for U.S. Department of Energy (DOE).

Johansson, K.B., Båfält, M.H. and Pålsson, J., 1998, "Solid Oxide Fuel Cells In Future Gas Turbine Combined Power Plants", CIMAC Congress 1998 Copenhagen, pp.277-285.

Massardo, A.F. and Lubelli, F., 2000, "Internal Reforming Solid Oxide Fuel Cell–Gas Turbine Combined Cycles (IRSOFC-GT): Part A-Cell Model and Cycle Thermodynamic Analysis", ASME Journal of Engineering for Gas Turbines and Power, Vol.122, pp.27-35.

Mori, N., Abe, T. and Watanabe, T., 2000, "Study on SOFC Combined Cycle Power Generation System", Transactions of JSME (B), Vol.66, No.652, pp.3262-3267.

Nishida, K., Takagi, T., Kinoshita, S. and Tsuji, T., 2000, "Performance Evaluation of Regenerative, Steam/Water Injection and Combined Gas Turbine Systems", 4th JSME-KSME Thermal Engineering Conference, vol.1, pp.73-78.

Rao, A.D. and Samuelsen, G.S., 2001, "A Thermodynamic Analysis of Tubular SOFC Based Hybrid Systems", ASME Turbo Expo, New Orleans, Louisiana, Paper 01-GT-0522.